NANOTECHNOLOGY'S BIG IMPACT

By Nadia Halim

Imagine a doctor injecting a patient with tiny devices that can rove the body in search of cancer cells or disease-causing bacteria. Such devices would deliver medicine targeted specifically to a diseased organ or to the bacteria.

Though still years away scientists are trying to make such a scenario possible through nanotechnology, a hot research area in which scientists use atoms and molecules to build materials that can be used in many areas, such as health care, clean energy sources, and shrinking electronics.

BACKGROUND GRAPHIC: ISTOCK

These "nanomaterials" measure between 1 and 100 nanometers. Derived from "nanos"—the Greek word for "a small person"—a nanometer is 1 billionth of a meter. In comparison, a strand of hair is roughly 100,000 nanometers wide.

One of the main appeals of nanomaterials is that they have different properties than everyday materials. For example, they do not melt at the same temperature as everyday materials and do not conduct electricity like everyday materials.

These different properties are due to an increase in the surface area of nanomaterials and to their unusual shapes—such as tubes and hollow balls—which can affect how durable they are, how they conduct electricity and heat, and how they absorb light.

Nanotubes and Nanowires

An essential part of the nanotechnology toolkit is a tiny cylinder, called a nanotube, which has attracted widespread attention since the early 1990s. A nanotube is basically a sheet of pure, carbon graphite rolled into a cylinder. Nanotubes are usually a few nanometers in diameter and between 1 and 100 micrometers—1 thousandth of a millimeter—in length.

In an individual graphite layer, called graphene, carbon atoms form a series of six-sided hexagons next to one another. So, when a graphene sheet is rolled up to form a tube, the tube's wall is made of carbon hexagons (Fig. 1). The hexagons can be parallel to the axis of the tube (Figs. 1a and 1c) or form a helix that winds along the tube (Fig. 1b).

A nanotube's diameter and how the hexagons are arranged on the wall affect the way nanotubes conduct electricity, making them useful for making electronic components much smaller than those currently used. Also, these tiny tubes are lighter and stronger than steel so they could make good body armor. Research from Alan Windle, a professor of materials science at the University of Cambridge, United Kingdom, suggests that carbon nanotubes in the shape of long, yarn-like fibers could outperform even the strongest bullet-proof materials on the market.

Solid rods of silicon or other materials that are only a few nanometers wide are called nanowires. A nanowire's length is much longer than its width and it behaves like a wire in which electrons can move, thus conducting an electric current.

Nanowires have shown potential applications in solar cells, which harvest the sun's energy and turn it into electricity more efficiently than present solar cells. Also, researchers have used nanowires to build sensors that can detect disease-triggering molecules in the body or harmful chemicals in the air.

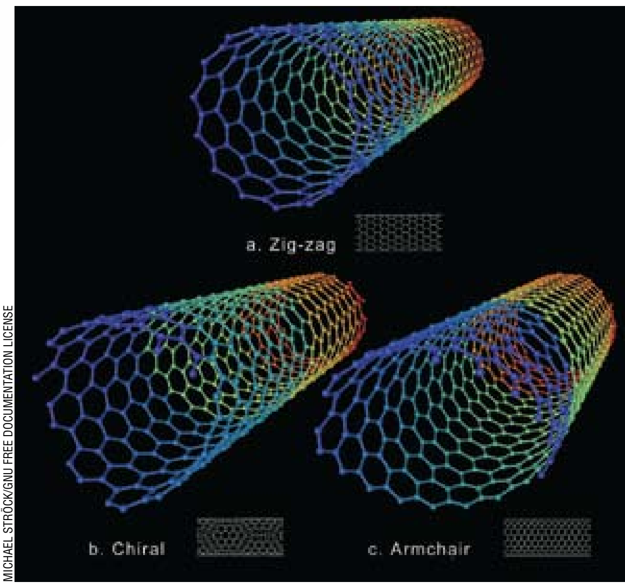

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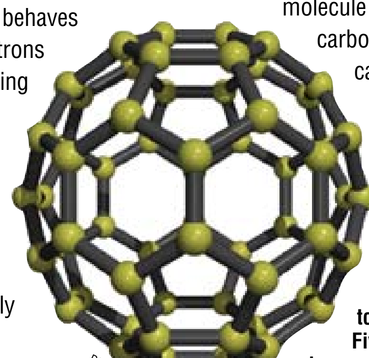
Figure 1. Structures of different types of carbon nanotubes: (a and c) Hexagons parallel to the axis of the tube; and (b) hexagons forming a helix that winds along the tube.

