Modeling the Targeted Capture of Magnetic Nanoparticles in Vascular Blood Flow Systems under High-Gradient Magnetic Field

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INTRODUCTION

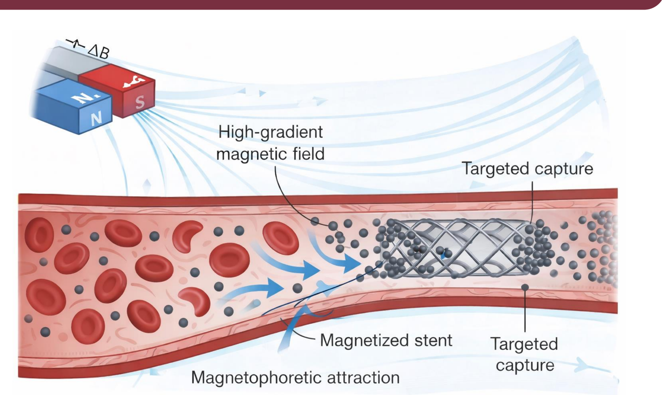
Targeted capture of magnetic nanoparticles within vascular systems under high-gradient magnetic fields offers a promising strategy for localized drug delivery and diagnostic targeting in flowing blood environments. In micro vessels and small arteries, particle transport is governed by the interplay between magnetophoretic attraction toward magnetized implants,

$$\mathbf{F}_m = \frac{V_p \Delta\chi}{\mu_0}(\mathbf{B}\cdot\nabla)\mathbf{B},$$

The resulting magnetophoretic drift relative to the bloodstream determines whether particles marginate toward the vessel wall and achieve capture on magnetized targets, providing a quantitative framework for evaluating targeting efficiency under realistic vascular flow conditions.

OBJECTIVE

The objective of this work is to develop model aims to quantify particle trajectories and capture efficiency near magnetized vascular elements.



MATERIALS AND METHOD

Material Properties			
Paramagnetic	Fe2O3	Size = 100 nm	X = 7380 x10^{-6} cm^3/mole
Blood	λ = 0.05 s	ρ = 1060 kg/m^3	$\mu \approx 3.5 \times 10^{-3}$ Pa·s

- To simulate the above system, a finite element-based numerical simulation technique was applied using COMSOL Mutlitphysics 6.1.
- The coupled problem involves solving three key governing equations; Static magnetic field, Laminar flow, and Transport of dilute species.
- Simulations were conducted in 2D, and the computational domain as discretized into 290804 triangular mesh elements.

BIFURCATED VASCULAR MODEL

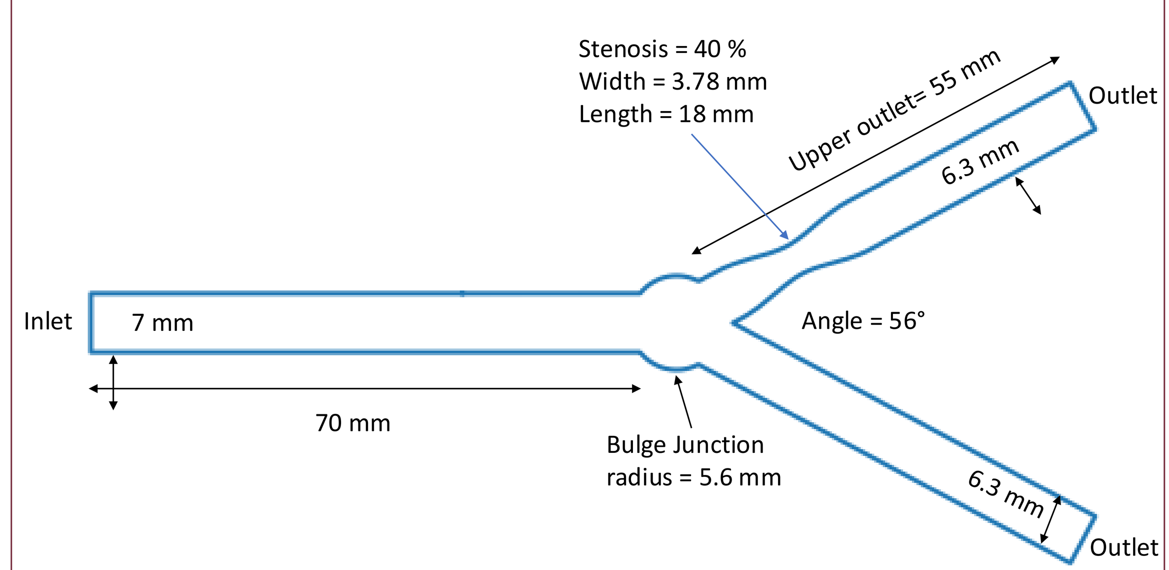


Figure 1: Two-dimensional geometry of the bifurcating channel with a localized stenosis used in the numerical simulations. All the dimensions are in mm.

