

NANOMECHANICS

Macromolecules flex their muscles

It will take a concerted effort for nanomachines to express themselves on a macroscopic scale. Could self-organizing helical polymers help?

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While reading these words, spare a thought for the billions of molecules that must change their shape slightly in a collective manner so that you can flex your muscles. The dream of many scientists working on nanomachines is to design molecular systems that can behave like this. The goal is to make molecules that can, in response to some trigger, change their shape in a way that results in a mechanical function. The major challenges facing researchers in this field are to develop methods for controlling the direction of the motion and to get large numbers of molecules to work in unison so that ultimately they can perform work. Recently, Virgil Percec and co-workers¹ from the University of Pennsylvania in Philadelphia have shown how helical polymers can provide such capabilities. These polymers, in which each individual molecule can stretch and contract, can be organized into fibres in such a way that their concerted action can move objects 250 times their own mass.

Percec and colleagues have elegantly combined the principles of self-organization and polymer chemistry to achieve macroscopic mechanical motion. By simply increasing or decreasing the temperature of an extruded piece of their artificial 'muscle', it can be made to extend and contract in a fully reversible manner (Fig. 1). Upon heating, the helical polymer chain unwinds increasing its length. Cooling results in the reverse process. But this molecular movement alone is not enough to provide function on a macroscopic scale. For this to happen, many molecules must work in concert, which requires their axes to be collinear. In other words, all the helical polymer chains have to self-organize into long fibres and assemble into cylindrical domains along a common axis.

In order to control this self-assembly process, each unit in the polymer is equipped with a dendritic wedge protruding from the helical backbone. The dendritic wedge is

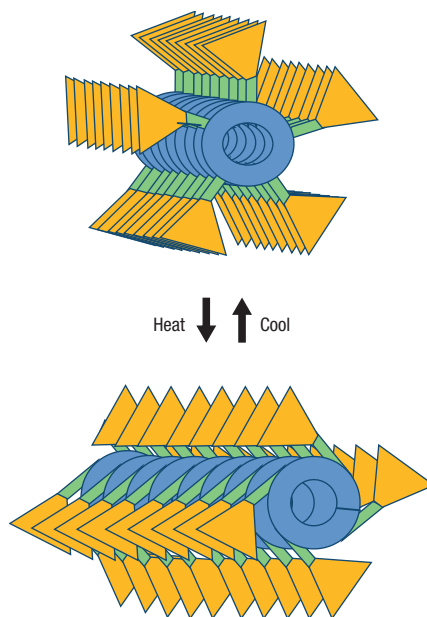


Figure 1 A change in temperature results in the reversible expansion or contraction of a helical polymer (blue). The polymer used is a polyphenylacetylene with dendritic side chains (yellow), which can flip between a cisoid (top) and transoid (bottom) conformation. When many of these polymers are made to work together, they can function as an artificial 'muscle'.

essential for the supramolecular columnar organization of the polymer chains, and simultaneously protects them so they remain in the fibre-like structure. Finally, a process called polymer extrusion is used to achieve ordered orientation of the fibres over macroscopic dimensions. Thanks to these innovative design features, constructive movement of many fibres occurs, exclusively along the fibre axis. Thus, by changing the temperature, the polymer can be used as a nanomechanical actuator.

Achieving thermal motion at the molecular level is far from challenging — indeed molecules move incessantly owing to Brownian motion. The expansion and contraction of a material as a result of temperature change is an equally ubiquitous

phenomenon. The challenge to nanoscientists is to rise above this random Brownian regime and achieve molecular-level motion with full directional control using an energy source. In many respects this has already been achieved in recent years with a remarkable array of molecular systems^{2,3}. However, to take this to the micro- and macroscopic level, and ultimately to be able to perform work, requires coordinating the directed movement of ensembles of molecular machines.

At the microscale, Stoddart and co-workers⁴ have demonstrated that self-assembled monolayers of molecular motors can be used to bend micro-cantilevers. Although self-assembled monolayers allow molecules to work in concert, there are inherent limits on the total effective work that can be done. The advantage of supramolecular chemistry, and liquid crystals in particular, is that large numbers of molecules can be shepherded into collective directional motion. Recently, light-driven molecular rotary motors acting as a dopant were shown to control the alignment of liquid crystals, which translated into work sufficient to move microscale objects with complete directional control⁵.

The use of polymers within this field is particularly attractive because molecular motion can be expressed at even larger length scales — bridging the gap between the nano and macro worlds. The ability to control structure, organization and dynamics at different hierarchical levels is crucial to this endeavour. The work of Percec and colleagues is a beautiful demonstration of the interplay of covalent and non-covalent molecular interactions. The careful design of helical polymers that respond to temperature change and the ability to achieve precise supramolecular organization are the key features that make this muscle-type action possible.

