Out of cleanroom, self-assembled magnetic artificial cilia

OUT OF CLEANROOM, SELF-ASSEMBLED MAGNETIC ARTIFICIAL CILIA

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ABSTRACT

Micrometer-sized hair-like structures called cilia,are abundant in nature and have various functionalities such as fluid pumping and sensing. Many efforts have been made to mimic the fluid pumping function of cilia, but most of the fabrication processes of these "artificial cilia" are tedious and expensive, hindering their practical applications. In this paper a cost-effective in situ fabrication technique is demonstrated. The cilia are constructed by self-assembly of micron sized magnetic beads and encapsulated with soft polymer coatings. Actuation of the cilia induces an effective fluid flow, and the cilia lengths and distribution can be adjusted by varying magnetic bead concentration and fabrication parameters.

KEYWORDS: Artificial cilia, microfluidics, fabrication, fluid manipulation

INTRODUCTION

In nature, microscopic hair-like structures called cilia and flagella are present in abundance. Their function may be in actuation, sensing, thermal regulation, or surface energy modification. Various efforts have been made to develop micro actuators that mimic natural cilia and flagella movements.[1] However, a big disadvantage of all approaches taken up to now is that the fabrication techniques are tedious and costly for making real-life products. They either require micro-system techniques like photolithography[2, 3, 6-8], or have low reproducibility due to lack of control in fabrication[9], or the fabrication processes are labor-intensive and time consuming [3-5].

The objective of this work is to develop a cost and time efficient, out of cleanroom method of making magnetically actuated artificial cilia which are able to generate net flow. Artificial cilia made in this way can be introduced into microfluidic devices in a straightforward manner. Our method not only enhances the prospect for effective fluid manipulation by artificial cilia, but also opens up other applications that can benefit from the versatile functions of natural cilia.

CONSTRUCTION OF ARTIFICIAL CILIA

The fabrication process is shown in Figure 1. Artificial cilia were constructed by self-assembling magnetic beads (MBs) into chains in an external magnetic field perpendicular to the substrate. Then a layer of soft polymer was coated on the surface of the MBs and the substrate, stabilizing the shape while providing flexibility required for effective actuation. The precursor for creating those coatings used in this study was Poly(butyl acrylate) (PBA) nanoparticle latex. Electrostatic attraction was used to promote adhesion between magnetic beads and PBA nanoparticles. This was achieved by using negatively charged MBs which were coated with anionic polyelectrolyte Poly(acrylic acid), and positively coated PBA latex nanoparticles which were synthesized with emulsion polymerization using a cationic surfactant Cetyl Trimetylammonium Bromide (CTAB) as emulsifier, shown in Figure 1(e).

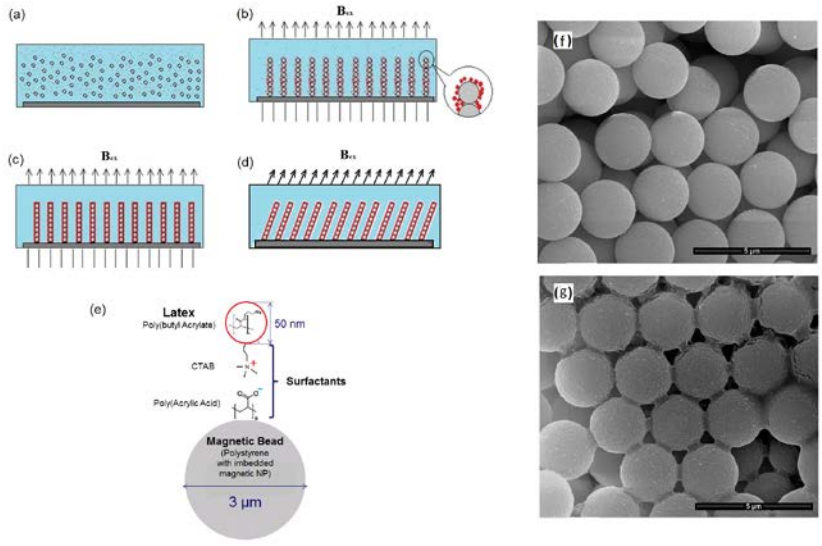

Figure 1: (a-d) Fabrication process of artificial cilia; (e) schematic drawing of the latex coating; (f) and (g) uncoated and coated magnetic beads

A current driven, eight-pole electromagnetic setup was previously developed in our group[10]; it offers great flexibility in generating arbitrarily orientated and periodically changing magnetic fields. In a typical fabrication process, we applied a vertical field of 4~8 mT with downward gradient of ~0.2 mT/mm. The beads self-assembled into vertically oriented chains and 'stand' on the bottom surface. After the MBs were assembled, the fluid cell was heated to 40 °C in order to accelerate the coating process of the PBA latex nanoparticles on the MBs, as well as sinter the coated latex nanoparticles into a continuous layer which attached to the surface of the MBs. The fluid cell was then cooled down to 20 °C after 20min.

MATERIALS AND METHODS

PBA nanoparticle latex was prepared by emulsion polymerization in the following steps: (1) 12.5g Butyl Acrylate (Sigma-Aldrich) and 0.25g CTAB were dissolved in 140mL of deionized water in a double jacket glass reactor; (2) after nitrogen degassing during 30 min, 10mL 0.2%wt potassium persulfate (KPS) solution was injected into the mixture with a syringe, the mixture was kept at 60 °C with 500 rpm mechanical stirring during the reaction; (3) the product was collected after 12 hours and dialyzed (deionized water as buffer, sample to buffer ratio 1:100) for 48h in 20 °C with 500 rpm stirring and stored at 4 °C before use.

