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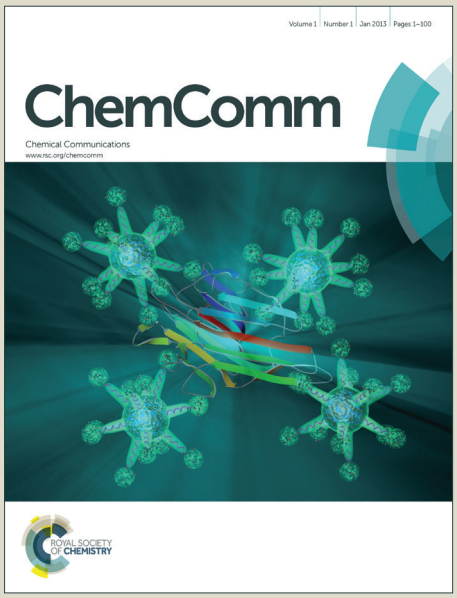

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DNA-functionalized Pt nanoparticles as catalyst for chemically powered micromotor: Toward signal-on motion-based DNA biosensor

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We present here the construction of a DNA biosensor based on a tubular micromotor that only produces motion signal in the presence of DNA target. This "turn on" characteristic of the sensor is achieved by the recruitment of Pt nanoparticle-DNA conjugate as motion-inducing catalyst for micromotors through DNA hybridization. Our work potentially offers new design strategies for motion-based biosensors with higher specificity.

Catalytic micro/nanomotors that are capable of converting chemical energy into autonomous motion have found applications in various fields ranging from biomedicine to environmental management.[1-6] In particular, developing motion-based sensors from those devices has attracted considerable attention, because the motion sensing platform does not require sophisticated analytical instruments and potentially offers spatial resolution.[1, 7] The first report by Wang and co-workers provided a foundation for the construction of motion-based sensors.[8] In this work, the observation that silver ion enhances the speed of a Au-Pt bimetallic nanowire in hydrogen peroxide solution was used for the detection of silver ion. This silver ion – enhanced nanomotor speed effect was also adopted to design the first motion-based biosensor to detect DNA and RNA.[9] Recently, enzyme-modified nanorods have been used as motion sensors for the specific substrates of the enzyme.[7]

The pioneering works on developing motion sensing and biosensing platforms relied on bimetallic nanowires that produce self-electrophoretic or self-diffusive movement in fuel solutions.[1, 10] However, the motion of this nanomotor is limited in low-ionic strength solutions, thus the use of that device might be challenging in some practical applications.[1, 2] Considerable efforts on the construction of motion-based sensors have recently focused on using tubular micromotors. These self-propelled devices are capable of moving in complex media such as biological fluids or high-ionic strength solution, and therefore might offer applications in diverse environments.[5, 11, 12] For examples, Wang and co-workers developed a catalase enzyme-based micromotor to detect chemical toxins.[13] These toxins inhibit the activity of catalase, therefore reducing the speed of micromotor. In other works, Cu/Pt microtubes were used for the detection of heavy metal ions or sulphur-containing compounds.[14, 15] Most of these developed sensors function in the "deactivation mode", in which analytes poison the activity of motion-inducing catalysts and decrease the speed of motor sensors. Thus, those sensors have low specificity and selectivity.[3] *In this work, we present an alternative design for a motion-based DNA biosensor from tubular micromotors that only produces motion signal in the presence of the analyte target.* This "signal on" sensor may be particularly useful for sensing applications requiring specificity as well as developing programmable and logic devices based on DNA hybridization, which is important for detection of specific DNA strands.

Our design principle for a "signal on" motion-based DNA sensor is illustrated in Figure 1. We chose Pt nanoparticles (PtNP) conjugated to DNA as catalyst to drive the motion of micromotors in a hydrogen peroxide solution. This catalyst is only attached to the micromotor in the presence of the DNA target, thus provides the signal-on characteristic of the sensor. In more details, the inner gold layer of a PEDOT/Au microtube[16] was first modified with 11-mercaptoundecanoic acid (MUA) to form a thiol monolayer. DNA **1** (Table S1) was then attached to the gold layer by the standard EDC/NHS coupling. The excess MUA on the gold surface play a role as spacers to enhance DNA hybridization. In addition, carboxylate groups of free MUA help to maintain the negative charge of the gold surface, thus minimizing the non-specific adsorption of negative Pt nanoparticles on the surface in the subsequent steps. In the presence of DNA target **3** (Table S1), Pt nanoparticles (PtNP)

