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ARTIFICIAL MINI-HEART: AN INTERNAL MICROPUMP BASED ON MAGNETICALLY ACTUATED ARTIFICIAL CILIA THAT CAN INDUCE FLOWS IN A MICROFLUIDIC CHANNEL NETWORK

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ABSTRACT

Here we report the fabrication of an internal micropump based on **magnetically actuated artificial cilia (MAAC)** that functions like an **artificial mini-heart**. The micropump can provide versatile flows in a **microfluidic channel network**, when the MAAC are actuated to perform a **tilted conical movement**. Compared to other pumping methods, this in-situ micro-pump does not need tubing or electrical connections, which reduces the usage of reagents by minimizing “dead volumes”, allows the construction of a more compact system, avoids undesirable electrical effects and accommodates a wide range of fluids.

KEYWORDS: Magnetically Actuated Artificial Cilia, Artificial Mini-Heart, In-situ Micropump, Versatile Flows

INTRODUCTION

In humans and animals, the **heart** cyclically pumps blood through the blood vessels of the circulatory system, providing the body with oxygen and nutrients, as well as assisting in the removal of metabolic waste. Recent years, artificial cilia are reported to be very effective in generating substantial fluid flows in microfluidic devices [1]. Here we report the fabrication of an integrated micropump based on **magnetically actuated artificial cilia (MAAC, Fig. 1a)** which functions like an **artificial mini-heart**. It can provide circulatory flows in microfluidic devices with closed branched channel networks resembling **blood vessel networks (Fig. 1b)** when MAAC are actuated by a home-built rotating magnet to perform a **tilted conical movement** [2]. In addition to circulatory flows, **direction-controllable flows** and **pulsatile flows** can be created by tuning the rotating mode of the magnet.

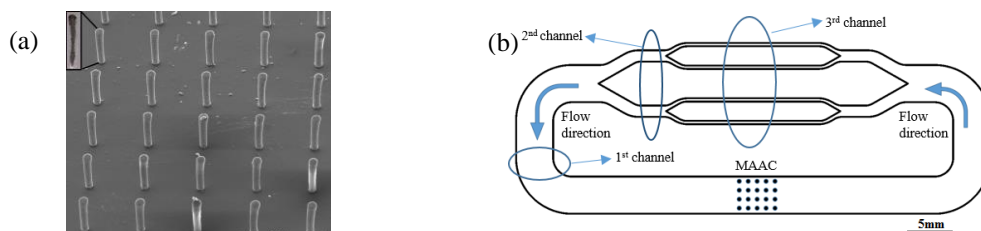


Figure 1: (a) A SEM image of micro-molded MAAC with a length, diameter and pitch of 50, 350, and 350 μm respectively; the insert is the optical image of a single cilium which shows that CIP are linearly aligned within the cilium forming a chain. (b) Schematic of a blood vessel-shaped microfluidic chip with indications of the circulatory flow direction, MAAC area which forms the artificial mini-heart, and observation areas.

EXPERIMENTAL

MAAC were fabricated using a micro-molding process (Fig. 2) which consists of **six** steps: **(1)** a mold featured with micro-wells was fabricated using photo-lithography with SU-8 as photoresist; **(2)** a homogenous PDMS and carbonyl iron powder mixture (PDMS-CIP) was prepared and poured onto the mold, followed by a degassing procedure; **(3)** the upper part of PDMS-CIP outside of the micro-wells, was removed; **(4)** pure PDMS was poured onto the mold, which would eventually form the base for the cilia; **(5)** the mold was placed on top of a permanent magnet (with a surface field of 0.4T) to align the CIP within micro-wells in order to increase MAAC's magnetic response, and the mold together with the magnet was put into an oven to cure the mixture at 80 $^{\circ}\text{C}$ for 2 hours; **(6)** the cured pure PDMS layer with PDMS-CIP micropillars was peeled off. Finally, we obtained MAAC with a length, diameter and pitch of 50, 350, and 350 μm respectively, “standing” on a transparent PDMS base (Fig. 1a).