COMPUTATIONAL GRID

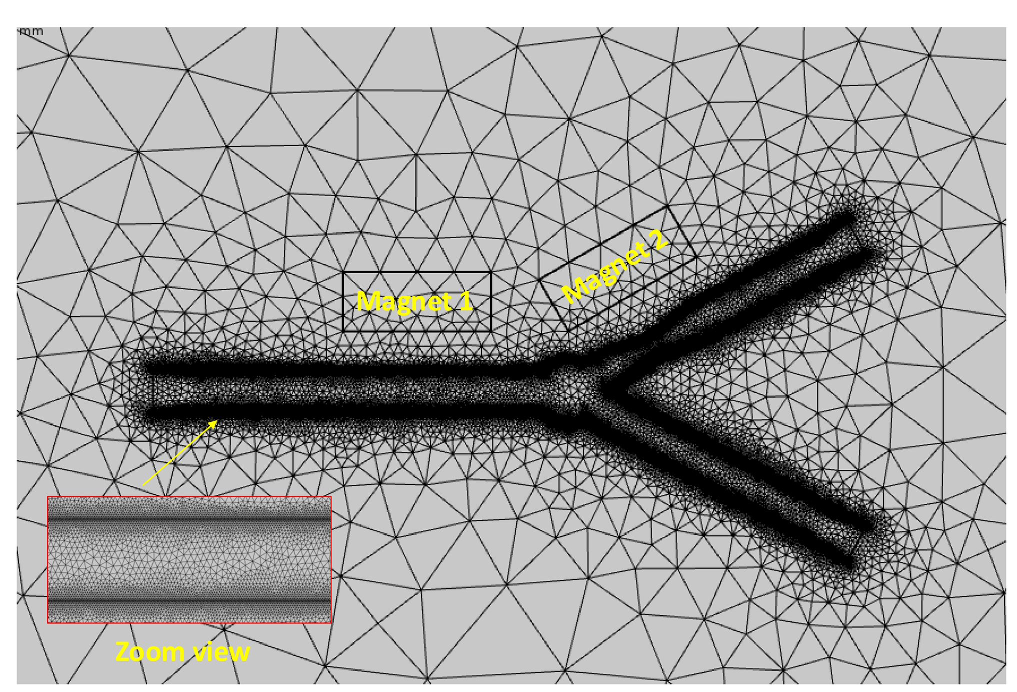


Figure 2: Computational mesh of the bifurcating channel with localized stenosis. The mesh is refined near the bifurcation and stenosed region to accurately resolve velocity and concentration gradients.

GOVERNING EQUATIONS

Mass and momentum balance

$$\nabla\cdot\mathbf{u_f} = 0.$$

$$\rho\left[\frac{\partial\mathbf{u_f}}{\partial t} + \mathbf{u_f}\cdot\nabla\mathbf{u_f}\right] = \mu\nabla^2\mathbf{u_f} + (\rho-\rho_l)\mathbf{g} + \frac{\chi_f}{\eta}(\mathbf{B}\cdot\nabla)\mathbf{B}$$

drag force $\mathbf{F}_d = -6\pi\eta R_p\mathbf{v}_{mig}$

convective-diffusive equation $\frac{\partial c}{\partial t} + \nabla\cdot\mathbf{N} = 0$

flux $\mathbf{N}_b = \left[\frac{2R_p^2\Delta\chi}{9\mu_0\eta}c(\mathbf{B}.\nabla)\mathbf{B} + \frac{2R_p^2\nabla\rho}{9\eta}c\mathbf{g}\right].\mathbf{n}$

