Racing with Nature: Artificial Nanomachines That Keep Running on Light, Both Left and Right

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PERSPECTIVE

ABSTRACT

Nature's molecular motors and nanomachines perform marvelous tasks, especially on the level of single cells. Can artificial ones compete? In this issue, You *et al.* demonstrate a photon-driven molecular machine where switching the color of the light switches the direction of motion of the molecular motor. While having inferior performance characteristics, this novel motor may become the forerunner of a new generation of sophisticated and practical competitors with Nature's ancient, but highly important, nanomachines.

Following the Olympic motto, "*Citius, Altius, Fortius*" ("Faster, Higher, Stronger"), there is a nano-Olympics going on concerning nanorunners and nanoswimmers, *i.e.*, molecular nanomotors. In contrast to macroscopic motion, whether by animals or machines, nanosized motions operate under low Reynold's number conditions, and the random Brownian thermal motions dominate the dynamics. Only within the past decade, interest has commenced regarding nanoscopic movement, which is indispensible in nature.[1] Early life, on the single-cell level, already utilized directed molecular motion along microtubules or directed ionic transport in ion channels. Artificial nanomachines, which are based on either small synthetic molecules or DNA, have all been inspired by the enzyme-based molecular motors existing in nature. In contrast to nanomachines based on small molecules, DNA-based walkers are more comparable in size with Nature's molecular motors and could be more easily synthesized by automated synthesizers and rationally designed into some quite complicated structures.

There has been obvious interest in stimuli-responsive movable nanomachines. In the "race" with natural molecular motors, all artificial walking motors fall short in terms of efficiency and performance. However, while natural molecular motors are constrained to using only ATP as fuel, artificial nanomachines could be developed with the use of various energy sources and, therefore, may eventually win this race. Previous workers have explored DNA walkers that utilize energy supplied by DNA hybridization[2−4] or by the hydrolysis of the DNA/RNA backbone[5−8] or ATP molecules.[9] Tan's group recently reported the first light-powered DNA walkers. The use of photonic energy allows autonomous and controllable movement.[10] In this issue of *ACS Nano*, Tan *et al.*[11] report a new light-powered DNA locomotion device, which is capable of autonomous and reversible motion along an oligonucleotide track; moreover, this device could select its route in a multipath system, based on the wavelength of the light used.

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As can be seen in Figure 1, the main advance in this work is that the direction

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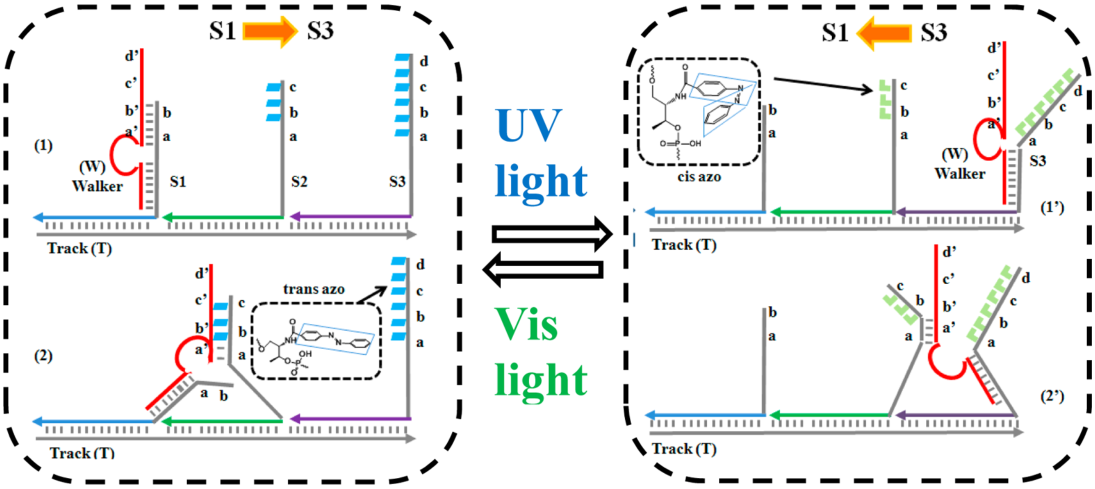

Figure 1. Principle of the DNA-based walking device. The locomotion of the walker is realized through toehold-mediated strand displacement. (a) Visible light irradiation (azobenzene, *trans*) triggers walker motion in the direction of S1→S3; (b) UV light (azobenzene, *cis*) induces the reverse movement of S3→S1.

