Am J Cardiovasc Dis 2025;15(6):395-404
www.AJCD.us /ISSN:2160-200X/AJCD0168817

Original Article

Effect of external magnetic and electric fields on blood flow and drug transport in a cardiovascular tube

Binyam Zigta Teferi

Wachemo University College of Natural and Computational Science Department of Mathematics, Hossana, Ethiopia

Received September 15, 2025; Accepted December 8, 2025; Epub December 15, 2025; Published December 30, 2025

Abstract: Cardiovascular diseases (CVDs) remain the leading cause of death worldwide, and efficient drug delivery (DD) is critical for treatment success. The use of external electric (EF) and magnetic fields (MF) offers a promising approach to enhance targeted drug transport in vascular systems. This study investigates the effect of combined electric and magnetic fields (EMF) on blood flow and drug delivery (DD) in a cardiovascular tube model. The governing equations for momentum, energy, and concentration were formulated using magneto-hydrodynamics (MHD) theory with slip boundary conditions and external electromagnetic forces (EEF). Similarity transformations reduced the equations to ordinary differential form (ODEs), which were solved numerically using MATLAB code. Increasing magnetic field strength reduced flow resistance while improving drug penetration, whereas the electric field (EF) enhanced solute dispersion via electro-osmotic effects (EOE). The combined effect significantly improved concentration profiles along the tube. Conclusion: The findings suggest that external electromagnetic fields (EEF) can optimize drug delivery (DD) efficiency, providing a theoretical framework for advanced cardiovascular therapies.

Keywords: Magneto hydrodynamics, cardiovascular tube, drug delivery, electric field, magnetic field, biomedical transport

Introduction

Targeted drug delivery is a significant innovation in modern medicine, especially for cardiovascular diseases (CVDs), which remain the leading cause of death worldwide [1]. Systemic administration of drugs by traditional routes often lacks efficacy, systemic toxicity, and biodiversity at the site of interest. In recent past, physical approaches, specifically magnetic and electric fields have shown great promise to enhance accuracy and efficacy of drug delivery systems, especially in complex biological settings such as blood vessels [2-4].

Magnetic targeting technique employs super paramagnetic nanoparticles (NPs) (such as Fe_3O_4 or γ-Fe_2O_3) as drug carriers for delivery. They can be guided by an external magnetic field (EMF) to accumulate in targeted locations, such as arterial plaques or ischemic tissue [5]. When employed in the circulatory system, these magnetically responsive particles circumvent the turbulent and pulsatile character of blood flow, allowing targeted therapeutic intervention with reduced systemic side effects [6].

Electric field (EF) mediated drug delivery (DD), also known as electro transport or iontophoresis, is the use of controlled electric field for driving charged molecules through biological membranes or tissues [7]. Electric fields in cardiovascular use can regulate electrophoretic force, enhance endothelial permeability, and facilitate trans-vascular migration of drug nanoparticles [8].

Also, the combined effect of magnetic and electric fields referred to as magneto-electro-hydrodynamic (MEHD), contributes complex flow interactions that significantly influence nanoparticle trajectories, drug diffusion rates, and permeability of carriers within vascular networks [9, 10].

The approach is especially useful in micro vascular or permeable arterial conditions, where blood flow behavior deviates from classical Newtonian assumptions due to the presence

https://doi.org/10.62347/RYQF6012

Table 1. Effect of magnetic field on blood velocity profiles in cardiovascular tube

Magnetic Field in Tesla (*T*)	Peak velocity in (*cm/sec*)	Wall shear stress in (Pa)
0.0	12.5	1.2
0.5	10.8	1.4
1.0	9.2	1.6

of plasma cell interactions and viscoelastic properties of blood [11]. As shown in **Table 1**, increasing the magnetic field intensity leads to a reduction in peak blood velocity, while the wall shear stress increases due to enhanced Lorentz force effects. The physical configuration of the cardiovascular tube, including the application of external magnetic and electric fields, slip boundary conditions at the arterial wall, and the direction of nanofluid flow for enhanced targeted drug delivery, is schematically illustrated in **Figure 1**.

Recent computation and experimental work has considered the effects of multiphase magneto hydrodynamics flow (MHD), including conditions like slip boundary conditions (SPC), nanoparticle diffusion (NPD), Brownian motion (BM), thermophoresis (TP), and chemical reactions [12-14]. These are important when modeling targeted drug delivery by hybrid nanoparticles or metallic fluids, such as Ferro fluid or liquid metals (e.g., mercury, gallium alloys), with enhanced conductivity and field sensitivity [15].