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conjugated to DNA probe **2** (Table S1) are recruited to the gold surface via specific DNA hybridization. After extensive washing to remove excess DNA-PtNP conjugates in solution, modified microtubes are suspended in hydrogen peroxide solution. Pt nanoparticles on the gold surface catalyse the decomposition of

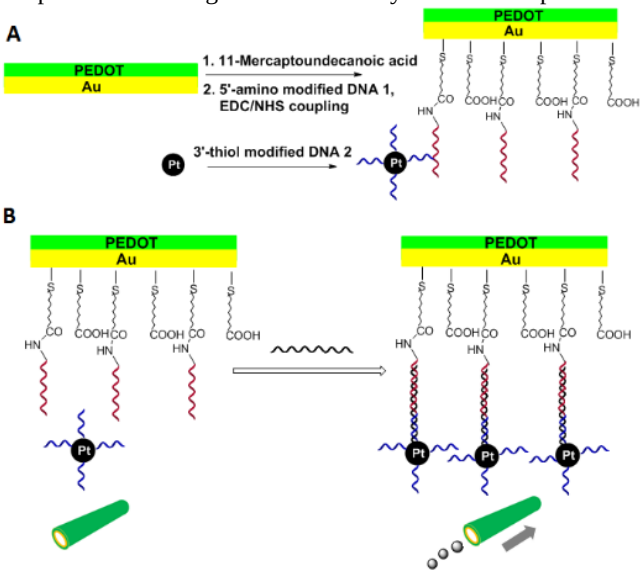

Figure 1. Scheme for the construction of a motion-based DNA biosensor from PEDOT/Au microtubes. **(A)** Immobilization of DNA **1** on the inner gold surface of the microtubes via EDC/NHS coupling reaction and preparation of PtNP-DNA conjugate. (**B**) The principle for DNA detection by introducing PtNP-DNA conjugate to the microtubes via specific DNA hybridization

hydrogen peroxide to form oxygen gas that drives the motion of modified microtubes through a bubble-induced propulsion mechanism.[11, 12] Therefore, motion signal of the microtube sensor can be used to detect the presence of the DNA target.

In our first experiment, 5 µM of the DNA **3** was used to join PtNP-**2** conjugate to DNA **1** on the gold surface of microtubes. After 5 minutes of incubation in a solution containing 5 % hydrogen peroxide and 1% sodium cholate, motion of microtubes was tracked by an inverted microscope. Figure 2

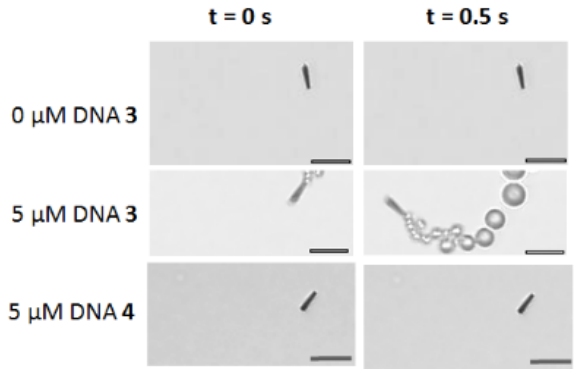

Figure 2. Images for the trajectory of micromotors in the absence and the presence of the DNA target **3** and the presence of non-complementary DNA **4.** Chemical fuel solution contains 5 % hydrogen peroxide and 1 % sodium cholate. Scale bar is 20 µm

showed time-lapsed images for the trajectory of microtubes in the presence and absence of DNA target **3** at t = 0 seconds and t= 0.5 seconds. The data clearly demonstrated that PtNP catalyst was recruited to microtube in the presence of DNA target **3** and induces the motion of microtube in hydrogen peroxide solution. In contrast, no motion of microtubes was observed in the absence of the DNA target even after 5 minutes of tracking. This suggests that the amount of PtNP-DNA conjugates presented in the microtubes due to non-specific adsorption on the gold surface with negative charge characteristic is too low to produce the motion signal. In addition, the presence of a non-complementary DNA **4** (Table S1) also resulted in no motion of microtubes.

