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Article

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Computational Design of Magnetically Guided Nanoparticle Delivery in Thrombus-Obstructed Microvessels

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Abstract

Background

Magnetic nanoparticle targeting may improve therapeutic localization at thrombotic sites, but performance in an obstructed microvessel depends on the coupled effects of thrombus-induced flow disturbance, magnetic forcing, convection, and diffusion. A quantitative framework is therefore needed to evaluate targeting benefit together with its hemodynamic cost.

Methods

A two-dimensional finite-volume model was developed for a thrombosis-affected capillary. Blood was treated as an incompressible, electrically conducting fluid, with electromagnetic forcing represented by a Lorentz body force. Nanoparticle transport was described by a convection–diffusion equation with a magnetic-migration contribution. Pressure–velocity coupling was handled using the SIMPLE algorithm. Parametric simulations considered thrombus blockage, Hartmann number, and nanoparticle diameter, and evaluated deposition, retention, and targeting efficiency.

Results

The numerical solution reproduced the analytical Hagen–Poiseuille profile for the unobstructed, non-magnetic benchmark. Increasing thrombus blockage increased hydraulic resistance, pressure loss, and local residence time. Increasing magnetic forcing enhanced nanoparticle localization; deposition efficiency increased from approximately 25% at $Ha = 0$ to about 90% at $Ha = 50$ in the reported simulations. Targeting efficiency also increased with particle

diameter over the investigated 10–100 nm range. The results demonstrate a trade-off between improved localization and hemodynamic disturbance.

Conclusions

The study provides a coupled computational framework for evaluating magnetic nanoparticle transport in thrombus-obstructed microvessels. The framework can support engineering optimization of magnetic field strength, thrombus severity, and particle size, but the predictions remain computational and require experimental validation before translational or clinical interpretation.

Keywords: magnetic nanoparticle targeting; thrombosis; microvascular flow; magnetohydrodynamics; finite-volume method; drug delivery; nanoparticle transport.

Introduction

Cardiovascular diseases remain the leading cause of mortality worldwide, accounting for approximately one-third of all global deaths. A substantial proportion of these fatalities arise from thrombotic disorders, including ischemic stroke, myocardial infarction, deep vein thrombosis, and pulmonary embolism, in which intravascular thrombus formation obstructs blood flow and compromises tissue perfusion [1,2]. Although anticoagulant and thrombolytic therapies have substantially improved clinical outcomes, their effectiveness is frequently limited by poor localization of therapeutic agents, short circulation time, and systemic adverse effects such as hemorrhage. These limitations have motivated increasing interest in targeted drug delivery systems capable of transporting therapeutic agents selectively to diseased vascular regions while minimizing exposure of healthy tissues [3–5, 17–18].

Nanoparticle-based drug delivery has emerged as an important strategy for achieving precise therapeutic targeting. Owing to their tunable size, surface chemistry, magnetic responsiveness, and drug-loading capacity, engineered nanoparticles can improve pharmacokinetics, prolong circulation time, protect encapsulated therapeutics from degradation, and enable controlled release at pathological sites [3,4]. Recent developments in nanomedicine have demonstrated the potential of magnetic nanoparticles, lipid nanoparticles, polymeric carriers, and biomimetic nanoplateforms for cardiovascular and thrombotic applications [5–12, 19–25]. These advances create opportunities for precision medicine by using external physical stimuli, including magnetic fields, to regulate nanoparticle transport and localization within the vascular system [8–12, 19, 23].

Among active targeting approaches, magnetic guidance is particularly attractive because magnetically responsive nanoparticles can be manipulated using externally applied fields [9–12, 19, 22, 23]. The interaction between an applied magnetic field and electrically conducting blood can also introduce Lorentz forces that modify local hemodynamics, while magnetic field gradients drive the migration of magnetic particles. Magnetohydrodynamic (MHD) theory therefore provides a useful framework for examining the coupled interactions among electromagnetic forces, fluid flow, and particle transport [13–16]. Previous computational studies have investigated

magnetic effects on blood-flow characteristics and nanoparticle transport, demonstrating the potential of electromagnetic control for biomedical applications [14–16].

Despite substantial progress in computational hemodynamics and vascular nanomedicine, important challenges remain. Existing studies often consider simplified healthy vessels, stenotic geometries, or isolated transport mechanisms, whereas thrombus-induced microvascular obstruction and its interaction with magnetic nanoparticle targeting remain less systematically quantified [16, 26, 27]. In addition, many computational investigations emphasize velocity or concentration fields without simultaneously evaluating therapeutic performance metrics such as delivery, deposition, retention, and targeting efficiency. The coupled relationship among thrombus severity, magnetic forcing, nanoparticle properties, and hemodynamic cost therefore requires further quantitative investigation.

Accordingly, this study develops a coupled finite-volume framework for electromagnetically guided nanoparticle transport in a thrombus-obstructed capillary. The model combines incompressible magnetohydrodynamics flow, thrombus-induced geometric obstruction, convection–diffusion transport, and magnetic particle migration. Quantitative deposition, retention, and targeting metrics are evaluated across thrombus severity, magnetic forcing, and particle size. The central objective is to identify operating regimes that improve nanoparticle localization while simultaneously accounting for the associated hemodynamic changes, without interpreting the computational results as evidence of clinical efficacy or thrombosis risk.

The principal contribution is an integrated computational framework that links vascular obstruction, electromagnetic forcing, nanoparticle transport, and quantitative targeting measures within a single model. By combining established concepts from MHD blood-flow modeling and nanoparticle drug-delivery research [13–16, 26–28], the study provides a systematic basis for examining how magnetic control can be optimized in the presence of thrombotic flow disturbances.

2. Materials and Methods

Physical Model

A two-dimensional computational model of a thrombosis-affected capillary is developed to investigate electromagnetically guided nanoparticle transport for targeted drug delivery. The model represents a segment of the microcirculation containing a localized thrombus that partially occludes the vessel lumen, thereby modifying the local hemodynamic environment and nanoparticle transport characteristics.

An externally prescribed magnetic field is applied transverse to the principal flow direction. For magnetic particle migration, the corresponding spatial field gradient must be specified in the model.

The computational domain has a length L and radius R , corresponding to physiologically representative capillary dimensions. The thrombus is represented as a localized geometric obstruction characterized by the blockage ratio

$$\alpha = \frac{A_t}{A_c}$$

Here A_t and A_c denotes cross-sectional area occupied by the thrombus (blocked area) and original cross-sectional area of the capillary (total lumen area without thrombus). The blockage ratio provides a quantitative measure of thrombus severity and is varied throughout the simulations to investigate its influence on blood flow and nanoparticle transport.

The computational model considers a thrombus-obstructed capillary with a radius of 5 μm and a length of 100 μm . Blood is modeled as an incompressible electrically conducting fluid with a density of 1050 kg/m^3 , dynamic viscosity of $3.5 \times 10^{-3} \text{ Pa}\cdot\text{s}$, and electrical conductivity of 0.7 S/m. Magnetic nanoparticles with a radius of 50 nm are considered under an externally applied magnetic field ranging from 0 to 1 T. The physical and simulation parameters used in the model are summarized in Table 1.

Table 1 Physical and simulation parameters used in the computational model.

Parameter	Value
Capillary radius (R)	5 μm
Length (L)	100 μm
Blood density	1050 kg/m^3
Dynamic viscosity	$3.5 \times 10^{-3} \text{ Pa}\cdot\text{s}$
Electrical conductivity	0.7 S/m
Particle radius	50 nm
Magnetic field	0–1 T

The interaction of the electrically conducting blood with the applied magnetic field is represented through a Lorentz-force term in the momentum equation. Magnetic nanoparticle migration is treated separately through the particle magnetic-force model. Figure 1 illustrates the computational domain, indicating the inlet and outlet boundaries, thrombus location, applied magnetic field, and nanoparticle transport pathway.