RESULTS: MAGNETIC FIELD

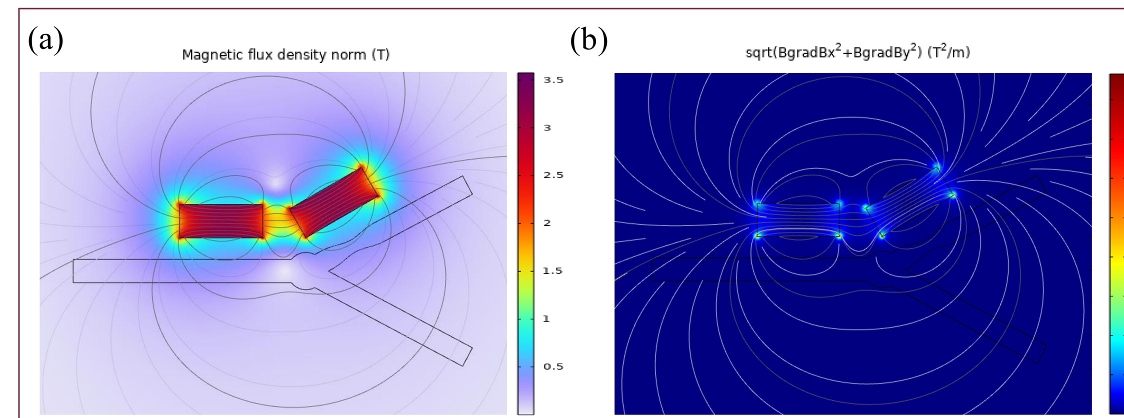


Figure 3: (a) Magnetic flux density distribution, and (b) corresponding magnetic field gradient profile. The applied magnetic field is 0.5 T in a stenosis region.