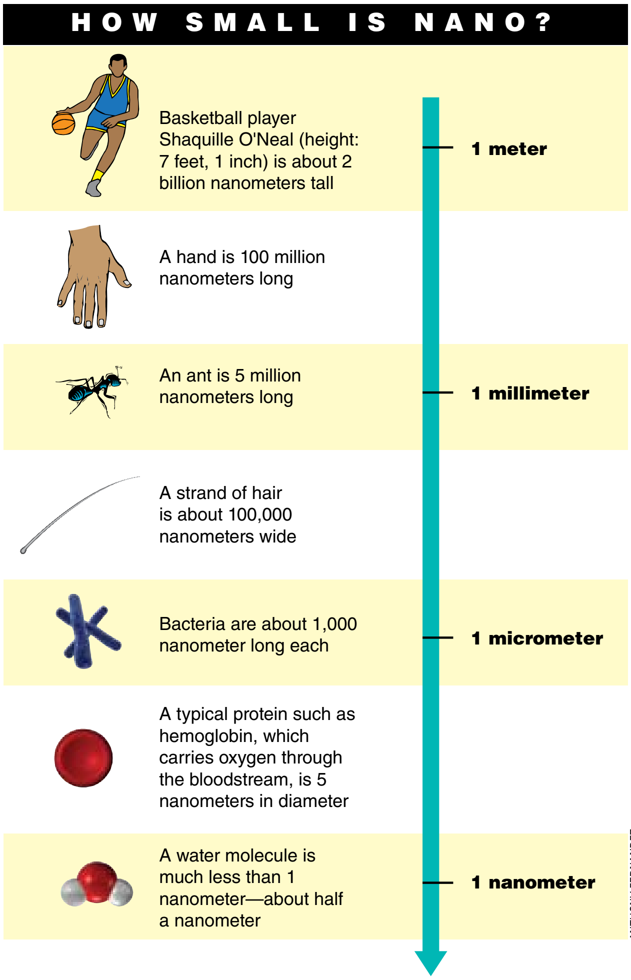
Nanoballs

Another important structure used extensively in nanotechnology is called a fullerene or "buckyball." This hollow soccer ball-shaped molecule is made of 60 carbon atoms, each carbon atom bonded to three adjacent carbon atoms (Fig. 2). The sphere is about 1 nanometer in diameter. Other existing buckyballs contain either 70 or 80 carbon atoms.



PAUL R.C. KENT, OAK RIDGE NATIONAL LAB

Figure 2. Structure of a buckyball. The buckyball has 60 carbon atoms, each carbon atom bonded to three adjacent carbon atoms. Five-sided pentagons and six-sided hexagons are arranged on the surface.



ANTHONY FERNANDEZ

Several academic laboratories and companies are developing modified buckyballs for therapeutic uses. Luna Innovations, a company based in Roanoke, Va., that develops products for the health care, telecommunications, energy, and defense markets, is testing buckyball-based therapeutics to block inflammation, swelling, and pain associated with medical conditions, such as allergies, arthritis, and wound healing.

This technology is based upon the buckyballs' unique ability to trap harmful free radicals, which increase inflammation and can damage or kill cells. Free radicals are molecules that have an uneven number of electrons. Some free radicals form as part of an immune response targeting viruses and bacteria. Environmental factors such as pollution, radiation, cigarette smoke, and herbicides may create free radicals, too.

The unpaired electron makes free radicals highly reactive. To become stable, free radicals seek to pair that lone electron by taking an electron from another molecule. When this molecule loses its electron, it becomes a free radical itself. This chain reaction ultimately damages the cell when the body cannot cope with too many free radicals.

Luna Innovations has shown that buckyballs can neutralize a dangerous free radical when its unpaired electron is transferred to the buckyball forming a bond. When tested in human-cell culture experiments and mice, Luna Innovations found the buckyballs blocked allergic response.