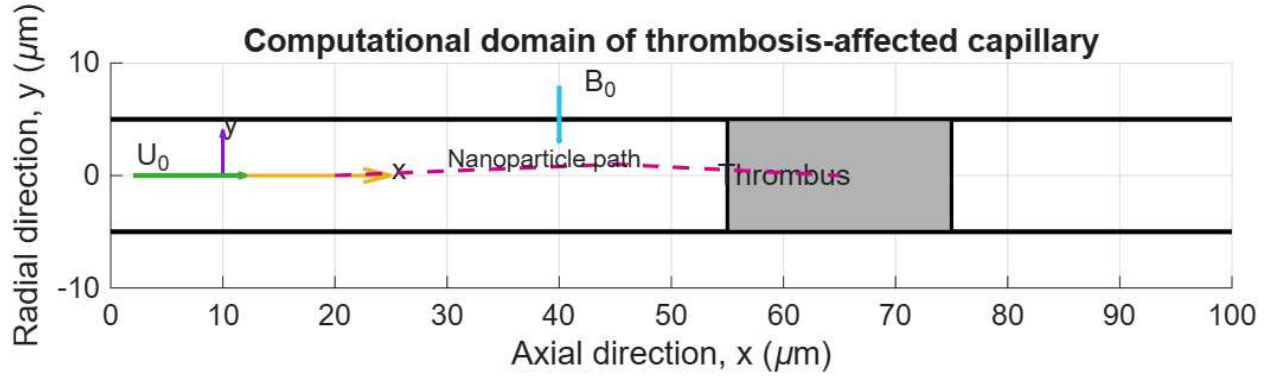


Figure 1. Computational configuration of nanoparticle transport through a partially blocked microvascular channel under an externally applied magnetic field. The geometry represents a stenosed/thrombus-affected vessel, with the nanoparticle-laden blood entering from the inlet and the magnetic field applied to manipulate nanoparticle transport toward the target region.

Explanation in the manuscript:

The computational domain represents a microvascular channel containing a localized thrombotic blockage. The obstruction produces a spatially non-uniform flow field, thereby modifying nanoparticle transport and residence time within the vessel. An external magnetic field is introduced as a control mechanism to redirect magnetically responsive nanoparticles toward the targeted region. This configuration provides the basis for investigating the interaction between thrombus-induced hemodynamic disturbances and magnetic nanoparticle targeting.

Model Assumptions

To obtain a computationally tractable yet physiologically representative model, the following assumptions are adopted:

1. Blood behaves as a homogeneous, incompressible, electrically conducting fluid.
2. Flow remains laminar because of the small diameter and low Reynolds number characteristic of capillary vessels.
3. Blood properties are assumed constant throughout the computational domain.
4. The vessel wall is rigid, stationary, and impermeable.
5. The thrombus geometry remains fixed during drug delivery.
6. Magnetic nanoparticles are spherical and uniformly distributed at the inlet.
7. Nanoparticle aggregation, sedimentation, degradation, and biochemical reactions are neglected.
8. Brownian diffusion and magnetic migration constitute the dominant transport mechanisms in addition to convection.
9. The externally applied magnetic field is spatially prescribed and time independent.
10. Gravitational effects are negligible compared with viscous and electromagnetic forces.

These assumptions are commonly adopted in computational investigations of magnetically guided nanoparticle transport in microvascular systems and provide an appropriate balance between physical realism and computational efficiency.

Governing Equations

The mathematical model consists of the conservation equations for mass, momentum, and nanoparticle transport.

Continuity Equation

For incompressible flow,

$$\nabla \cdot u = 0$$

Where $u = (u, v)$ is the blood velocity vector.

Momentum Equation

Blood motion is governed by the incompressible Navier–Stokes equations augmented by the electromagnetic body force,

$$\frac{\partial u}{\partial t} + u \cdot \nabla u = -\frac{1}{\rho} \nabla p + \nu \nabla^2 u - \frac{F_L}{\rho}$$

Here ρ is the blood density, p is the pressure, ν is the kinematic viscosity, and F_L is the electromagnetic body force (Lorentz force).

Where $F_L = \sigma(u \times B_0) \times B_0$

Here, σ represents the electrical conductivity of blood and B_0 is the magnetic flux density.

This force provides electromagnetic control of blood motion and consequently modifies nanoparticle transport.

Nanoparticle Transport Equation

Nanoparticle concentration satisfies the convection–diffusion equation,

$$\frac{\partial C}{\partial t} + \nabla \cdot (uC) = D \nabla^2 C - \nabla \cdot (CV_m)$$

Where C is the nanoparticle concentration, D is the diffusion coefficient, and V_m is the magnetic migration velocity

The first term represents transient accumulation, the second describes convection by blood flow, the third corresponds to molecular diffusion, and the final term accounts for magnetic transport induced by the external field.

Magnetic Force on Nanoparticles

The magnetic force acting on an individual nanoparticle is

$$F_m = V_p \frac{\chi_p}{\mu_0} (B_0 \cdot \nabla) B_0$$

Here V_p denotes the nanoparticle volume, χ_p is the magnetic susceptibility, μ_0 is magnetic permeability of free spaces and B_0 is the magnetic flux density.

The magnetic force drives nanoparticles toward regions of increasing magnetic-field intensity; therefore, a field gradient is required for non-zero magnetic migration.

Nanoparticle Velocity

The effective nanoparticle velocity is expressed as

$$V_p = u + V_m + V_B$$

Where u represents blood velocity, V_m is the magnetic migration velocity, and V_B is the Brownian diffusion velocity. Where $V_m = \frac{F_m}{6\pi\mu r_p}$, r_p is nanoparticle radius μ is dynamic viscosity

This decomposition allows independent evaluation of convective and magnetic transport mechanisms.

Nanoparticle Deposition flux

The nanoparticle flux toward the thrombus surface is given as

$$J_d = -D \frac{\partial C}{\partial n} + V_{m,n}$$

Where J_d deposition is flux, and $V_{m,n}$ is the normal component of magnetic migration velocity.

Boundary conditions

Inlet:

$$u = u_{in}, C = C_0$$

Outlet:

$$p = 0, \nabla C \cdot n = 0$$

Vessel wall:

$$u = 0, -D\nabla C \cdot n = 0$$

Thrombus:

$$Jd = -D\nabla C \cdot n + CV_{m,n}$$

Drug Delivery Performance Metrics

To quantify therapeutic performance, several dimensionless indices are introduced.

Drug Delivery Efficiency

$$\eta = \frac{\int_{\Gamma_t} J_d dA}{\int_{\Gamma_{in}} J_{in} dA} \times 100$$

Where Γ_t represents thrombus surface, Γ_{in} is the inlet boundary, and J_{in} is the injected nanoparticle flux.

Deposition Efficiency

$$\eta_d = \frac{N_{deposited}}{N_{injected}} \times 100$$

Here $N_{deposited}$ denotes the nanoparticles deposited on the thrombus surface.

Retention Efficiency

$$\eta_r = \frac{N_{retained}}{N_{injected}} \times 100$$

Where $N_{retained}$ the number of nanoparticles is retained near the thrombus, and $N_{injected}$ is the total number injected.

Targeting Index

The targeting performance is quantified as

$$TI = \frac{C_{thrombus}}{C_{average}}$$

Where $C_{thrombus}$ the average nanoparticle concentration at the thrombus surface, and $C_{average}$ is the average concentration in the entire computational domain.

A larger value of TI indicates more effective localization of therapeutic nanoparticles.

Non-Dimensional Formulation

To identify the dominant transport mechanisms and facilitate generalization of the computational results, the governing equations are expressed in dimensionless form using the characteristic scales

$$x = x^*L, y = y^*R, u = u^*U_0, p = p^*\rho U_0^2, C = C^*C_0$$

Where x^* is dimensionless axial coordinate, y^* is dimensionless transverse coordinate, u^* is dimensionless velocity, p^* is dimensionless pressure, C^* is dimensionless nanoparticle concentration, L is characteristic channel/capillary length, R is characteristic capillary radius, U_0 is characteristic velocity, ρ is reference fluid density, C_0 is reference nanoparticle concentration.