The average speed of modified microtubes after hybridizing with 5 µM DNA target and the PtNP-**2** conjugate is about 210 µm/sec. This value is apparently lower than the speed of a bilayer microtube with an electrodeposited Pt inner layer that can reach up to 2 mm/sec at the same concentration of hydrogen peroxide.[16] A previous study showed that Pt nanoparticle catalyst with high surface area can enhance the speed of microtubes prepared by a particle-assisted rolling method compared to a Pt film catalyst.[17] However, in our case, the amount of Pt nanoparticles introduced inside the DNA-modified microtube through DNA hybridization might be low due to the monolayer characteristic of DNA on the gold surface. In addition, Pt nanoparticles were modified with thiol DNA and the presence of sulphur on the Pt surface has been known to reduce the catalytic activity of this material.[18] Those observations are probably attributed for the lower speed of microtube modified with a PtNP-DNA conjugate compared to that of microtubes with a Pt layer prepared by electrodeposition.

The response of microtube motion to the concentration of DNA target was next investigated. We only observed a slight

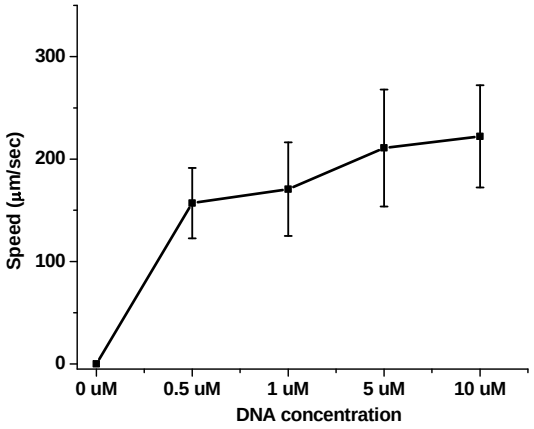

Figure 3. The average speed of micromotor at various concentrations of the DNA target **3**

increase in speed of micromotor, from 157 µm/sec at 0.5 µM (1 pmol) of **3** to 222 µm/sec at 10 µM (20 pmol) of **3** (Figure 3). When the amount of the DNA target is below 1 pmol, only a small portion of micromotors (<10%) produces motion after 5 minutes of tracking, indicating the detection limit of our biosensor is about 1 pmol. This sensitivity is apparently lower than that of a DNA sensor based on nanomotor.[9] However, it is necessary to note that the nanomotor-based sensor did not detect DNA directly. Instead, it sensed silver ion that was produced in the presence of the DNA target and hydrogen peroxide. Thus, the low DNA detection limit of that sensor derives from the high sensitivity of the sensor toward silver ion.

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The poor resolution of the micromotor speed upon changing DNA concentration in our biosensor is probably due to the low catalytic activity of PtNP-DNA conjugate as mentioned above. Therefore, the gold surface of micromotors might need to be saturated with the catalyst, which requires the presence of relatively high concentration of the DNA target, to be able to produce efficient motion. Although the current sensor is a threshold sensor for the DNA target, we envision that the sensitivity could be improved for quantification by using a catalyst with higher activity. For example, reducing the ratio of DNA strands per Pt nanoparticle might enhance the catalytic activity of PtNP-DNA conjugate because this helps to increase the number of accessible catalytic sites on the Pt surface. Another approach is using catalase enzyme biocatalyst that was shown to have higher activity than Pt film catalyst.[19] Those alternative designs are of interest for our future investigation.

Conclusions

In this study, we have reported a design for a "signal on" DNA biosensor from tubular micromotors. The sensor produces the motion signal based on the recruitment of Pt nanoparticle catalysts via specific DNA hybridization in the presence of the DNA target. Although the sensitivity of the sensor needs to be improved, we believe our design principle could be applied to develop motion-based sensing platforms that require high selectivity or to construct programmable and logic devices. In addition, DNA hybridization is a principle for numerous biorecognition processes including the binding between DNA aptamer and small molecules or protein. Therefore, our motion-based design is not limited to DNA detection but can be extended to detection of other analytes such as small molecules and proteins.

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Notes and references

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