BLOOD FLOW DYNAMICS

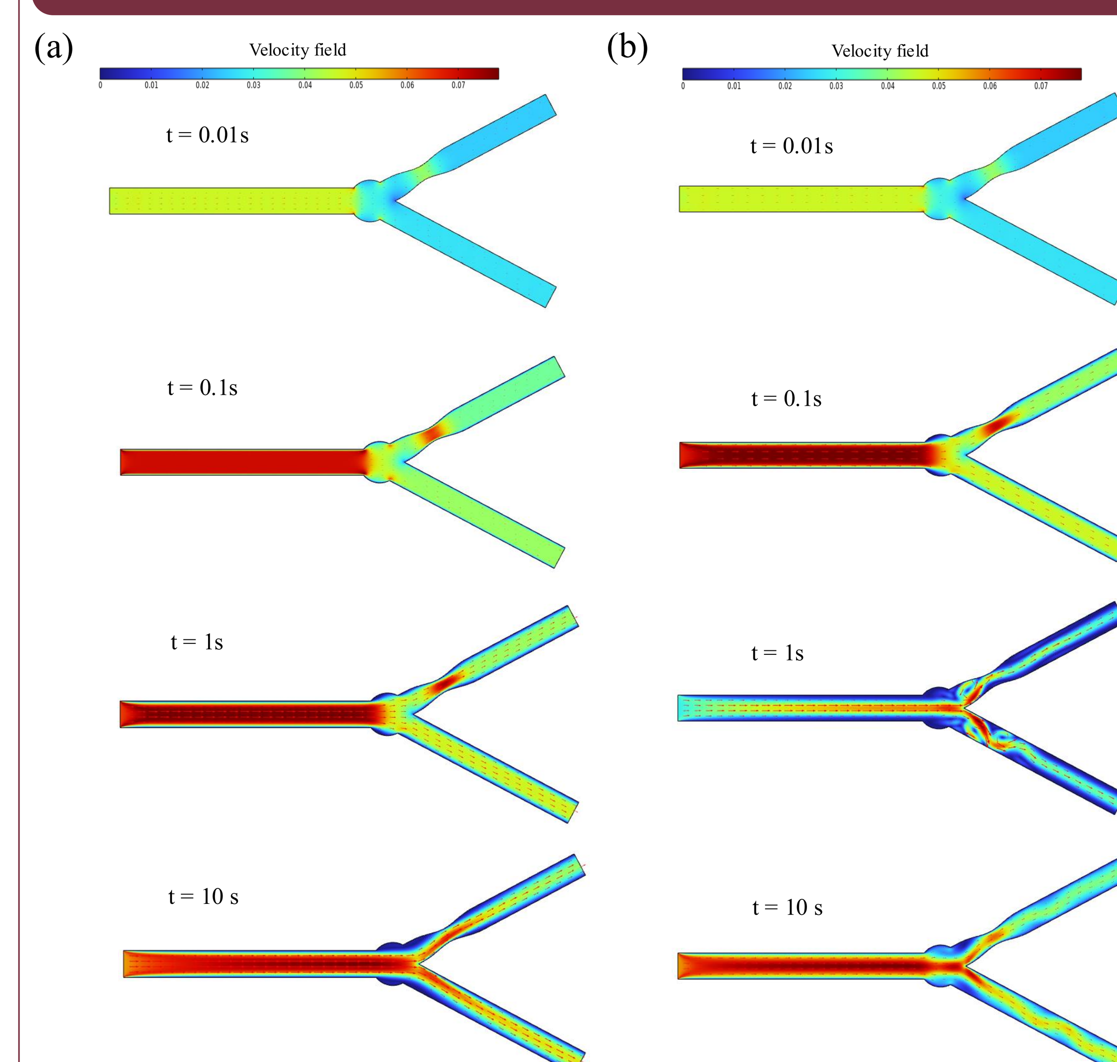


Figure 4: Velocity magnitude contours with the velocity vectors in the bifurcating channel with localized stenosis. Two different pressure difference ΔP (a) 0.001 Pascal and for (b) 0.01 Pascal are applied. Flow acceleration is observed near the junction and within the stenosed region, followed by redistribution into the two branches.

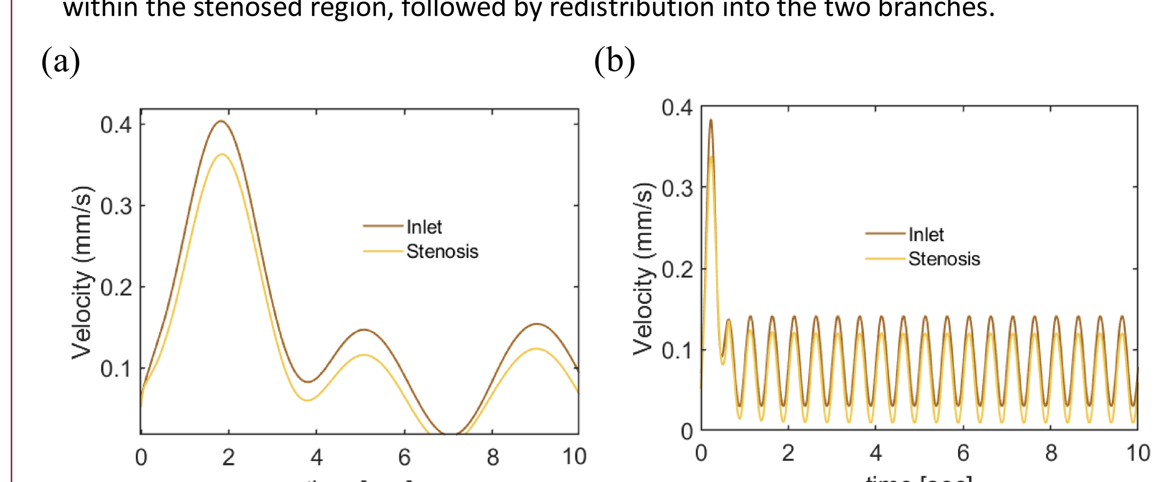


Figure 5: Time variation of velocity at the middle of inlet and within the stenosed region under pulsatile flow conditions. Two pressure difference ΔP (a) 0.001 Pascal and for (b) 0.01 Pascal are applied. The stenosis exhibits lower peak velocities due to flow constriction.