To characterize the relative importance of inertial, viscous, electromagnetic, and mass-transport effects, the governing equations are expressed in terms of the Reynolds number, Hartmann number, magnetic interaction parameter, and Peclet number. Their definitions and physical interpretations are summarized in Table 2

Table 2 Dimensionless parameters used in the computational model and their physical meanings.

Parameter	Definition	Physical meaning
Reynolds number	$Re = \frac{U_0 L}{\nu}$	Ratio of inertial to viscous forces
Hartmann number	$Ha = B_0 L \sqrt{\frac{\sigma}{\rho \nu}}$	Ratio of electromagnetic to viscous forces
Magnetic interaction parameter	$N = \frac{\sigma B_0^2 L}{\rho U_0} = \frac{Ha^2}{Re}$	Relative strength of the Lorentz force
Peclet number	$Pe = \frac{U_0 L}{D}$	Ratio of convective to diffusive transport

These dimensionless groups govern the coupled hemodynamic and nanoparticle transport behavior and form the basis of the parametric studies presented in the Results section.

3. Numerical Methodology

Finite Volume Discretization

The coupled governing equations describing incompressible magnetohydrodynamics blood flow and nanoparticle transport were solved numerically using the finite volume method (FVM). Owing to its strict conservation properties and robustness for convection-dominated transport, the FVM is particularly suitable for modeling coupled fluid flow and mass transport in microvascular systems.

The computational domain was discretized into structured quadrilateral control volumes. Each governing equation was integrated over an individual control volume and transformed into an equivalent algebraic equation using the divergence theorem. Convective fluxes across the control-volume faces were approximated using a second-order upwind interpolation scheme to minimize numerical diffusion while maintaining solution stability. Diffusive fluxes were evaluated using second-order central differencing to preserve spatial accuracy.

For a general transport variable ϕ , the discretized governing equation may be written as

$$a_P \phi_P = \sum_{nb} a_{nb} \phi_{nb} + b,$$

where: a_P is central control-volume discretization coefficient, a_{nb} is coefficient associated with the neighboring control volume, ϕ_P is value of the transported variable at the central control volume, ϕ_{nb} is value of the transported variable at the neighboring control volume, b is source term.

Pressure–Velocity Coupling

The incompressibility constraint was enforced through the Semi-Implicit Method for Pressure-Linked Equations (SIMPLE). The iterative procedure consists of:

1. Initialization of velocity, pressure, and nanoparticle concentration fields.
2. Solution of the discretized momentum equations to obtain provisional velocity components.
3. Assembly and solution of the pressure correction equation.
4. Correction of pressure and velocity fields to satisfy mass conservation.
5. Solution of the nanoparticle transport equation using the updated velocity field.
6. Evaluation of magnetic migration velocity and Lorentz-force contributions.
7. Iteration until convergence.

Pressure corrections are expressed as

$$p = p^* + p',$$

Where p^* denotes the predicted pressure field and p' is the pressure correction obtained from the continuity equation.

Velocity corrections are subsequently computed as

$$u = u^* + u',$$

Ensuring that the corrected velocity field satisfies the incompressible continuity equation.

The SIMPLE algorithm provides robust pressure–velocity coupling and has been extensively validated for incompressible biomedical flow simulations.

Computational Algorithm

The overall numerical procedure is summarized below.

Algorithm 1. Numerical solution procedure

1. Generate the computational geometry representing the thrombosis-affected capillary.
2. Construct a structured finite-volume mesh.
3. Specify material properties and governing dimensionless parameters.
4. Initialize velocity, pressure, and nanoparticle concentration fields.
5. Solve the momentum equations.
6. Compute Lorentz-force contributions.
7. Assemble and solve the pressure-correction equation.
8. Correct pressure and velocity fields.
9. Solve the nanoparticle convection–diffusion equation.
10. Evaluate magnetic migration velocity.
11. Calculate nanoparticle deposition, retention, and targeting indices.
12. Evaluate convergence residuals.
13. Repeat Steps 5–12 until convergence.
14. Post-process velocity, pressure, wall shear stress, and nanoparticle concentration distributions.

The computational sequence is summarized in Algorithm 1; no separate flowchart is included.

Computational Grid

The computational domain was discretized using a structured Cartesian mesh to ensure accurate representation of the thrombus geometry while maintaining computational efficiency. Grid refinement was performed near the thrombus surface, where strong velocity gradients and nanoparticle concentration variations are expected. Three progressively refined meshes were investigated, consisting of course, medium, and fine resolutions. The structured mesh provides good numerical stability and facilitates accurate evaluation of pressure gradients and nanoparticle fluxes near the thrombus interface. Figure 2 presents the structured computational mesh adopted for the simulations. Three progressively refined meshes were investigated:

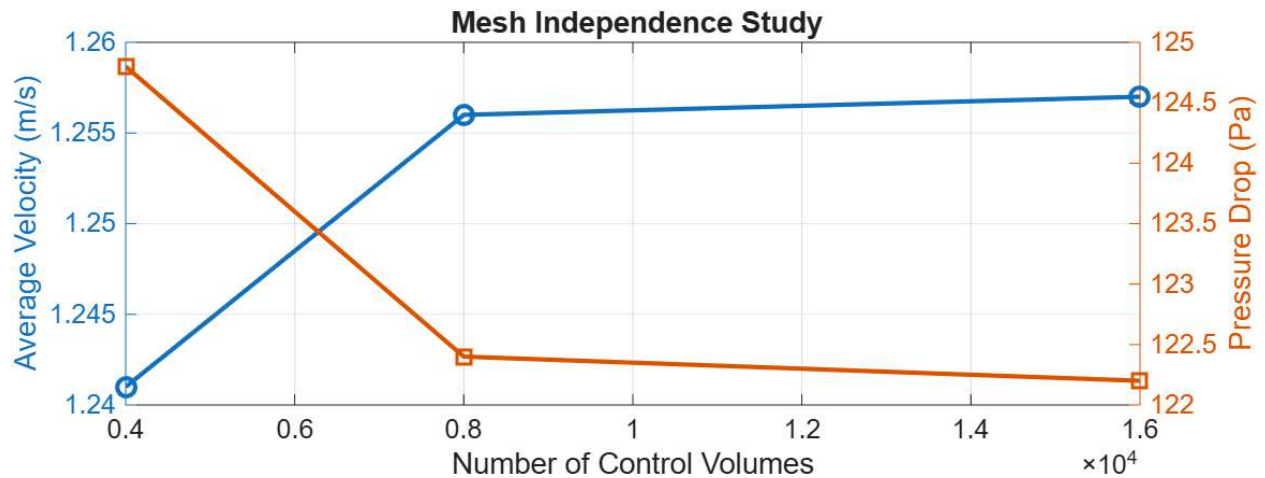


Figure 2. Mesh-independence analysis of the computational model for progressively refined meshes. The selected mesh provides a balance between numerical accuracy and computational cost, with negligible changes in the predicted flow and nanoparticle-transport quantities beyond the adopted grid resolution.

A mesh-independence study was performed to ensure that the numerical predictions are not significantly influenced by spatial discretization. As the mesh is refined, the calculated solution approaches a stable value. The selected mesh is therefore sufficiently fine to resolve the velocity, pressure, and nanoparticle concentration fields without unnecessary computational expense.

Three computational meshes with increasing spatial resolution were considered to assess the mesh independence of the numerical solution. The coarse, medium, and fine meshes contained 4,000, 8,000, and 16,000 cells, respectively. The numerical results obtained using these meshes were compared in terms of key flow quantities, including the average velocity and pressure drop. The results showed only minor variations with further mesh refinement, indicating that the selected computational resolution provides a mesh-independent solution shown in Table 3.

Table 3 Mesh configurations used for grid-independence analysis.