Nano-drug delivery

Scientists are turning to nanotechnology to solve other health care issues. For instance, the standard pill that is swallowed does not efficiently get a drug to the right place and in the right amount. It releases a drug quickly, but its concentration rapidly decreases in the body. So, patients need to take medication often.

Tejal Desai, of the University of California at San Francisco, is developing a better way to deliver medicines to the body. Her group has designed a microchip with nanometer-sized channels that will be able to steadily release a drug over time.

By using pores as small as 7 nanometers in diameter, the scientists observed constant release for tiny molecules of glucose. The steady release of the glucose molecules over time is a result of the tiny size of the nanochannels, which limits how fast the molecule can be released.

Then there are other obstacles to overcome in drug delivery. A good oral drug delivery vehicle has to survive extreme acidity and digestive enzymes as well as mechanical agitation in the stomach, and transfer the drug across a mucous layer, which is meant to keep out foreign invaders, such as pathogens.

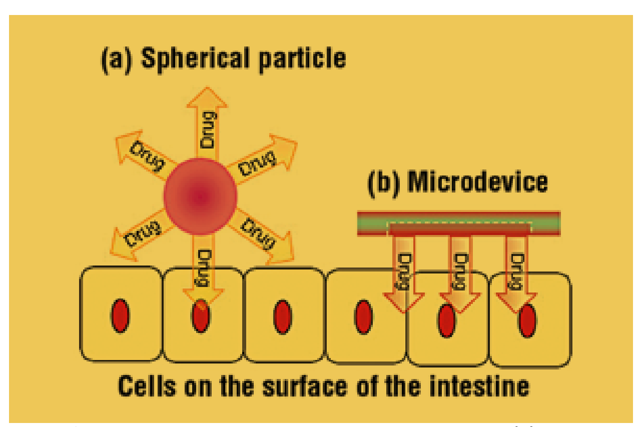
"If you can prolong the residence time of a drug or a drug carrier at the site of interest, and if you can improve the contact between the drug-delivery device and your absorbing surface, you can increase the amount of drug available to the body," Desai says. To accomplish this, she and her team have created a flat delivery device which is able to dock on the intestinal wall and release drug through it (Fig. 3). This way, most of the drug goes to the targeted area.

Buckyballs have high potential for drug delivery. This approach involves attaching drug molecules to the carbon atoms on the surface of the buckyball. Other chemical groups are added to make the molecules water soluble. This allows the medicine-loaded buckyball to be absorbed by the bloodstream when swallowed or injected. The buckyball can then release the drug upon reaching a chemical trigger, such as a change in pH or a particular chemical substance, such as those released by cancer cells.

Future challenges

Though the potential for nanotechnology is great, there are still many hurdles to overcome before nanomaterials and nanomachines become part of everyday life. One important challenge is creating better manufacturing methods. Creating large quantities of nanoscale materials is still time-consuming and expensive.

"It's like trying to make things out of Lego blocks with boxing gloves on your



TEJAL DESAI, UNIVERSITY OF CALIFORNIA AT SAN FRANCISCO

Figure 3. Drugs can be delivered through the intestine by (a) a traditional spherical particle, which releases drug in all directions, but not all the drug makes it into the intestinal cells. Alternatively, (b) a microdevice, such as the one devised by Tejal Desai and colleagues, delivers all the drug directly to the intestinal cells.

hands," says Ralph Merkle, senior research fellow at the Institute for Molecular Manufacturing, Palo Alto, Calif.

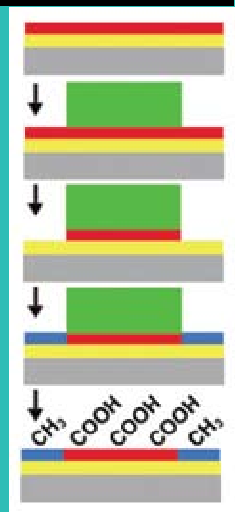
The next step will be to take the gloves off and develop methods of snapping atoms together. New technologies will have to be developed to safely and reliably do so, and standards and measurements will need to be created to ensure the quality of the resulting nanomaterials.

HOW TO BUILD NANOMATERIALS

There are basically two ways to build nanomaterials. Researchers can modify a starting material much like an artist shapes a sculpture from a slab of marble, adding to it and taking material away from it. With this method, called the "top-down" approach, a material is altered by mechanical or chemical means.

