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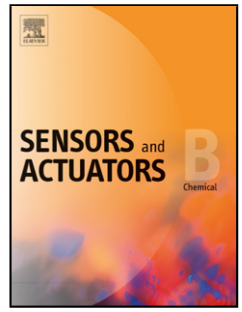

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Versatile microfluidic flow generated by moulded magnetic artificial cilia†

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Highlights

- Magnetic artificial cilia (MAC) with tunable particle distribution are fabricated
- The improved MAC can generate water flow speeds of at least 260 μm/s
- Versatile microfluidic flows are successfully created in microfluidic devices
- MAC can form a fully integrated micro-pump in microfluidic devices

Magnetic artificial cilia (MAC) are flexible hair-like micro-actuators inspired by biological cilia. When integrated in a microfluidic device and actuated by an external (electro-)magnet, MAC can generate fluid flows. Our MAC are made of a composite material of polydimethylsiloxane (PDMS) and magnetic microparticles (Carbonyl iron powder). In this paper, we demonstrate a fabrication process based on micro-moulding to manufacture MAC, in which we can vary the magnetic particle distribution within the cilia from (1) a random distribution, to (2) a linearly aligned distribution to (3) a concentrated distribution in the tips of the cilia. Magnetization measurements show that the aligned distribution leads to a substantial increase of magnetic susceptibility, which dramatically enhances their response to an applied magnetic field. When integrated in a microfluidic channel, the improved MAC can induce versatile flows, for example (i) circulatory fluid flows with flow speeds up to 250 μm/s which is substantially above the performance of most of the previously developed artificial cilia, (ii) direction-reversible flows, (iii) oscillating flows, and (iv) pulsatile flows, by changing the magnetic actuation mode. Compared to other pumping methods, this on-chip / in-situ micro-pump requires no tubing or electric connections, reducing the usage of reagents by minimizing "dead volumes", avoiding undesirable electrical effects, and accommodating a wide range of different fluids. These results demonstrate that our MAC can be used as versatile integrated micropump in microfluidic devices, with great potential for future lab-on-a-chip applications.

Keywords: Magnetic artificial cilia; Micro-pump; Versatile microfluidic flow; Micro-moulding; Magnetic particle distribution; Lab-on-Chip

1. Introduction

Microfluidics is the science and technology of systems that manipulate fluids at small scales (typically from 10^{-4} to 10^{-8} liters) for applications such as chemical synthesis and biological analysis [1]. In this field, (micro-)pumping is a paramount function. Nowadays, most adopted approaches either need large peripherals, such as pneumatic control systems or syringe pumps, or they are expensive and/or cumbersome to integrate. To address these issues, researchers have sought inspiration from nature to create truly integrated microfluidic pumps by mimicking the functionality of biological cilia. Biological cilia are micro-hairs with a typical length between 2 and 15 μm, which are found ubiquitously in nature [2]. By moving in a coordinated, asymmetric manner, cilia are very effective in generating flows in a low Reynolds number environment where inertial effects are negligible and the flow is dominated by viscous effects [2]. For example, the collective asymmetric motion of cilia covering the body of a paramecium propels the body forward at a speed of 10 times its body length per second.

In recent years, a number of methods and technologies have been developed to fabricate man-made analogues of biological cilia - artificial cilia - including electrostatic cilia [3], magnetic artificial cilia (MAC) [4]–[6], optically-driven cilia [7], hydrogel-actuated artificial cilia [8], resonance-actuated artificial cilia [9][10], and pneumatically actuated artificial cilia [11]. Among these, MAC are the most promising because (1) MAC can be externally actuated within microfluidic channels by permanent magnets or electromagnets without the need for physical connections to peripheral equipment, (2) MAC have an instantaneous response to the external stimulus, and (3) magnetic actuation is compatible with biological fluids.

In 2007, Evans *et al.* [12] used polycarbonate track-etched (PCTE) porous membranes as sacrificial templates to fabricate PDMS - ferrofluid based magnetic nanorod arrays with a size similar to that of natural cilia. MAC created using this technique were actuated by an offset-positioned rotating permanent magnet, such that they moved in a way mimicking the beat shape of the embryonic nodal cilia (the so-called 'tilted conical beat') [6]. This tilted conical motion of cilia was demonstrated by Downton and Stark [13] to be a simple yet effective asymmetric nonreciprocal motion to generate net fluid flows. In 2009, Vilfan *et al.* [14] exploited the self-assembling ability of magnetic colloidal micro-beads subjected to an external magnetic field, and created MAC consisting of magnetically linked chains which were anchored to electroplated nickel dots. Babataheri *et al.* [15] and Wang *et al.* [16] employed similar approaches to produce MAC with the addition of a polymer coating to achieve permanent linking between