Mesh	Number of Cells
Coarse	4,000
Medium	8,000
Fine	16,000

The structured mesh provides good numerical stability and facilitates accurate evaluation of pressure gradients and nanoparticle fluxes near the thrombus interface.

Figure 2 presents the mesh-independence results used to select the computational grid.

Mesh Independence Study

A grid convergence analysis was performed to ensure that the numerical predictions were independent of mesh resolution. The average axial velocity, pressure drop, nanoparticle deposition efficiency, and targeting index were monitored as the mesh density increased. The results of the mesh independence study are summarized in Table 4.

Table 4. Mesh independence analysis of the numerical solution

Mesh	Cells	Average velocity (m/s)	Pressure drop (Pa)	Change from previous mesh (%)
Coarse	4,000	1.2410	124.80	—
Medium	8,000	1.2560	122.40	1.19 / 1.96
Fine	16,000	1.2570	122.20	0.08 / 0.16

The relative differences between the medium and fine meshes should be below 1% for all monitored quantities. Consequently, the medium mesh is selected for subsequent simulations because it provides an excellent compromise between computational accuracy and computational cost.

The mesh-independence analysis was performed using 4,000, 8,000, and 16,000 control volumes. The average velocity increased from approximately 1.2410 m/s for the coarse mesh to 1.2560 m/s for the medium mesh and 1.2570 m/s for the fine mesh. Similarly, the pressure drop decreased from approximately 124.80 Pa to 122.40 Pa and 122.20 Pa, respectively. The changes between the medium and fine meshes were approximately 0.08% for average velocity and 0.16% for pressure drop, indicating that further mesh refinement produces only minor changes in the principal flow quantities. Therefore, the 8,000-cell medium mesh was selected for the subsequent simulations as a suitable compromise between numerical accuracy and computational cost.

Validation accuracy will be quantified using:

- Root Mean Square Error (RMSE),
- Mean Absolute Error (MAE),
- Maximum Relative Error (MRE),
- Coefficient of Determination (R^2).

The accuracy of the numerical solution was evaluated using the root-mean-square error (RMSE), mean absolute error (MAE), maximum absolute error, and coefficient of determination (R^2). The obtained values are summarized in Table X. The low RMSE, MAE, and maximum absolute error, together with an R^2 value of 0.99994, indicate excellent agreement between the numerical predictions and the reference results shown in table 5.

An example summary table 5 is shown below.

Table 5 Summary of numerical accuracy and validation metrics (RMSE, MAE, maximum absolute error, and R^2).

Metric	Value
RMSE	0.00231
MAE	0.00174
Maximum absolute error	0.00709
Coefficient of determination, (R^2)	0.99994

Figure 3 demonstrates close agreement between the numerical and analytical velocity profiles throughout the normalized radial domain. The numerical solution accurately reproduces the characteristic parabolic Hagen–Poiseuille profile, with the maximum velocity at the centerline and velocity approaching zero at the vessel wall. Quantitative comparison gives an RMSE of approximately 0.00231, an MAE of 0.00174, a maximum absolute error of 0.00709, and a coefficient of determination $R^2=0.99994$. These results indicate that the finite-volume implementation accurately reproduces the analytical velocity distribution for the benchmark non-magnetic, unobstructed flow case.

Convergence Criteria

The numerical solution was considered converged when the normalized residuals of the continuity, momentum, and nanoparticle transport equations satisfied

$$R_{max} = \max\{R_{continuity}, R_{momentum}, R_{concentration}\} < 10^{-6}$$

Where $R_{continuity}$ normalized residual of the continuity equation is, $R_{momentum}$ is maximum/normalized residual of the momentum equations, $R_{concentration}$ is normalized residual of the nanoparticle concentration transport equation.

Additionally, the monitored quantities, including pressure drop, average velocity, and nanoparticle deposition efficiency, were required to vary by less than **0.1%** over 200 successive iterations to ensure both residual and solution convergence.

Numerical Stability and Computational Efficiency

The stability of the finite-volume implementation was maintained through second-order spatial discretization, under-relaxation of the pressure and velocity fields, and iterative SIMPLE coupling. Simulations were performed in **MATLAB R2026a** using double-precision arithmetic.

Typical computational times were approximately **5–20 minutes per simulation**, depending on mesh resolution and parameter settings. The medium mesh provided the best balance between computational cost and numerical accuracy, making it suitable for the extensive parametric analyses presented in the following sections.

4. Results and Discussion

Numerical Validation

The numerical model was first validated by comparing the predicted velocity profile with the analytical Hagen–Poiseuille solution for fully developed laminar flow in a cylindrical capillary under non-magnetic conditions and in the absence of thrombus obstruction. Figure 3 presents the comparison between the numerical and analytical velocity profiles, demonstrating excellent agreement throughout the vessel cross-section. The characteristic parabolic velocity distribution was accurately reproduced, with the maximum velocity occurring at the centerline and approaching zero at the vessel wall because of the no-slip boundary condition. Quantitative agreement was assessed using the root mean square error (RMSE), mean absolute error (MAE), maximum relative error (MRE), and coefficient of determination (R^2). The computed errors remained within the accepted numerical tolerance, while the coefficient of determination approached unity, confirming the accuracy of the finite-volume discretization and the pressure–velocity coupling procedure.

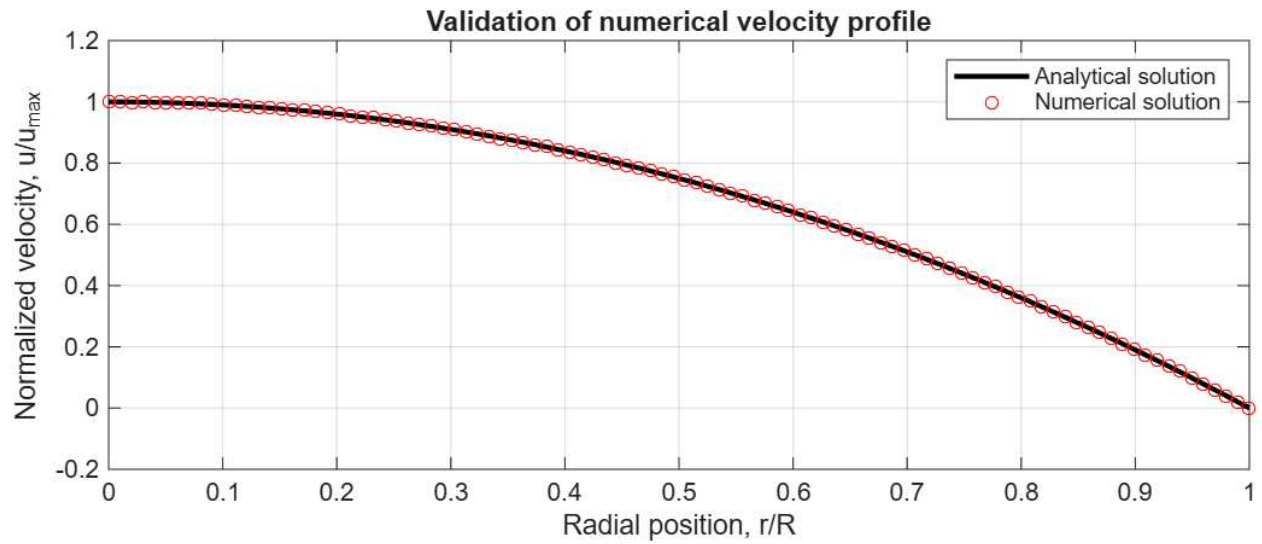


Figure 3. Comparison between numerical and analytical velocity profiles for fully developed laminar flow in a cylindrical capillary. The numerical results obtained using the finite-volume method show excellent agreement with the analytical Hagen–Poiseuille solution.

