

Supplementary information

Magnetic nanoparticle swarm with upstream motility and peritumor blood vessel crossing ability

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The main body of the magnetic field generation system consists of six electromagnetic coils, which are improved from the Helmholtz coils. Unlike the nested arrangement of conventional Helmholtz coils, the distance between the two coils in this paper is exactly equal to the outer diameter of the solenoid coils, which is designed to maximize the working space while maintaining the internal magnetic field strength and uniformity. Three pairs of identical magnetic field generators are distributed orthogonally according to a Cartesian coordinate system to control the generation of uniform magnetic fields in XYZ directions. Each of the circular electromagnetic coils used has the same number of turns, diameter, and other parameters, see Table. S1. The frame of the coils is printed with a non-conductive photosensitive resin that can withstand temperatures over 65°C during coil operation, avoiding unwanted eddy current effects and heat dissipation. In addition to the solenoid coil, the hardware section includes an NI data acquisition card (USB-6211, National Instruments), three DC drivers (DZRALTE-040L080, Advanced Motor Control), and three DC power supplies (LW-2006KD). The digital signal generated by the PC is passed to the data acquisition card, which converts the digital signal to the corresponding voltage signal by digital-to-analog conversion, and then amplifies the signal through the DC drivers and finally feeds it to the solenoid coil to generate the desired signal. The signal is amplified by the DC driver and finally fed into the electromagnetic coil to generate the required magnetic field.

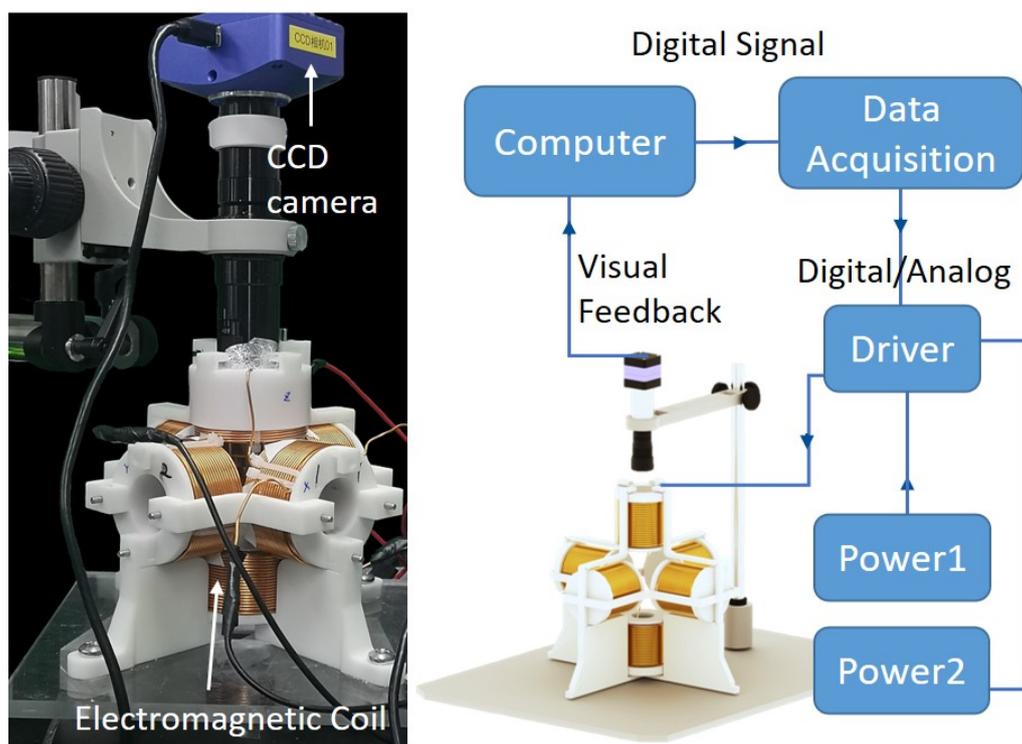


Fig. S1: Physical view of the magnetic navigation system. The magnetic navigation system is composed of 6 electromagnetic coils, 2 power sources, 1 data acquisition, 3 drivers, 1 controller (computer), and 1 CCD camera.

