Nanoparticle Transport Using Motor Proteins

by Bruce Bunker, George Bachand, Andrew Boal, Susan Rivera, Joe Bauer, and Ron Manginell

Motivation—In living systems, molecular motors called motor proteins are used to assemble and manipulate objects ranging in size from proteins to muscles. Sandia is currently exploring the extent to which these molecular machines can be exploited within artificial microfluidic systems to manipulate nanometerials. As a first step, we are developing the basic components of an energy-consuming active transport system that can be used to pick up, transport, and deposit nano-particles within a microfluidic system. The active transport system is based on the interactions between self-assembled monolayers containing the motor protein kinesin and short (5-10 μm long) segments of 25 nm diameter protein tubes called microtubules. In the presence of a fuel source (adenosine triphosphate or ATP), the head groups in the motor proteins "walk" along specific sites on the microtubule. When the kinesin motors are tethered within self-assembled monolayers (Fig. 1), the collective action of the motors can propel microtubule "shuttles" across a substrate surface.

Accomplishment—We have now demonstrated that microtubule shuttles can be functionalized to carry nanoparticles across a surface, and have also developed surface functionalization schemes for substrates that allow nanoparticles to be collected and deposited in desired regions within a microfluidic system. Random incorporation of the chemical handle biotin has been used to provide binding sites for streptavidin-coated gold nanoparticles. Video images obtained in a fluorescence microscope show that large numbers of particles can be carried by each microtubule without interfering with transport (shuttles continue to move at velocities of up to 2 μm/sec — Fig. 2). However, for the case of streptavidin-coated CdSe quantum dots, it appears that particle loadings are so high that the motor proteins can no longer bind to the microtubules. To overcome this problem, we have used functionalized microtubules as "seeds" to grow hybrid microtubules in which the ends of the tubes contain no functional groups. The non-functionalized segments serve as "engines" for the microtubule "train" whose central segment serves as the "car" for carrying nano-cargo. Transport measurements show that the hybrid microtubules laden with quantum dots are readily transported across monolayers containing the motor proteins (Fig. 2). Work is in progress to utilize this active transport system to: (1) assemble conductive interconnects using gold particles (by analogy to the natural assembly of diatom skeletons from silica nanoparticles), and (2) reconfigure arrays of quantum dots in analogy to the color changing system of the chameleon.

Significance—Self-assembly processes represent the current state-of-the-art for organizing nano-scale objects into macroscopic materials. While objects ranging in complexity from self-assembled monolayers to meso-porous materials can be produced via self-assembly, the range of structures that are possible from such assembly are limited by diffusion and equilibrium interactions between assembling components. By progressing to active assembly processes using energy-consuming molecular machines such as motor proteins, we should ultimately be able to create or reconfigure highly non-equilibrium structures. The research reported here represents an important first step in controlling active assembly. We have shown that motor protein systems can be used to pick up, transport, and deposit nanoparticle cargo within artificial microfluidic systems. The next step in the process will involve learning how to actively program transport and cargo manipulation functions.

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Contact: Bruce Bunker; Biomolecular Materials & Interfaces, Dept. 1116Phone: (505) 284-6892; Fax: (505) 844-5470; E-mail: bcbunke@sandia.gov

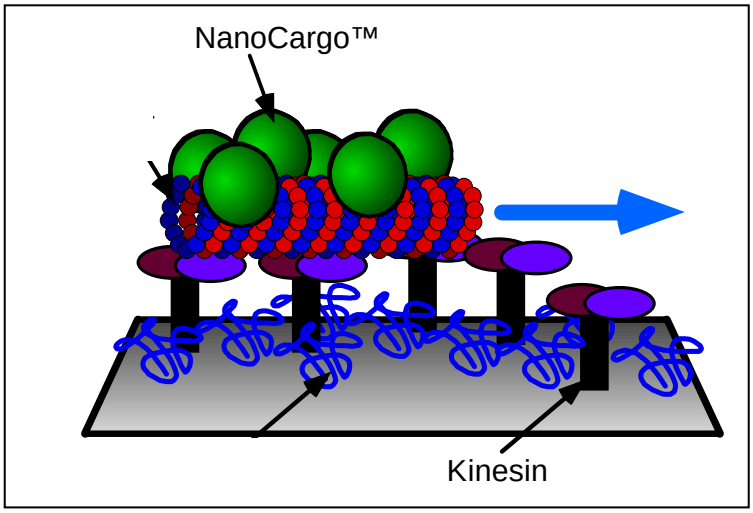

Figure 1. Schematic showing the monolayer geometry used to deploy motor proteins for active transport in artificial microfluidic substrates. Black tails of kinesin motors are tethered within a monolayer (blue lines) on a substrate surface. ATP-activated motion of head groups (ovals) propels a microtubule and its associated nanoparticle cargo.

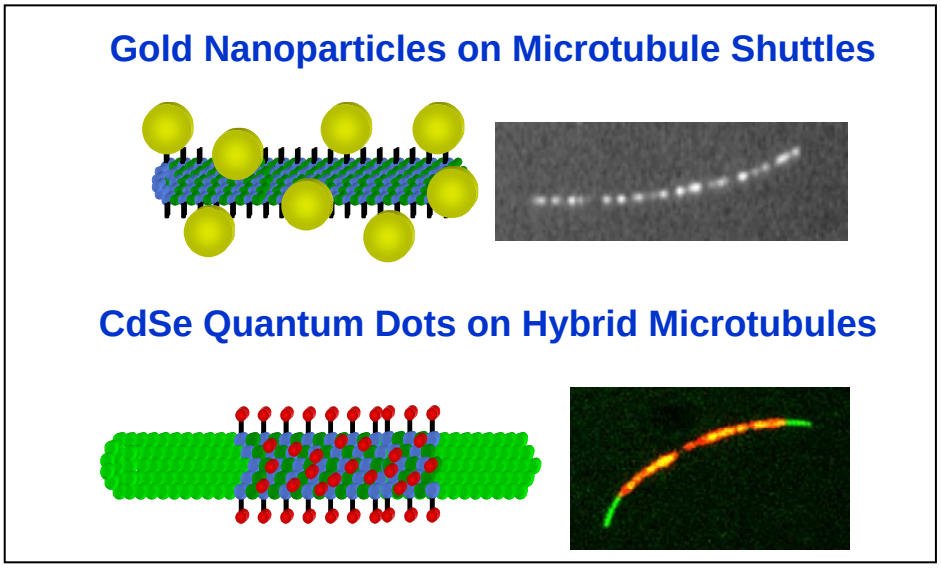

Figure 2. Top – Random functionalization of microtubules allows for attachment (left) and transport (right) of fluorescently labeled gold nanoparticles. Bottom – Hybrid microtubule (left) forms a "nanotrain" in which normal tubulin (green) provides transport, while functionalized tubulin (blue) carries quantum dot cargo. Microtubules shown in the micrographs on the right are around 8 μm long, and are taken from video images in which both types of shuttles crawl along the substrate surface. The bright spots in the upper micrograph are gold nanoparticles. In the bottom image, the green regions are fluorescently labeled tubulin, while the red and gold areas are regions laden with quantum dots.