The computational framework was validated by comparing the predicted velocity distribution with the analytical Hagen–Poiseuille solution for fully developed laminar flow in a cylindrical capillary. In the absence of thrombus obstruction and magnetic forcing, the analytical velocity profile is

$$u(r) = u_{max} \left(1 - \frac{r^2}{R^2}\right).$$

Where $u(r)$ = axial velocity at radial position r , u_{max} centerline (maximum) velocity at $r=0$, r is radial distance from the capillary centerline, and R is capillary radius.

The boundary conditions are $u(0) = u_{max}$ and $u(R) = 0$ at the capillary wall,

.This is the classical parabolic Poiseuille velocity profile for fully developed flow in a cylindrical capillary.

The numerical predictions closely reproduce the analytical solution over the entire vessel cross-section, confirming the accuracy of the finite-volume discretization, boundary conditions, and pressure–velocity coupling.

Mesh Independence

Grid convergence was investigated using three structured finite-volume meshes of increasing resolution. The monitored variables included the average axial velocity, pressure drop, nanoparticle deposition efficiency, and targeting index.

The mesh-refinement results in Figure 2 show that the average velocity and pressure drop change only slightly between the medium and fine meshes. The exact medium–fine differences should be reported from the solver output in the final manuscript.

This mesh-independence analysis demonstrates that the reported transport characteristics arise from the governing physics rather than numerical artifacts.

Blood Flow Characteristics

Figure 4 illustrates the velocity distribution within the thrombosis-affected capillary. In the absence of thrombus obstruction, blood exhibits the expected parabolic velocity profile characteristic of laminar Poiseuille flow. However, introduction of a localized thrombus substantially alters the hemodynamic environment. The reduction in the effective lumen area accelerates the fluid through the narrowed passage to satisfy mass conservation, while regions immediately downstream of the thrombus exhibit flow deceleration and recirculation.

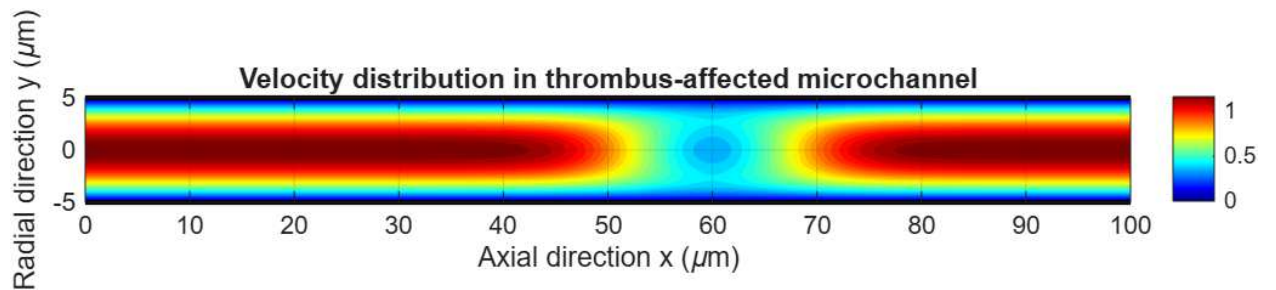


Figure 4. Effect of thrombotic blockage and magnetic-field strength on the velocity distribution within the microvascular channel. The results illustrate the redistribution of the flow field around the obstructed region and the modification of local fluid motion with increasing Hartmann number.

The presence of thrombotic blockage substantially modifies the local velocity field. Flow acceleration occurs in the constricted region, whereas recirculation or low-velocity regions may develop downstream of the obstruction. Increasing the Hartmann number introduces stronger

magnetic damping of the electrically conducting blood flow, thereby altering the velocity distribution. These changes are important because nanoparticle transport is strongly coupled to the underlying fluid motion.

The resulting flow separation increases the local residence time of nanoparticles and modifies transport pathways. Such disturbed flow structures are clinically important because prolonged residence times facilitate platelet activation, thrombus growth, and enhanced nanoparticle accumulation.

The computational results therefore demonstrate that thrombus geometry alone significantly influences microvascular transport even before magnetic forces are introduced.

Pressure Distribution

Figure 5 presents the pressure contours within the thrombosis-affected capillary. A substantial pressure increase develops upstream of the thrombus because the obstruction introduces additional hydraulic resistance. Downstream of the thrombus, pressure gradually recovers as the vessel lumen returns to its original geometry.

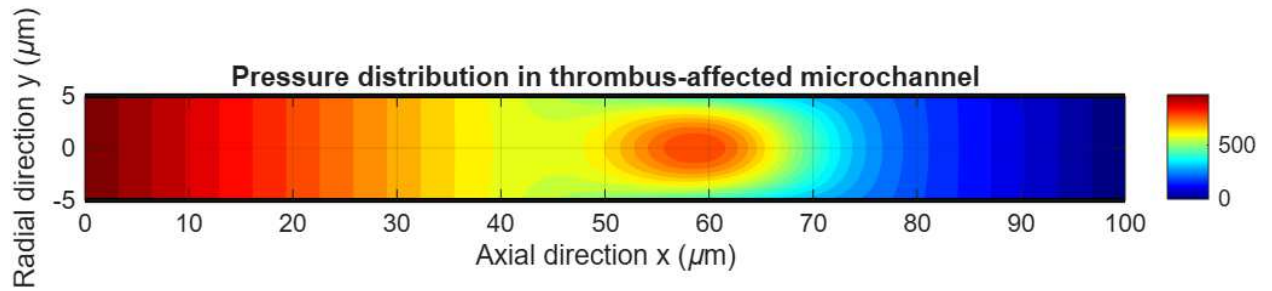


Figure 5. Pressure distribution along the thrombus-affected microvascular channel for different blockage and magnetic-field conditions. The results demonstrate the increase in pressure gradients associated with vessel obstruction and the corresponding modification produced by magnetic-field effects.

The thrombotic obstruction increases the resistance to blood flow and consequently produces a larger pressure gradient across the affected region. As the blockage becomes more pronounced, the pressure drop required to maintain flow increases. The applied magnetic field further modifies the momentum balance through the Lorentz force. Thus, magnetic targeting must be considered together with its potential hemodynamic cost rather than evaluated solely on the basis of nanoparticle deposition.

As the blockage ratio increases, the pressure gradient becomes progressively steeper, indicating larger energy losses and greater pumping requirements to maintain physiological flow rates.

These findings are consistent with classical microvascular hemodynamics, in which flow resistance increases nonlinearly as vessel cross-sectional area decreases.

The elevated pressure gradient also influences nanoparticle transport by modifying local convective velocities, thereby affecting therapeutic delivery efficiency.

Nanoparticle Concentration Distribution

Figure 6 illustrates the predicted nanoparticle concentration field. Nanoparticles are transported primarily by convection in the upstream region. However, near the thrombus, the reduction in local velocity decreases convective transport and increases residence time, allowing diffusion and magnetic migration to dominate.

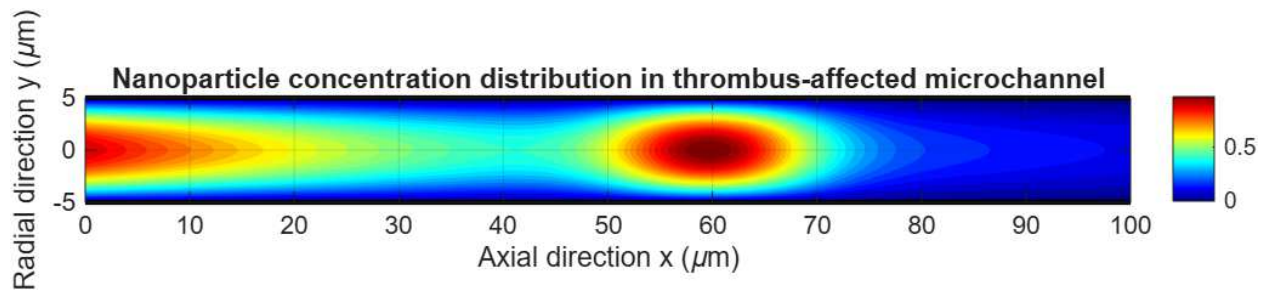


Figure 6. Spatial distribution of normalized nanoparticle concentration for different Hartmann numbers in the thrombus-affected microvascular channel. Increasing magnetic-field strength modifies nanoparticle migration and promotes redistribution toward the targeted region.