An electron beam or light are usually used to create these incredibly small structures. The techniques are called electron beam lithography and photolithography, respectively. In electron beam lithography, a focused beam of electrons forms the circuit patterns needed for depositing material on or removing material from a surface. In contrast, photolithography uses light for the same purpose.

Photolithography is limited in the size of the patterns it creates by the wavelength of visible light, which range between 400 nanometers and 700 nanometers. Narrower features can be made by using ultraviolet light with shorter wavelengths, between 380 nanometers and 10 nanometers, which is more expensive. In contrast, electron beam lithography produces patterns in the order of 20 nanometers but takes longer and is expensive.



An example of a "top-down" technique to make nanomaterials called photolithography.

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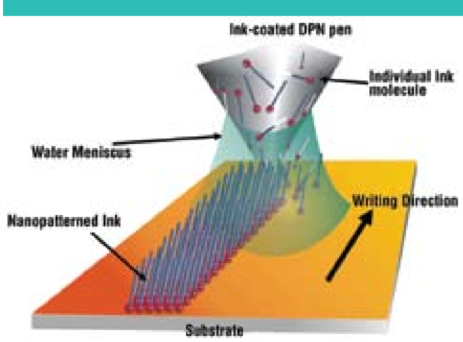

An example of a "bottom-up" technique to make nanomaterials called dip-pen nanolithography (DPN).

NANOINK, INC.

Alternatively, the "bottom-up" approach starts with individual molecules or atoms and brings them together to form a product in which every atom is in a designated location. Often molecules are designed and created so that they can spontaneously self-assemble when a chemical or physical trigger is applied. An example of this in nature is the formation of a double strand of DNA, the genetic material in every cell.

Weak interactions play an important role in bottom-up manufacturing. These bonds can be made and broken much more easily than the covalent bonds that bind most atoms in molecules.

Although bottom-up processes are less developed and understood, they hold great promise for the future, because they lead to a wider variety of structures. In practice, both top-down and bottom-up methods are useful and being actively pursued, but the ultimate goal of building products with atomic precision will require a bottom-up approach. Some scientists foresee a day when nanomachines will be programmed to replicate themselves, or to work synergistically to build larger machines.

Along with the promise to improve the quality of life, nanotechnology still holds many unknowns. While the basic research is conducted by scientists and engineers, several programs are looking at the possible societal and ethical impacts of nanotechnology. Others are testing the safety of exposing our environment and our bodies to nanomaterials.

For instance, mice and fruit flies have been exposed to carbon nanotubes with mixed results. In one study, mice were injected with water-soluble carbon nanotubes. Kostas Kostarelos, a professor of pharmacy at the University of London's School of Pharmacy, and colleagues found that the nanotubes were harmlessly excreted intact in urine. Other studies have found that inhaled nanotubes can accumulate in the lungs and cause inflammation.

Since the data is limited and many more studies are necessary to help determine the real risks of nanomaterials, the U.S. Congress has stepped into the field. Earlier this year, the U.S. House of Representatives passed a bill that requires federal agencies participating in the National Nanotechnology Initiative—a program established in 2001 to coordinate nanotechnology research among various federal agencies—to develop a plan for environmental and safety research. A similar bill is expected in the U. S. Senate soon. While the safety debate continues, scientists will forge ahead in their search for nanotechnology solutions to life's challenges.

SELECTED REFERENCES

Northwestern University, Discover NANO: http://www.discovernano.northwestern.edu/index_html [June 2009]

Video clip of Tejal Desai and her laboratory, PBS Kids, Dragonfly TV, Real Scientists: http://pbskids.org/dragonflytv/scientists/scientist67.html [June 2009]

Bullis, K. The Year in Nanotech. *Technology Review*, Jan 3, 2008: http://beta.technologyreview.com/computing/19983/ [June 2009]

Goodman, S. Researchers Look to Make "Messy" Nanotech Production "Clean and Green." *The New York Times*, April 13, 2009.

Inman, M. Nanotech: The Shape of Things to Come. *New Scientist*, Feb 27, 2008: http://www.newscientist.com/article/mg19726451.800-nanotech-the-shape-of-things-to-come.html?full=true [June 2009]

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