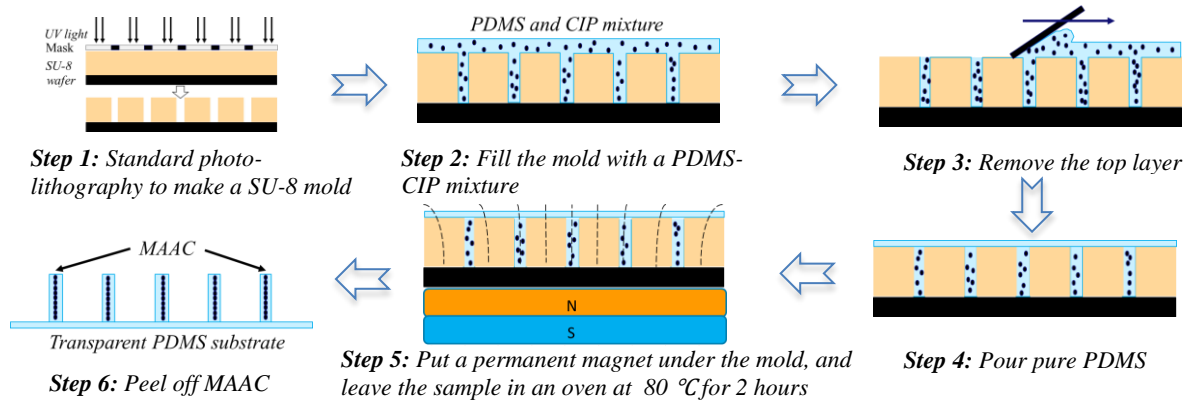


Figure 2: Schematic diagram of the micro-molding process to fabricate MAAC which have a strong magnetic response.

RESULTS AND DISCUSSION

In order to characterize the fluid flow generation property, MAAC were integrated into a water-filled blood vessel-shaped microfluidic channel network (Fig. 1b) which was created using soft-lithography. The MAAC were actuated to perform a tilted conical motion at 10 Hz (Fig. 3a), and the resulting fluid flow was characterized by tracking seeding particles manually using commercial software named ImageJ. A volumetric flow rate of 0.9 $\mu\text{L}/\text{min}$ was induced, corresponding to maximum velocities of 6.9, 12.7 and 24.4 $\mu\text{m}/\text{s}$ in various parts of the channel network, as shown in Figure 3b. Notably, well-controlled fluid flow, such as direction-reversible and pulsatile flows, can be generated by tuning the motion of the actuating magnet because our MAAC follow the magnetic field swiftly. A video of the cilia motion and corresponding flows in the blood vessel-shaped channel can be found on <https://youtu.be/OUxik9s0fKY>.

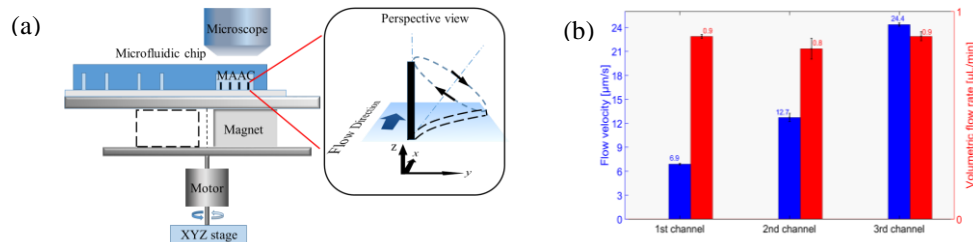


Figure 3: (a) scheme of MAAC; the insert shows the schematic drawing of the tilted conical motion of actuated MAAC in perspective view. Illustrations are not to scale. (b) Flow velocities and volumetric flow rates observed in various parts (designated in Fig. 1b) of the blood vessel-shaped channel network at actuation frequency of 10 Hz.

CONCLUSION

Magnetically actuated artificial cilia (MAAC) with strong magnetic response have been successfully fabricated. These MAAC are capable of generating versatile flows in closed microfluidic channel networks, mimicking the fluid pumping functionality of our own hearts. Our artificial “mini-heart” could provide a compact and integrated device to create physiologically relevant flow in these microchannels.

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