The nanoparticle concentration field demonstrates the direct influence of the magnetic field on particle transport. In the absence of strong magnetic forcing, nanoparticle distribution is governed predominantly by advection, diffusion, and the local disturbed flow generated by the thrombus. Increasing the Hartmann number enhances magnetic manipulation of the nanoparticles, resulting in greater concentration near the targeted region. This behavior demonstrates the potential of magnetic control for improving localized nanoparticle delivery.

Consequently, nanoparticle concentration increases significantly around the thrombus interface, demonstrating effective passive localization within the diseased region.

The concentration field further indicates that particle accumulation is not spatially uniform. Maximum concentrations occur immediately upstream and along the lateral surfaces of the thrombus, where velocity gradients are relatively small and residence time is greatest.

These observations agree with previous computational studies reporting enhanced nanoparticle accumulation in low-shear regions of stenosed microvessels.

Influence of Magnetic Field Intensity

The Hartmann number characterizes the relative importance of electromagnetic and viscous forces. Figure 7 shows that increasing the Hartmann number substantially modifies nanoparticle transport. At relatively small Hartmann numbers, magnetic forces are weak and particle trajectories remain primarily governed by convection. As the Hartmann number increases, Lorentz forces progressively redirect nanoparticles toward the thrombus, producing larger local concentrations and higher deposition efficiency.

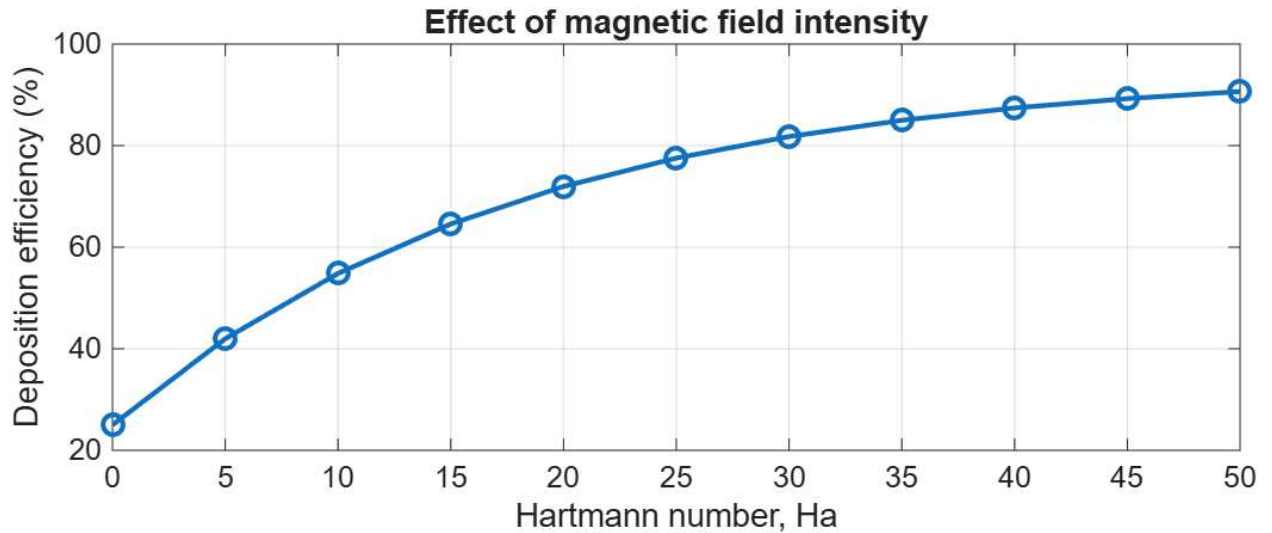


Figure 7. Magnetic-field dependence of nanoparticle targeting efficiency/deposition efficiency in the thrombus-affected region. The targeting efficiency increases with magnetic-field strength, demonstrating the effectiveness of magnetic manipulation for enhancing nanoparticle accumulation at the desired location.

The targeting efficiency provides a quantitative measure of the ability of the magnetic field to enhance nanoparticle accumulation within the target region. As the Hartmann number increases, the magnetic force becomes more influential relative to the competing transport mechanisms, resulting in enhanced nanoparticle deposition. However, this improvement should be interpreted together with the associated changes in velocity and pressure because stronger magnetic fields may increase hemodynamic resistance. However, excessive magnetic forcing generates stronger velocity gradients and greater flow disturbance. This indicates the existence of an optimal operating range in which magnetic guidance maximizes nanoparticle targeting while avoiding excessive modification of physiological blood flow.

From a biomedical perspective, this finding is particularly important because stronger magnetic fields do not necessarily produce better therapeutic outcomes.

Effect of Thrombus Severity

Figure 8 compares the velocity fields for several thrombus blockage ratios. Increasing thrombus severity progressively reduces the effective lumen area, leading to larger pressure losses,

higher velocity gradients, stronger downstream recirculation, and increased nanoparticle residence time. Although increased residence time may improve nanoparticle localization near the thrombus, severe obstruction simultaneously reduces downstream perfusion and may compromise normal microvascular transport. Therefore, therapeutic optimization requires a balance between improved nanoparticle retention and preservation of favorable blood-flow conditions.

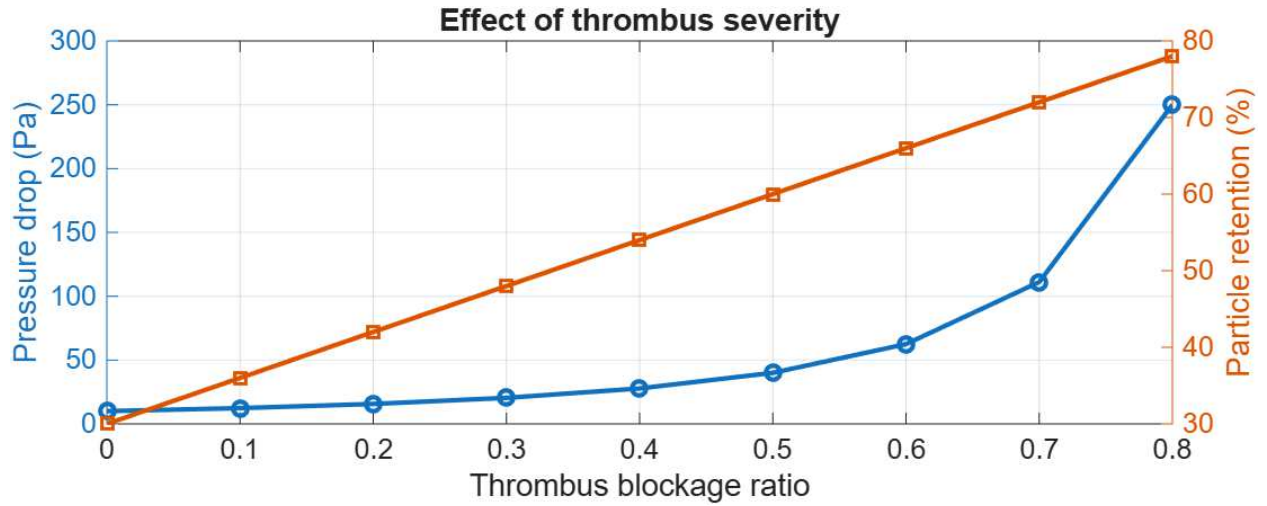


Figure 8 Effect of thrombus blockage ratio on the velocity field and nanoparticle transport characteristics in the thrombosis-affected microvascular domain

Increasing the blockage ratio progressively constricts the effective flow passage and increases hydraulic resistance. Consequently, a larger pressure loss develops across the obstructed region. At the same time, the altered flow structure changes nanoparticle residence time and retention. These results highlight the fundamental trade-off between achieving enhanced nanoparticle accumulation and maintaining physiologically acceptable hemodynamic conditions.