With this increasing control and exploitation of molecular motion, are we then any closer to molecular machines? Looking at the complex functions that biological nanomachines perform, it is clear that our present systems are still very primitive and that tremendous challenges remain. The controlled and directional

motion at the molecular, microscopic and macroscopic level achieved thus far sets the stage to couple molecular motion to useful functions and to build nanomechanical devices. In order to take a major step forward — and this is arguably the most important message to take from Percec *et al.* — it is insufficient

to be able to handle the structure and function of molecules: organization at different hierarchical levels, dynamics and communication between molecules all need to be held under exquisite control. This exciting move from molecules to molecular systems opens a new era in molecular- and nanoscience.

References

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INSTRUMENTATION

Carbon nanotubes on the brain

The performance of metal electrodes used for studying brain function and relieving the symptoms of medical conditions can be significantly improved by coating them with carbon nanotubes.

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Faulty electrical signals in the brain occur in medical conditions such as tetraplegia, Parkinson's disease, epilepsy and depression among many others. At present, brain-machine interfaces can be used to help understand brain function and restore the movement in tetraplegia^{1,2}. At the cellular level this interface is established between neurons (the electrically excitable cells of the brain) and electrodes, and the final contact on the machine side has usually been the metal surface of an electrode. The challenge for researchers in this field is to lower the impedance of the electrodes — that is, their electrical resistance to an alternating current — to increase sensitivity when they are being used to record signals, and to increase the delivery of electrical charge when they are being used to stimulate neurons. On page 434 of this issue, Edward Keefer and co-workers³ offer a solution to this problem by using carbon nanotubes to coat various metal electrodes.

The unique mechanical, chemical and electrical properties of the carbon nanotubes make them one of the most promising materials for application in neural prosthesis⁴. High mechanical strength is important because the electrodes need to penetrate tissue, and the ability to operate as ballistic conductors — materials that do not significantly slow down the flow of electrons — should aid in lowering impedance and increasing charge transfer. With these characteristics in mind, Keefer

and co-workers, who are based at the University of Texas Southwestern Medical School, the Texas Scottish Rite Hospital for Children, Vanderbilt University and the University of North Texas, investigated the use of nanotube-coated electrodes in preparing brain-machine interfaces. Importantly, the material also appears to be biocompatible⁵.

Initial experiments in the absence of brain cells showed that coating indium tin

oxide electrodes with nanotubes reduced the impedance by ~20-fold and increased the charge transfer by ~45-fold. Next, neurons were grown on an array of planar gold electrodes, half of which were over-coated with nanotubes (Fig 1a). Neuronal networks were established with success on both types of electrode, and the activity of neurons was measured for up to three months. The stimulation delivered via nanotube-coated electrodes was more effective than that via

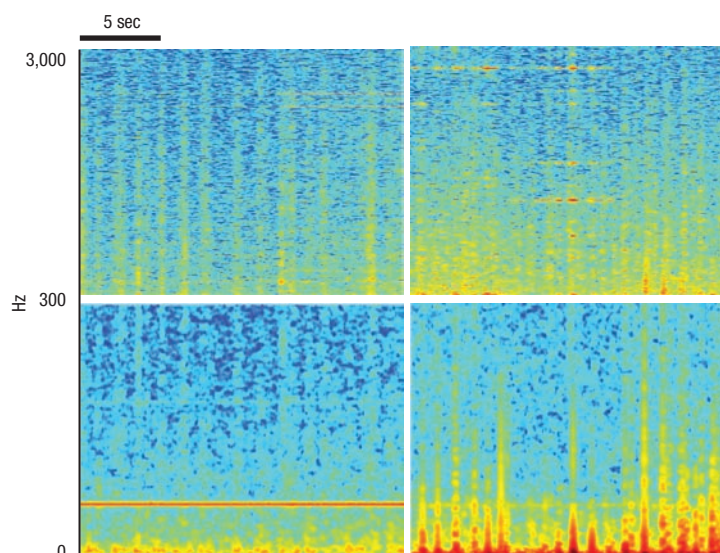


Figure 1 Spectrographs from 20 seconds of brain activity recorded from the motor cortex of an anaesthetized rat using bare metal electrodes (left) and nanotube/polypyrrole-coated electrodes (right) over two different frequency ranges: 0–300 Hz (lower panel) and 300–3,000 Hz (upper panel). The colour scale runs from high intensity (red) to low intensity (blue). The coated electrodes provide improved charge transfer, and there is little evidence of 60 Hz electric line noise contamination (the horizontal line in the lower left panel).