Conventional systemic drug delivery methods, such as oral or intravenous administration, often provide limited therapeutic efficiency in cardiovascular applications. A large proportion of the drug disperses throughout the body rather than concentrating at the diseased region, resulting in low target specificity and significant systemic side effects. Rapid metabolic clearance and hemodynamic washout further reduce local drug residence time, necessitating higher doses and increasing the risk of toxicity. Physiological barriers, including the vascular endothelium and limited permeability of target tissues, also hinder effective drug penetration. These challenges highlight the need for strategies that can localize and control drug distribution within the vascular network. The application of external magnetic and electric fields provides a promising approach to address these limitations by directing drug-laden carriers toward specific sites, enhancing transvascular transport, and enabling controlled release under physiological flow conditions.

Targeted drug delivery is particularly indicated in conditions where localized therapeutic action is required or systemic exposure can produce adverse effects. In cardiovascular applications, this includes atherosclerosis, restenosis following angioplasty, thrombosis, and ischemic lesions, where site-specific accumulation of anti-proliferative or anti-thrombotic agents can improve efficacy while reducing systemic toxicity. Tumor or ischemic tissues with limited perfusion similarly benefit from localized delivery to achieve sufficient therapeutic concentrations. Chronic cardiovascular disorders, such as hypertension or endothelial dysfunction, require sustained or controlled release near the diseased site to maintain therapeutic levels without frequent dosing. Moreover, sites of vascular inflammation or thrombus formation can be selectively targeted to enhance drug retention and improve therapeutic outcomes. Application of external magnetic and electric fields is a promising strategy to guide drug-laden carriers to these specific locations, enhance transvascular transport, and allow on-demand release, thus improving local efficacy while minimizing systemic side effects.

Accurate positioning of magnetic and electric fields is a prerequisite for the guidance of drug-laden carriers to target sites within the cardiovascular system. Magnetic fields, applied via external magnets or electromagnets, generate gradients that pull magnetically responsive particles toward specific vessels. Electric fields, delivered through intravascular electrodes or external electrodes, induce directional transport of charged or polar carriers via electrophoresis and electro-osmosis. Combined magnetic and electric fields could provide a coarse and fine control, respectively, thus enhancing local retention and transport. Field placement needs to take into consideration vessel depth and pulsatile blood flow while satisfying safety limits to avoid tissue damage; computational modeling and real-time imaging often assist in precise targeting.

The most recent studies have involved the inclusion of electromagnetic control in the modelling of cardiovascular flow and targeted

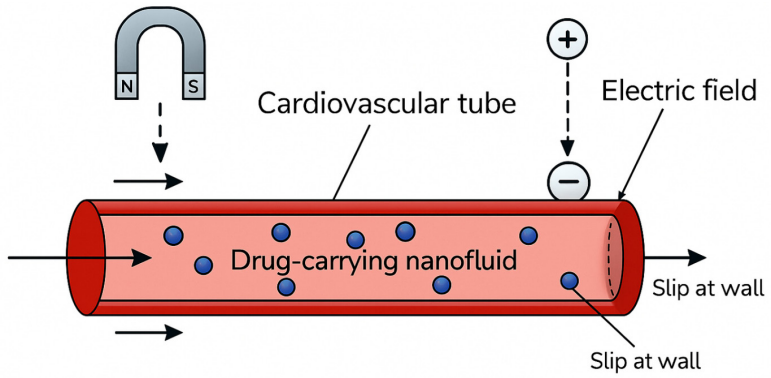

Figure 1. Schematic diagram illustrating the influence of external electromagnetic fields on enhanced drug delivery in a cardiovascular tube. This diagram illustrates how magnetic and electric fields affect enhanced drug delivery within a cardiovascular tube. The tube is shown as a horizontal red cylinder representing a blood vessel, containing a drug-carrying nanofluid described in pink with embedded blue particles that represent nanoparticles or drug molecules. (1) A magnetic field is applied perpendicular, depicted as a horseshoe magnet (N-S poles), directing the field lines downward through the tube. (2) An electric field is applied vertically across the tube from top to bottom. A "+" sign appears above and a "-" sign below. (3) Slip boundary conditions at the walls of the cardiovascular tube suggest partial fluid velocity at the boundaries. This improves flow control. (4) Arrows indicate the flow direction of the nanofluid along the length of the tube. (5) The figure illustrates how external electromagnetic forces can be used to control and improve the targeted delivery of therapeutic agents through the bloodstream.

therapy. Experimental proof of changed blood perfusion under a static magnetic field was given by Mayrovitz [16]. Vélez Salazar and Patiño Arcila [17] combined the dynamics of an electric field with blood pharmacokinetics to explain improved electrochemotherapy efficiency. Numerical studies on MHD effects in non-Newtonian blood through tapered arteries were conducted by Bhatti et al. [18], while Qiu et al. [19] demonstrated permeability enhancement driven by nanoparticles at cellular junctions. Complementary theoretical insights into magnetically induced rotational blood motion were presented by Sidorov [20].