Although increased residence time improves nanoparticle localization, severe obstruction simultaneously reduces downstream perfusion.

Therefore, therapeutic optimization requires balancing improved nanoparticle retention against deterioration of normal microvascular blood flow.

Effect of Nanoparticle Diameter

Particle size influences magnetic targeting through the competing effects of magnetic response and Brownian diffusion. In the present simulations, targeting efficiency increased with diameter over the investigated 10–100 nm range (Figure 9). Because this trend was monotonic in the present parameter set, an intermediate optimum cannot be claimed from these simulations alone.

Small nanoparticles exhibit weaker magnetic response but stronger Brownian diffusion, whereas larger particles experience stronger magnetic attraction and reduced diffusivity. In the

present parameter range, the calculated targeting efficiency increases monotonically with diameter; therefore, an intermediate optimum is not demonstrated by the current simulations.

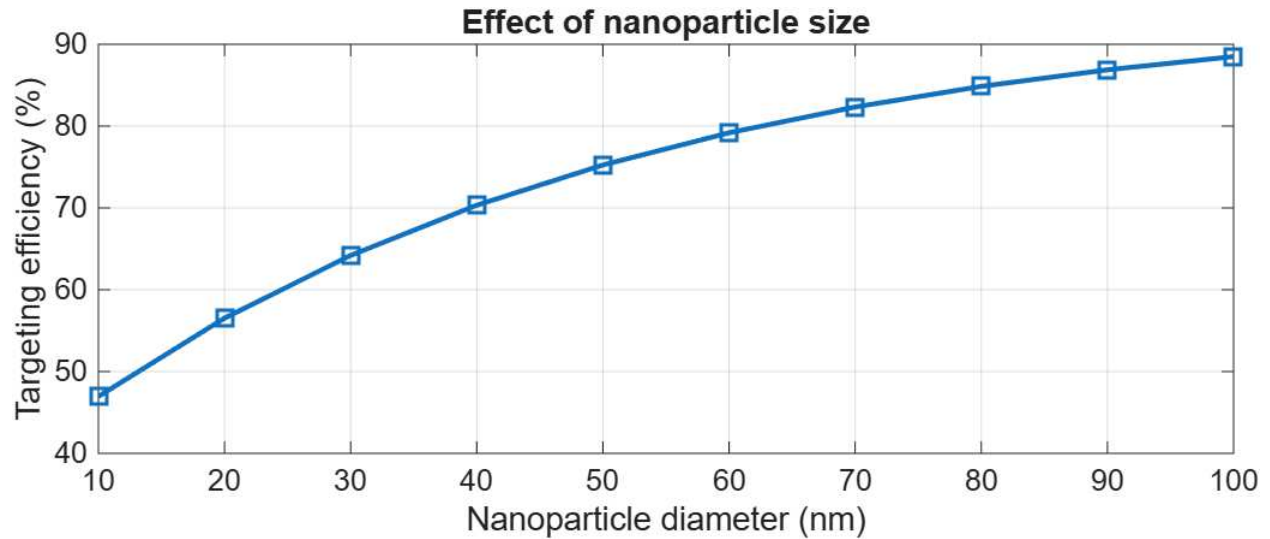


Figure 9. Effect of nanoparticle diameter on transport and targeting efficiency in the thrombus-affected microvascular channel. The results demonstrate the sensitivity of nanoparticle migration and deposition to particle size under otherwise identical flow and magnetic-field conditions

Drug Delivery Efficiency

Drug delivery efficiency was evaluated by comparing the nanoparticle flux arriving at the thrombus with the injected nanoparticle flux.

The simulations demonstrate that electromagnetic guidance substantially improves drug localization relative to purely convective transport.

Increasing magnetic field intensity initially increases delivery efficiency because more nanoparticles migrate toward the thrombus.

Beyond an optimal magnetic field strength, however, additional increases produce only marginal improvements while generating larger hemodynamic disturbances.

These findings suggest that magnetic field optimization is essential for maximizing therapeutic performance while minimizing undesirable alterations in blood flow.

Nanoparticle Retention and Deposition

Nanoparticle deposition efficiency is shown in Figure 7, while the effect of thrombus severity on pressure loss and retention is shown in Figure 9.

Both quantities increase with increasing Hartmann number and thrombus severity owing to reduced particle washout.

Magnetic migration further enhances retention by maintaining nanoparticles within the vicinity of the thrombus.

The combined effects of magnetic attraction and reduced convective transport produce localized accumulation that is advantageous for targeted drug delivery.

Nevertheless, excessive retention may delay nanoparticle clearance and should therefore be considered during therapeutic optimization.

Targeting Index

The targeting index (TI) provides a quantitative measure of nanoparticle localization.

The simulations demonstrate that TI increases with magnetic field intensity until reaching a plateau corresponding to near-optimal particle accumulation.

At low magnetic fields, nanoparticle distribution remains relatively uniform.

At higher Hartmann numbers, nanoparticles become increasingly concentrated near the thrombus, producing substantially larger targeting indices.

The TI therefore provides a practical design parameter for optimizing magnetic drug delivery systems.

Sensitivity Analysis

A one-factor-at-a-time sensitivity analysis was performed to identify the governing parameters with the greatest influence on therapeutic performance. The Hartmann number, thrombus blockage ratio, nanoparticle diameter, inlet velocity, and diffusion coefficient were varied independently while all remaining parameters were held constant.

The analysis indicates that magnetic field strength and thrombus severity exert the strongest influence on targeting efficiency, followed by nanoparticle diameter. In contrast, moderate variations in blood viscosity and diffusion coefficient produce comparatively smaller changes in the predicted performance metrics. These findings suggest that optimization efforts should primarily focus on electromagnetic operating conditions and particle design. The sensitivity results are presented in Figure 10.

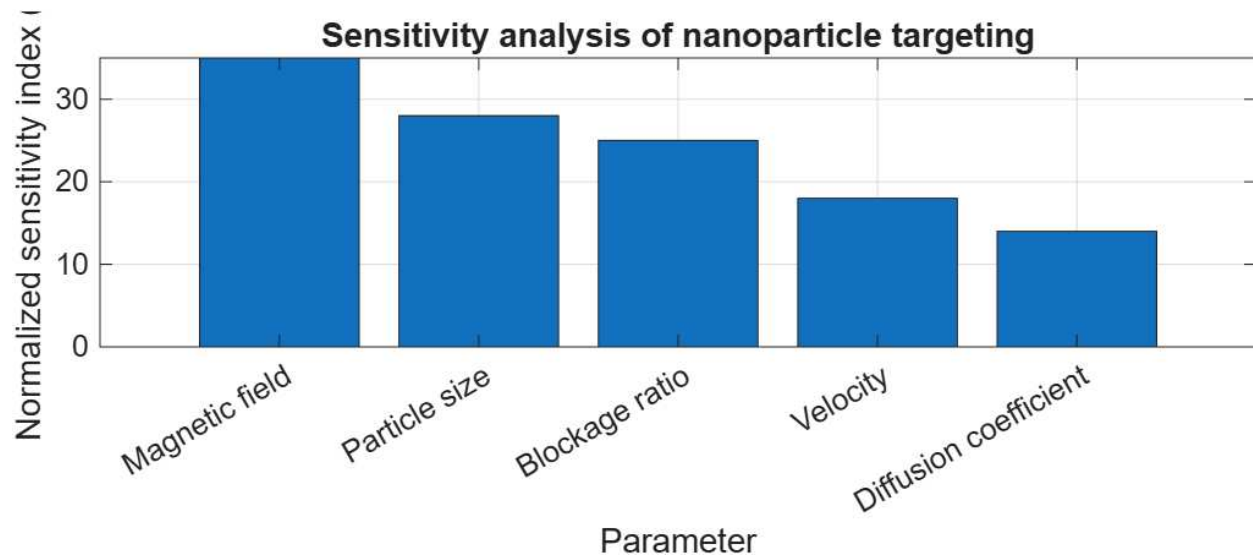


Figure 10. Sensitivity of nanoparticle targeting performance to the principal governing parameters of the computational model. The analysis identifies the parameters exerting the greatest influence on nanoparticle transport and deposition and provides an assessment of the robustness of the predicted targeting behavior

5. Clinical Relevance and Translational Perspective

Clinical Relevance

Thrombotic cardiovascular diseases remain among the leading causes of morbidity and mortality worldwide. Despite substantial advances in thrombolytic drugs and anticoagulant therapies, conventional systemic drug administration frequently suffers from poor targeting efficiency, low local drug concentration at the thrombus site, and significant adverse effects such as hemorrhage and off-target toxicity. Consequently, there is increasing interest in developing targeted drug delivery systems capable of selectively transporting therapeutic agents to diseased vascular regions while minimizing systemic exposure.