PARTICLE CAPTURE FROM BLOOD

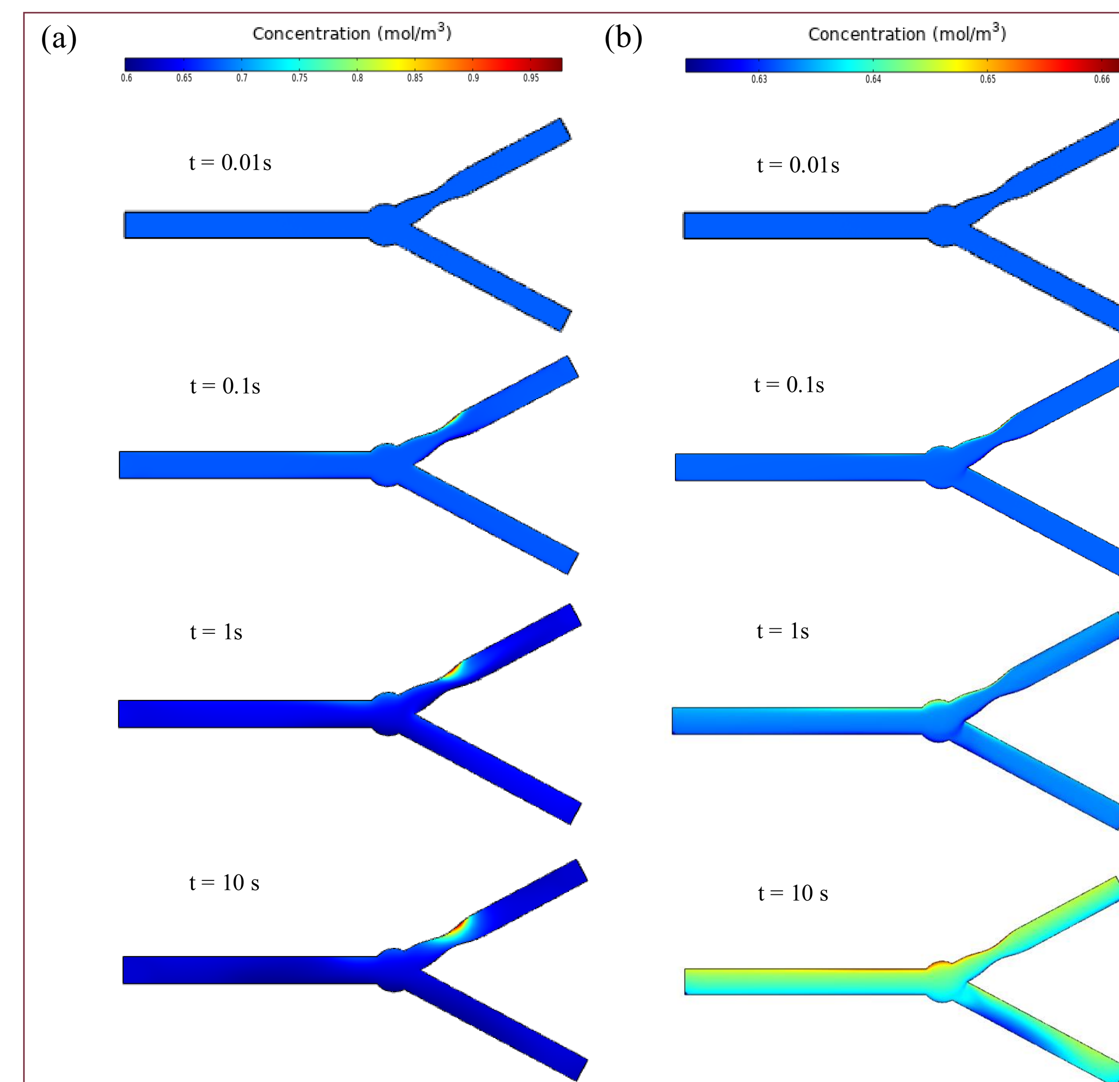


Figure 6: Time-evolution of particle concentration in a stenosed bifurcated vessel under an applied magnetic field of 0.5 T at two different pressure difference ΔP (a) 0.001 Pascal and for (b) 0.01 Pascal. The accumulation of particles is observed near the stenosis region due to magnetophoretic capture, leading to localized concentration enhancement with time.

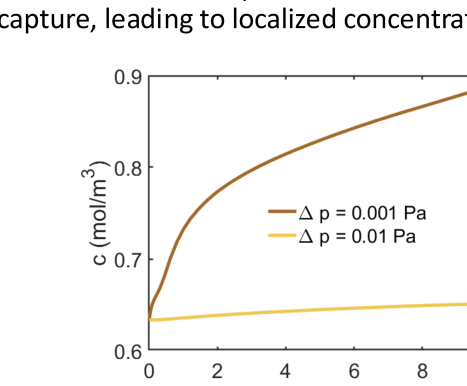


Figure 7: Comparison of nanoparticle accumulation at the stenosis over time for two imposed blood pressure.

CONCLUSIONS

I. Magnetic nanoparticle capture under a 0.5 T field is highly sensitive to local blood pressure and flow patterns in stenosed bifurcations.
II. Lower blood pressure produces more directed and stable flow through the stenosis, increasing particle residence time and capture efficiency.
III. Higher blood pressure induces stronger convective transport and flow instability, redistributing particles into both branches and reducing magnetic capture.
IV. These findings demonstrate that hemodynamic conditions are a key design and operational factor in optimizing magnetic targeting in vascular systems.

REFERENCES

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