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MATERIALS SCIENCE

Synthetic polymers with biological rigidity

Brush-like polymers with a rigidity similar to that of polymers in living cells have been synthesized and used to build force-responsive materials. The advance opens the door to applications in drug delivery and tissue engineering.

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The diverse physiology of cells and tissues is underpinned by materials consisting of macromolecules whose mechanical behaviour allows organisms to control and maintain their shape[1]. The construction of synthetic versions of these materials could allow artificial cells and tissues to be made, but preparing such materials has long been a major challenge. In a paper published on *Nature*'s website today, Kouwer *et al.*[2] report that they have produced the first synthetic polymers whose rigidity can be tuned to mimic that of a wide range of their biological counterparts. The authors' achievement will facilitate the construction of polymer networks that have highly tunable, force-responsive behaviour.

Synthetic polymers, such as polyethylene, nylon and silicone, were an important class of material in the twentieth century, finding diverse applications as paints, adhesives, fibres and plastics. But these polymer molecules behave rather like cooked spaghetti, because they have little rigidity along their length. Their flexibility is entirely due to the randomization of the polymer chains' configurations by thermal energy — the energy available to act on molecules at ambient temperature.

Biological polymers, which are formed from amino acids or nucleic acids, are very different. These materials are ubiquitous in nature, and include DNA; cytoskeletal filamentous proteins, such as actin, microtubules and intermediate filaments; and scaffolding molecules in the extracellular matrix, such as collagen and fibrin. Biological polymers are much more rigid than chemical polymers, and so are similar to partially cooked spaghetti. Because of this high rigidity, the energy required to bend biological polymers is comparable to that available from thermal energy, such that they bend much less than synthetic polymers at ambient temperature. This inherent rigidity makes the mechanical behaviour of biological polymers at the bulk scale qualitatively different from that of synthetic polymers[3].

Kouwer and colleagues have discovered that polyisocyanopeptide polymers, grafted with flexible side chains of a different polymer, serve as mimics of a protein structure known as a β-sheet, and self-assemble into helical structures similar to those formed by DNA and actin filaments. Moreover, the authors report that the polymers aggregate into bundles when heated in solution (Fig. 1), similar to the bundles formed by collagen and fibrin.

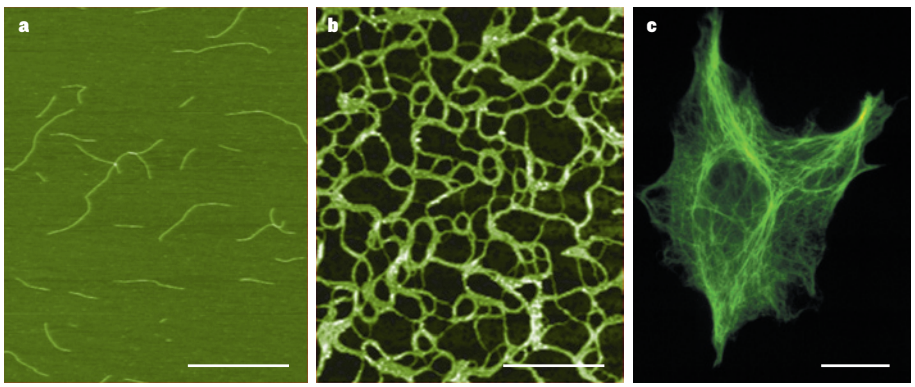
One way to characterize the rigidity of a material is through its persistence length: the higher the persistence length, the more rigid the polymer. The persistence length of biological polymers varies from about 100 nanometres for DNA to 1 millimetre for microtubules; by comparison, the effective persistence length of a flexible synthetic polymer is typically about 0.1 nm. When the authors characterized the mechanical properties of their polymers using force-spectroscopy techniques, they found that single polymer chains had a sizeable persistence length, 500 nm. They also found that this increased for larger bundles, consistent with the idea that rigidity correlates with bundle diameter. Kouwer and co-workers' materials therefore represent the first semi-flexible synthetic polymers to have tunable persistence lengths, and so might serve as building blocks for biomimetic materials.

One of the main consequences of increasing polymer rigidity is that it alters the mechanical response of crosslinked networks of the polymer. The mechanical rigidity of a material is described by a parameter known as the elastic modulus. For networks of flexible polymers (such as rubber), the elastic modulus depends only weakly on the density of the polymers or crosslinker connections. By contrast, in networks of semi-flexible polymers, the elastic modulus depends more strongly on these parameters[3].

A second characteristic of networks of semi-flexible polymers is that their response to stress is highly nonlinear[3]. Under increasing loads, conventional polymeric materials simply stretch until they break. Networks of semi-flexible polymers, however, stiffen under increasing load and have an elastic modulus that increases dramatically at a critical strain. Both of these distinctive properties of semi-flexible networks are typical of biological polymers, and are also found in Kouwer and colleagues' synthetic polymers.

Because of their unusual mechanics, the authors' materials are highly responsive to applied stress: as the applied stress increases, the elastic modulus also increases to minimize changes in deformation. This suggests that the materials will maintain their shape when subjected to a wide range of externally applied stresses. What's more, the polymers' highly tunable rigidity means that tiny quantities of polymer could be used to make materials that have a wide range of stiffnesses.

Kouwer and colleagues' polymers most closely mimic those found in intermediate filaments (Fig. 1), a class of intracellular polymer that is crucial for cell adhesion and migration and for maintaining cell shape[4]. It will be exciting to see if the authors' approach, or other approaches for making semi-flexible polymers, can be expanded to make synthetic



A, B, REF. 2; C, GOPAL MURTI/PHOTOTAKE

Figure 1 | Bundling fibres. Kouwer *et al.*[2] report the first synthetic polymer that has rigidity similar to that of biological polymers such as DNA. Single chains of the polymers (**a**) form bundles (**b**) when heated in solution. The polymers most resemble those found in intermediate filaments (**c**) inside cells. Scale bars: **a**, **b**, 250 nm; **c**, 85 μm.

mimics of DNA, actin filaments and microtubules. Another challenge will be to find a way of adding mechanochemically active components[5] — those that transform chemical energy into mechanical work — to the polymer. This would enable filaments to be made that exhibit exotic polymerization behaviour, such as treadmilling (in which one end of a filament grows while its other end shrinks), or which create dynamic instabilities or crosslinks, to form the basis of a molecular motor.

The ability to build 'active' soft materials that respond to external chemical and mechanical signals will provide opportunities in the areas of condensed-matter physics and materials science for years to come. Such materials might allow the construction of artificial cells and tissues that are more closely compatible physiologically with their counterparts in humans than currently available materials, so that they might be used in the next generation of drug-delivery and tissue-engineering technologies. Active soft materials might also change the way in which we engage with the physical world, by forming the basis of highly responsive and malleable materials and machines. Kouwer and co-workers' polymers are an exciting first step in these directions. ■

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