Magnetic artificial cilia generate microfluidic flow

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Cilia are microscopic hairs (typically tens of micrometers long) that can be found in nature in which they provide the function of generating (microfluidic) flows (see Fig. 1). One example is the propulsion of microorganisms that are covered with thousands of cilia oscillating asymmetrically in a concerted fashion. Another example are the cilia that cover the inner walls of the human lungs and the windpipe, to sweep mucus and dirt out of the airways in order to avoid infections. Inspired by these biological examples, we have developed a range of different types of “artificial cilia”, hair-like micro-actuators that can be used to pump or mix fluids when integrated in microfluidic devices. They can be made to respond to various stimuli, such as electric field, light and magnetic field, and some of them have been shown to produce effective fluid pumping and mixing [1].

However, the fabrication techniques adopted in making those functional artificial cilia involved either microfabrication techniques under cleanroom conditions, or the use of expensive sacrificial materials as molds. As a result, effective but expensive prototypes were made and they have little prospect to be used in commercial microfluidic applications. Recently, we have reported novel techniques to produce magnetic artificial cilia in out-of-cleanroom settings [2,3]. Especially the “roll-pulling” method we developed has great potential as a cost-effective method to create effective magnetic artificial cilia [4,5].

Figure 1: Examples of cilia found in nature. (a) Micro-organisms like paramecium are covered with microscopic hairs, cilia, that oscillate asymmetrically, so that they are able to propel the microorganism. (b) In our own bodies, cilia are present at a number of locations where they provide fluid flow, such as in our lungs and in our reproductive system.
An in-house-developed rolling setup was used to fabricate artificial cilia (Fig. 2a). The setup features a synchronized movement and an adjustable gap between the aluminum roll and the substrate holder. A poly(dimethylsiloxane) (PDMS) film with micropillars (Fig. 2b) is wrapped around to the roll. A substrate covered by a 200 μm thick liquid PDMS based precursor film containing iron particles travels beneath the roll and filaments are pulled out from the film by the micropillars. These filaments reach a certain critical length before breaking, creating artificial cilia on the substrate. Silica nanoparticles and a polyethylene oxide oxide/ PDMS block copolymer were added into the precursor to give the mixture exactly the right rheology, which is crucial for the formed artificial cilia to resist collapsing after their formation. A pair of vertically aligned electromagnetic poles is fixed above and below the moving parts to provide a magnetic field during fabrication for the vertical alignment of the artificial cilia. As a result, cone shaped slender artificial cilia with a length of about 300 μm and an aspect ratio of about 10 are created (Fig. 2c).

We integrated the artificial cilia into a recirculation microfluidic chip made of PDMS to characterize their flow generation capacity. A rotating magnet was placed underneath the cilia with its rotation axis at an offset with respect to the location of the cilia. This way, a time-dependent magnetic field was generated that actuated the cilia to perform a tilted conical motion (Fig. 2d), which generated a net fluid flow in the chip in this low Reynolds number setting. The flow speed was then characterized by tracking freely buoyant particles in the fluid. As shown in Fig. 2e, at an actuation frequency of 20 Hz, a flow speed over 120 μm/s was created in the flow chip.

Figure 2: Our magnetic artificial cilia, made with “roll-pulling”. (a) Schematic of the roll-pulling setup; (b) liquid filaments being pulled out from the precursor film by micropillars, captured by high speed imaging; (c) micrograph of the resulting artificial cilia; (d) the artificial cilia are actuated with a rotating field along a tilted cone; (e) flow speed generated by artificial cilia in a microfluidic channel actuated using a rotating external magnetic field, as a function of rotation frequency.
The effectiveness of our magnetic artificial cilia and the scalable and cost-effective production process make this work a promising technological platform for future studies. The ability of the artificial in manipulating fluids could also be used in other applications, for example in mixing of different fluids in a low Reynolds number setting, or in anti-fouling for submerged sensors by actively repelling contaminants from their surfaces.

References