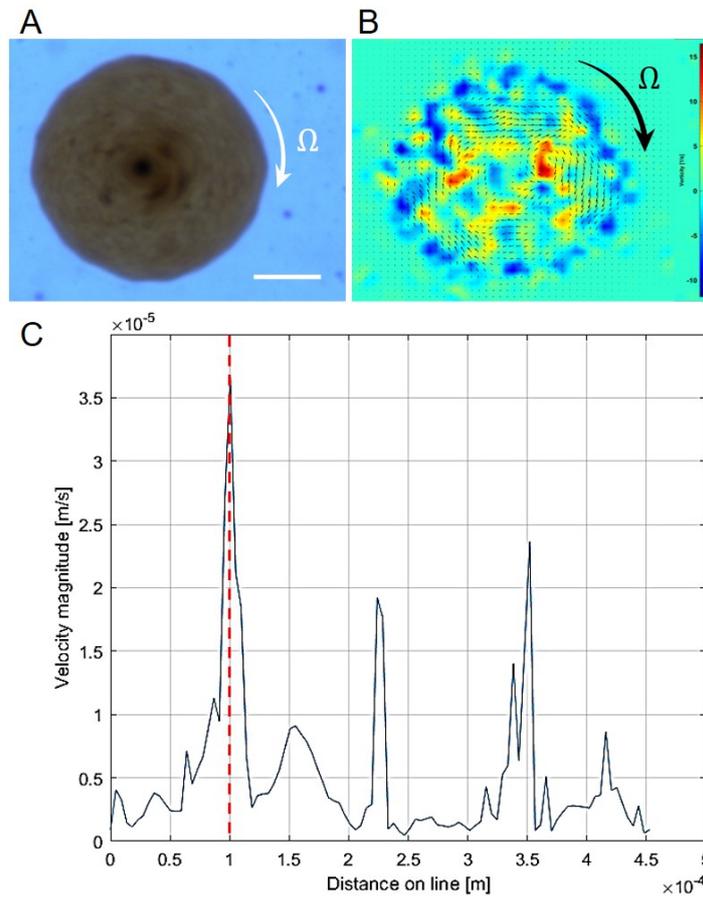


Fig. S2: Motion of vortex-like swarms monitored using particle image velocimetry (PIV). (A) Top view of a vortex-like swarm analyzed by PIV. The scale bar is $20 \mu\text{m}$. (B) Vortex volume distribution of the swarm monitored using PIV. (C) The velocity magnitude distribution of the swarm.

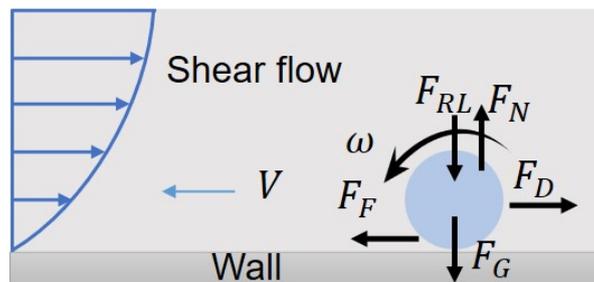


Fig. S3: Schematic diagram of the force analysis of VPNS moving upstream in the Poiseuille flow.

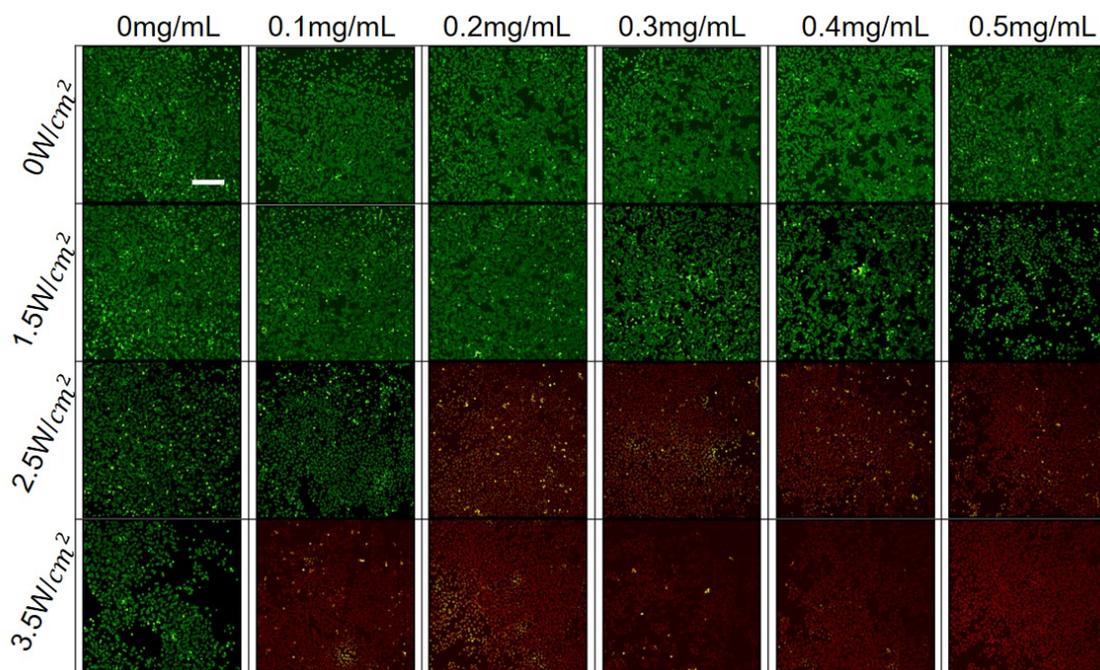


Fig. S4: Confocal laser scanning microscopy image of 4T1 cells stained with Calcein-AM and PI. Live cells are stained green with Calcein-AM, while dead cells are stained red with PI. The scale bar is 200 μ m.

Table. S1 PARAMETERS OF ELECTROMAGNETIC COILS

Description	Value	Units
Central working area size	72*72*72	mm
The coil number of turns	170	---
The outer diameter	72	mm
The inner diameter	40	mm
The length of the coil	37	mm
Coil resistance	1	Ω
Diameter of wire	1.89	mm