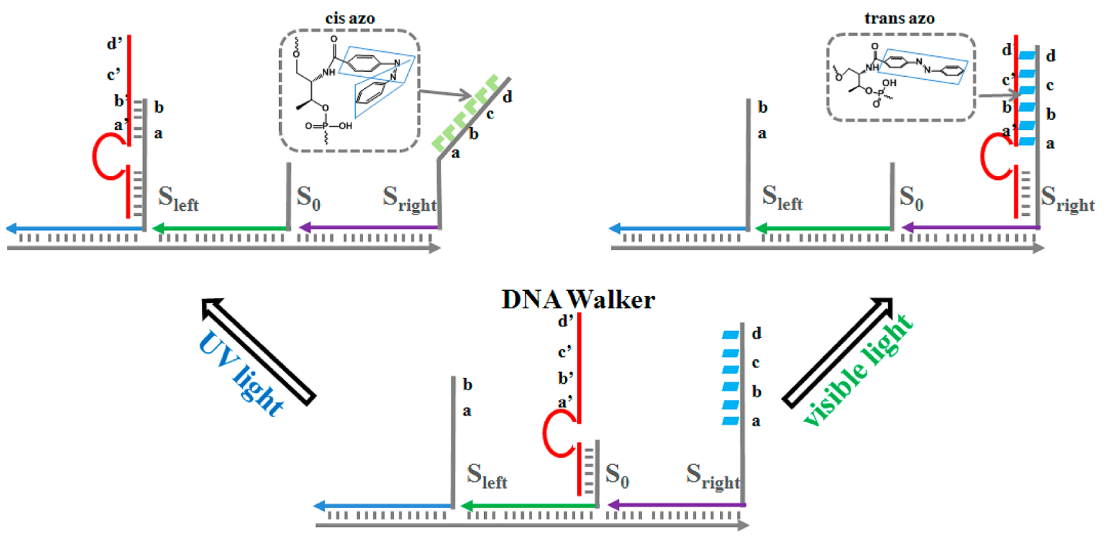

Figure 2. Programmed control of route selection at a junction. Left turn (S_0→S_{left}) was achieved under UV light irradiation, and right turn (S_0→S_{right}) was induced by visible light.

of motion can be switched, *i.e.*, controlled, by the color (wavelength) of the light. The motion can be stepwise in one direction, using visible light, or in the opposite direction, using ultraviolet light.

Furthermore, at a "junction", the walker can move to the left or move to the right, again by proper choice of the color of the light, *i.e.*, the photons that drive and control the direction of this nanocar (Figure 2).

Regarding the development of stimuli-responsive walking devices, there have been some recent reports on stimuli-responsive walkers that are based on either small molecular systems or DNA. Feringa *et al.* developed an electric-powered, four-wheel drive, single-molecule nanocar that travels over a copper surface.[12] Leigh *et al.* reported several two-legged molecular units moving along a four-foothold track stimulated by pH, redox condition change, or light.[13−15] Some recent efforts have been focusing on the development of stimuli-responsive DNA walkers: Willner *et al.* reported on bipedal DNA walkers activated by acid/base and Hg^{2+}/cysteine triggers.[16] Qu *et al.* also reported on a pH-sensitive molecular switch with translocation ability, but not in a directional and progressive manner.[17]

OUTLOOK AND FUTURE CHALLENGES

Regarding future outlook and challenges, efforts may first be taken on improving the performance of artificial walking motors, including the speed, accuracy, and the distance they can travel: right now, the record is around 100 nm (13 steps) for DNA-based walkers.[8] Meanwhile, more complicated systems, with networks of pathways and junctions (*e.g.*, two-dimensional or three-dimensional DNA origami tracks), may now be studied to examine the potential of walking devices.[18] The usage of these artificial devices for analytical, biomedical, and materials applications may be one major direction for the development of walking devices. Currently, these examples are still quite rare: the only instances are in transferring/assembling cargoes[4] and autonomous consecutive chemical synthesis.[19] On occasion, many walkers may need to collaborate in large groups so as to perform a practical function (*e.g.*, to mimic the force generation process for muscle contractions). Even though they are more controllable now, stimuli-responsive or non-ATP-fueled walks are still mostly performed in a non-autonomous way; that is, one has to add fuel step-by-step. In this respect, light-powered machines have definite advantages. In the near future, various types of fuel-powered machines could appear, driven by magnetic, electric, ultrasound, or other forces. Moreover, chemically stimulated walkers (such as with ATP or cancer cell markers as stimuli) could be used in the future as "*in situ* fueled" devices, outperforming natural molecular motors, which require the ATP environment. The future development of artificial walking motors may continue to be a game of the human mind, and a game of expanding our potential on the nanoscale, following the Olympic slogan, "*Citius*, *Altius*, *Fortius*".

Conflict of Interest: The authors declare no competing financial interest.

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