The present work develops a two stage mathematical model for cardiovascular drug transport considering the influence of both electric and magnetic fields. The model consists of blood as a non-Newtonian carrier phase and drug carrier nanoparticles (e.g., Fe_2O_3-H_2O nanofluid) as a dispersed phase separated by an interface in a permeable tube artery. The governing equations that is momentum, energy, and concentration are derived and solved with the help of similarity transformations and numerical analysis. The influence of the principal parameters such as Hartmann number, electric field strength, thermophoresis, and chemical reaction rate on velocity, temperature and concentration profiles of enhanced targeted drug delivery studied in depth.

Mathematical model and governing equations

Consider the axisymmetric, incompressible magneto hydrodynamics flow of a nanofluid drug carrier within a cylindrical permeable arterial tube. The flow is subjected to a transverse magnetic field and a radial electric field. The arterial wall exhibits partial slip, and transport processes such as Brownian motion, thermophoresis, and chemical reactions are included to simulate enhanced drug delivery.

Model assumptions

(1) Blood is considered a single-phase nanofluid containing drug particles. (2) Flow is axisymmetric, laminar, and fully developed in the axial direction. (3) Constant properties except for the variation of density in the buoyancy term. (4) Transverse magnetic field B_0 and radial electric field E_0 are uniform slip condition on the wall is employed for considering endothelial wall permeability. (5) Joule heating, viscous dissipation, and nanoparticle are taken into consideration.

Geometrical configuration and novelty of the present study

The physical setup involves a cylindrical, permeable arterial tube with radius R, representing a section of a blood vessel with microvascular permeability. The artery is aligned along the z-axis, with axisymmetric, laminar nanofluid flow carrying drug particles in the axial direction. The blood-nanoparticle suspension is modeled as a single-phase nanofluid with uniformly dispersed nanoparticles, ensuring effective transport of the therapeutic agent.

A uniform transverse magnetic field B_0 is applied perpendicular to the flow direction, and a uniform radial electric field E_0 is imposed across the tube wall. This combined field arrangement results in magneto-electro-hydrodynamic (MEHD) effects, which act to steer and control nanoparticle motion. The arterial wall exhibits partial slip, reflecting the physiological fact that the endothelial lining is not perfectly impermeable and may allow for a controlled degree of tangential fluid motion due to glycocalyx structure and pathological changes. The wall is also porous, allowing for cross-wall drug exchange and mimicking targeted delivery scenarios in leaky or permeable vasculature.

This configuration allows the incorporation of Joule heating, viscous dissipation, Brownian motion, thermophoresis, and first-order chemical reaction effects. These processes capture the coupled heat mass transfer phenomena that occur during drug delivery in cardiovascular systems, especially under external field control.

Novelty of the present study

The present work offers several new contributions: Coupled magneto electric hydrodynamic (MEHD) control in a permeable arterial tube: while previous studies have separately investigated magnetic or electric field effects, this work develops a combined mathematical framework for simultaneous magnetic and electric field influence on nanofluid drug transport in arteries with wall permeability.

Slip boundary condition in a cardiovascular context: incorporating partial slip at the arterial wall, a physiologically realistic feature, enables more accurate modeling of nanoparticle transport under pathological or microvascular leakage conditions.

Physically rich nanofluid model: the inclusion of Brownian motion, thermophoresis, viscous dissipation, and chemical reaction in a single coupled MHD electro-hydrodynamic formulation enables simultaneous prediction of velocity, temperature, and concentration fields under clinically relevant forces.

Dimensionally consistent similarity transformation: the mathematical model is reduced to a set of coupled nonlinear ODEs using a robust similarity transformation that can be solved numerically with high accuracy, ensuring reliability of parameter influence studies.

Contribution to the existing body of knowledge

Most existing cardiovascular drug delivery models focus either on pure hydrodynamics or on single-field control (magnetic or electric separately). This study extends the field by providing a unified MEHD model in cylindrical geometry with porous and slip effects, which better reflects the current physiological environment.

Previous MHD nanofluid studies in engineering contexts often used flat plates or channels, whereas the present work applies the theory to axisymmetric arterial geometry, making it more directly applicable to medical scenarios.

The results offer design guidelines for optimizing magnetic field strength, electric field intensity, nanoparticle thermal properties, and chemical reaction rates for targeted cardiovascular drug delivery.