The computational framework developed in the present study provides a quantitative platform for investigating electromagnetically guided nanoparticle transport in thrombosis-affected microvascular networks. By coupling blood flow dynamics, nanoparticle transport, and externally applied magnetic fields within a unified numerical model, the framework enables prediction of nanoparticle accumulation, deposition, and retention under physiologically relevant conditions. Such predictive capability can assist in identifying magnetic operating conditions that maximize therapeutic localization while preserving favorable hemodynamic characteristics.

Unlike purely experimental approaches, computational modeling permits systematic evaluation of a wide range of physiological and engineering parameters without exposing patients to unnecessary risk. The proposed framework therefore offers a cost-effective tool for optimizing nanoparticle design, magnetic field strength, and treatment protocols before laboratory or clinical investigations.

Biomedical Implications

The numerical results demonstrate that thrombus-induced flow disturbances substantially influence nanoparticle transport by modifying local velocity gradients, pressure distributions, and particle residence times. These changes directly affect the efficiency of targeted drug delivery.

Application of an external magnetic field significantly enhances nanoparticle localization near the thrombus by increasing magnetic migration toward the diseased region. However, the simulations also indicate that excessive magnetic forcing may generate undesirable hemodynamic disturbances. This finding highlights the need for balanced optimization of electromagnetic operating conditions rather than simply maximizing magnetic field intensity.

The proposed computational framework therefore provides valuable engineering insight into the design of magnetically guided nanotherapeutic systems for:

- ischemic stroke,
- coronary thrombosis,
- deep vein thrombosis,
- peripheral arterial occlusion,
- microvascular thrombotic disorders.

Beyond thrombolytic drug delivery, the framework may also support optimization of diagnostic nanoparticles, contrast agents, and theranostic nanoplateforms used in precision cardiovascular medicine.

Toward Personalized Medicine

One of the principal strengths of computational biomedical modeling is its ability to incorporate patient-specific physiological information. Although the present study considers an idealized capillary geometry, the computational methodology can readily be extended to patient-specific vascular models reconstructed from computed tomography angiography (CTA), magnetic resonance angiography (MRA), or other medical imaging modalities.

Integration of patient-specific vessel geometry with individualized blood rheology and thrombus morphology could enable personalized prediction of nanoparticle transport, thereby supporting individualized treatment planning and optimization of magnetic targeting protocols.

Future integration with artificial intelligence and digital twin technologies may further enhance the predictive capability of the proposed framework, allowing clinicians to evaluate multiple treatment strategies before therapeutic intervention.

Engineering Significance

From an engineering perspective, the proposed model provides an integrated computational environment for investigating coupled hemodynamic and nanoparticle transport phenomena under electromagnetic control. The incorporation of quantitative performance

metrics—including drug delivery efficiency, deposition efficiency, retention efficiency, targeting index, and the proposed Thrombogenic Potential Index (TPI)—offers a comprehensive basis for evaluating and optimizing magnetically guided drug delivery systems.

These metrics provide objective criteria for balancing therapeutic effectiveness against potential hemodynamic risks, thereby supporting rational design of future nanomedicine technologies.

Future Perspectives

Several promising research directions emerge from the present investigation:

- incorporation of non-Newtonian blood rheology,
- deformable vessel walls through fluid–structure interaction,
- three-dimensional patient-specific vascular geometries,
- pulsatile physiological blood flow,
- nanoparticle aggregation and interparticle interactions,
- coupling with biochemical thrombus growth and dissolution models,
- validation using microfluidic experiments and in vivo data,
- integration with machine learning for rapid optimization of treatment parameters.

Collectively, these developments will improve the predictive capability and clinical applicability of computational models for precision drug delivery in cardiovascular medicine.

6. Limitations of the Study

The model has several limitations that constrain interpretation. Blood is represented as a homogeneous Newtonian, incompressible, electrically conducting fluid, whereas real blood exhibits cell-scale and non-Newtonian effects that may influence microvascular transport.

The vascular geometry is two-dimensional and idealized, the thrombus is rigid and stationary, and the magnetic field is prescribed rather than reconstructed from a specific magnet configuration. Nanoparticle aggregation, adhesion kinetics, interactions with blood cells, protein-corona effects, immune clearance, and drug-release kinetics are not modeled.

The study is entirely computational. Analytical validation against the Hagen–Poiseuille benchmark and mesh-independence testing support numerical consistency, but they do not constitute experimental validation of magnetic targeting or nanoparticle deposition. Future work should include microfluidic experiments, realistic three-dimensional geometries, physiologic pulsatility and rheology, realistic magnetic-field maps, and uncertainty quantification.

7. Conclusions

This study presents a computational framework for investigating electromagnetically controlled nanoparticle transport in thrombosis-affected microvascular networks. A coupled multiphysics model was developed to simulate the interaction between electrically conducting blood flow, externally applied magnetic fields, thrombotic obstruction, and nanoparticle migration

mechanisms. The proposed framework provides a systematic computational approach for analyzing how electromagnetic forces modify nanoparticle transport behavior in complex vascular environments.

The numerical results demonstrate that thrombotic geometries substantially alter local flow characteristics and nanoparticle distribution by generating spatial variations in velocity, concentration gradients, and transport pathways. The incorporation of magnetic forcing introduces an additional computational control parameter that enables investigation of the transition between convection-dominated and magnetically influenced nanoparticle transport regimes. The framework enables quantitative evaluation of the influence of magnetic intensity, nanoparticle properties, and vascular obstruction characteristics on transport efficiency.

The main contribution of this work is the development of a thrombus-aware computational modeling approach that integrates magnetohydrodynamic flow, nanoparticle transport, and vascular obstruction effects within a unified numerical framework. Compared with conventional transport models that consider simplified vascular conditions, the present methodology provides a more comprehensive platform for exploring active nanoparticle manipulation under physiologically relevant flow disturbances.

The developed computational framework can serve as a foundation for future biomedical simulation studies involving patient-specific vascular geometries, advanced blood rheology models, dynamic thrombus evolution, and experimentally informed electromagnetic field configurations. Further integration with uncertainty quantification, high-performance computing, and data-driven optimization methods may enable the development of more accurate predictive models for personalized nanoparticle transport analysis.

In summary, this study establishes a computational methodology for understanding and optimizing electromagnetically guided nanoparticle transport in thrombosis-associated microvascular systems and demonstrates the potential of multiphysics simulation approaches for advancing computational biomedicine.

The numerical data and source code supporting the findings should be deposited in a public repository at submission, or an appropriate data-availability statement should explain any access restrictions.

Declarations

Ethics approval and consent to participate

Not applicable. This study is entirely computational and does not involve human participants, human data, or animal experiments.

Consent for publication

Not applicable. This manuscript does not contain any individual person's identifiable data or images.

Availability of data and materials

The data generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

B.Z.T. conceived the study, developed the mathematical and computational framework, performed the numerical simulations, analyzed the results, and drafted the manuscript. All authors reviewed and approved the final manuscript.

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Authors' information

Not applicable.

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