The following mixture was prepared and put into the fluid cell for fabrication of artificial cilia: 10 to 20 µL MBs suspension (2×10^9 beads/mL, volume is varied intentionally to adjust cilia configuration, see below), 10 µL PBA latex, 20 µL 0.14 M NaCl solution, 1 µL 1%wt Triton X-100 (Sigma-Aldrich®) and 80 µL deionized water were put in a microcentrifuge tube and mixed for 1 min on a vortex mixer to give a homogenous suspension. As a result the mixture had an overall MB concentration between 1.7×10^8 and 3.1×10^8/mL. Then 8.5 µL of the mixture was placed in the fluid cell which was subjected to ultrasonication for a few seconds for better dispersion before putting it into the magnetic setup.

ACTUATION AND CHARACTERIZATION

A net translational flow was successfully generated by magnetic actuation (Figure 2). Visualization of the fluid flow was achieved by adding florescent particles into the fluid cell. We have also observed that as the actuation frequency increases, the translational velocity increases in the low frequency range but decreases when the frequency is higher than 5 Hz. The explanation might be that the faster cilia movement at higher actuation frequency results in a higher viscous drag from the surrounding fluid, limiting the amplitude of the cilia motion. We also compared the translational velocity of the tracer particles at horizontal planes at various heights in the chamber and the result depicted in Fig. 5c shows a decrease in velocity as the focal plane moves away from the tips of artificial cilia towards the top of the fluid cell, with some back flow close to the top.

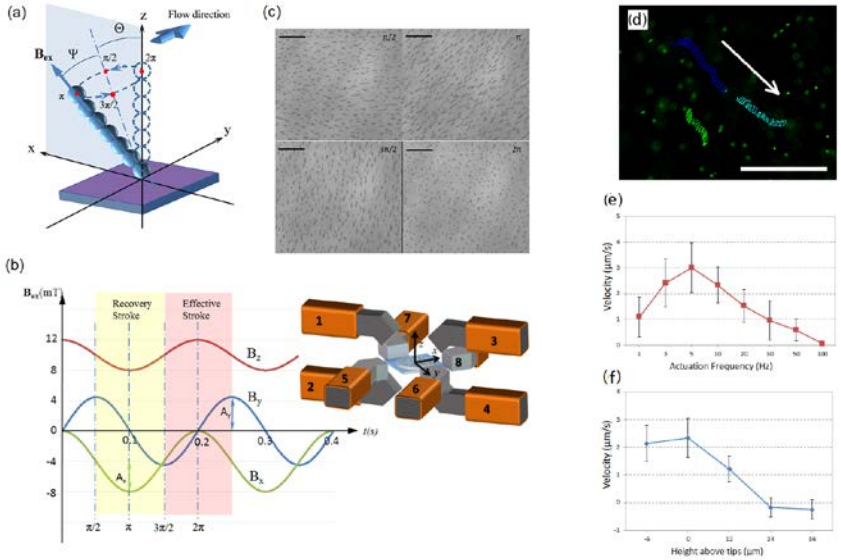

Figure 2: Actuation of artificial cilia. (a) 3D schematic drawing of the tilted conical motion; (b) voltage input for the magnetic setup to induce motion in (a); (c) top-down split views of artificial cilia in one rotation cycle; (d) traces of fluorescent particles suspended in water which was transported by the motion of cilia; (e) average velocity of tracer particles as a function of frequency, showing the net flow; (f) average velocity of tracer particles at different height levels in the fluid chamber.

We observed an effective fluid transportation effect (maximum flow velocity close to 5 µm/s) that is comparable to other reports using the similar geometry and artificial cilia motion [3,5]. A great advantage of our approach is that by eliminating the use of micro fabrication techniques, the cost and time required for fabrication is significantly reduced.

Meanwhile, being an in situ fabrication process, the method has the potential to 'plant' stable artificial cilia into existing microfluidic channels by injecting premixed building materials and apply an external magnetic field.

Although the length of the artificial cilia fabricated in the self-assembly process shows variation, the average length and density of artificial cilia can be controlled by varying the concentration of MBs or changing the strength of the applied magnetic field. Note that changing the cilia length at the same time influences the density of cilia surface coverage as more beads are used in constructing each individual cilium. As a result we can control the average length and surface coverage of the artificial cilia within a certain range. Generally the average aspect ratio of the cilia (the average number of beads in each cilium) can vary between 5 and 20, and the surface coverage between 0.8% and 3%.

There are several advantages of our approach compared to previous studies. First, the fabrication process is cost and time efficient, without the need for tedious microfabrication technologies which hinder practical application. Second, the magnetic self-assembling process combined with latex coating makes a stable structure after heating which remains intact in the absence of an external magnetic field. Third, this water based assembly approach provides the possibility of in situ fabrication of artificial cilia in existing microfluidic devices, which enables to use an additional standarizable modular process of integrating artificial cilia into devices, without the necessity to modify the fabrication process of the microfluidic devices themselves.

CONCLUSION

We have made magnetically actuated artificial cilia using a novel fabrication method. Magnetic beads were assembled into chains in an external magnetic field and a soft polymer latex was used to form elastic links between the beads through electrostatic attraction. We were able to adjust cilia density as well as their average length through varying the amount of beads and the external magnetic field strength during fabrication. The artificial cilia were actuated to move in a non-reciprocal manner and a net flow velocity of 3 μm/s was achieved at an actuation frequency of 5 Hz.

ACKNOWLEDGEMENTS

This research forms part of the research programme of the Dutch Polymer Institute DPI, project #689. Prof. Alex van Herk and Prof. Dick Broer from TU Eindhoven provided useful consultation and suggestions during the experiments. The authors would like to thank Judith van Wijk for the great help with the latex preparation and Marc van Maris for the assistance with SEM.

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