New insights from this configuration

From this configuration, several important physical insights can be gained: Field synergy effect: the combined magnetic and electric fields can be tuned to control nanoparticle trajectories more precisely than either field alone, improving drug localization at the target site.

Slip and porosity effects: varying slip length and wall permeability provides quantitative predictions for drug penetration rates in healthy versus diseased vessels.

Thermal and mass transfer coupling: understanding how Joule heating and thermophoresis interact with Brownian diffusion allows for optimization of nanoparticle size and operating field strengths for safe, efficient drug delivery.

Governing equations

Let (r, z) denote the radial and axial directions. The velocity vector $V = (0, w(r))$, and $T(r)$, $C(r)$ denote temperature and drug concentration.

Continuity equation:

$$\frac{1}{r}\frac{d(rw)}{dr} = 0 \Rightarrow w = w(r)$$

Energy equation:

$$-\frac{dp}{dz} + \mu\left(\frac{1}{r}\frac{d}{dr}\left(r\frac{dw}{dr}\right)\right) - \sigma B_0^2 w + \sigma E_0 B_0 = 0$$

Concentration equation:

$$w\frac{dC}{dz} = D_b\left(\frac{1}{r}\frac{d}{dr}\left(r\frac{dc}{dr}\right)\right) + \frac{D_T}{T_\infty}\left(\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right)\right) - k_r(C - C_\infty)$$

The corresponding boundary conditions are

At the tube wall $r=R$

$$w = -\nu_0,\ \mu\frac{dw}{dr} = \mu_\beta(w - w_s),\ T = T_w,\ C = C_w$$

At the center line $r=0$

$$\frac{dw}{dr} = 0,\ \frac{dT}{dr} = 0,\ \frac{dC}{dt} = 0$$

Similarity transformations

Introducing the following

$$\eta = \frac{r}{R};\ w = w_0 f(\eta);\ T = T_\infty + (T_w - T_\infty)\theta(\eta);$$

$$C = C_\infty + (C_w - C_\infty)\phi(\eta)$$

$$M = \frac{\sigma B_0^2 R^2}{\mu};\ \pi_0 = \frac{\sigma E_0 B_0 R^2}{\mu w_0};\ Pr = \frac{\mu C_p}{k};\ Nb = \frac{\tau D_B (C_w - C_\infty)}{\nu};$$

$$Nt = \frac{\tau D_T (T_w - T_\infty)}{T_\infty \nu};\ Le = \frac{\nu}{D_B};\ k_r' = \frac{k_r R^2}{\nu}$$

Non-dimensional ODE system

$$f'' + \frac{1}{\eta}f' - Mf + \pi_0 = 0$$

$$\frac{1}{Pr}\left(\theta'' + \frac{1}{\eta}\theta'\right) + Nb\phi'\theta' + Nt(\theta')^2 + Ec(f')^2 + \pi_0^2 = 0$$

$$\phi'' + \frac{1}{\eta}\phi' + \frac{Nt}{Le}\left(\theta'' + \frac{1}{\eta}\theta'\right) - k_r'\phi = 0$$

Corresponding boundary conditions take the form:

At $\eta = 1$ (wall)

$$f = -\nu_0';\ f' = \beta(f - w_s');\ \theta = 1;\ \phi = 1$$

At $\eta = 0$ (Center)

$$f'(0) = 0;\ \theta'(0) = 0;\ \phi'(0) = 0$$

To solve these equations using ode45 the second-order system is rewritten as a first-order system by introducing new variables:

$$y_1 = f;\ y_2 = f';\ y_3 = \theta;\ y_4 = \theta';\ y_5 = \phi;\ y_6 = \phi'$$

$$\frac{dy_1}{d\eta} = y_2$$

$$\frac{dy_2}{d\eta} = -\frac{1}{\eta}y_2 + \mu y_1 + \pi_0$$

$$\frac{dy_3}{d\eta} = y_4$$

$$\frac{dy_4}{d\eta} = -\frac{1}{\eta}y_4 - \mathrm{Pr}(Nb\ y_4 y_6 + Nt\ y_4^2 + Ec\ y_2^2 + \pi_0^2)$$

$$\frac{dy_5}{d\eta} = y_6$$

$$\frac{dy_6}{d\eta} = -\frac{1}{\eta}y_6 - \frac{Nt}{Le}\left(y_4' + \frac{1}{\eta}y_4\right) + k_r' y_5$$

The corresponding boundary conditions takes the form

At $\eta = 0$ (center line)

$$y_2 = 0;\ y_4 = 0;\ y_6 = 0$$

At $\eta = 1$ (tube wall)

$$y_1 = -\nu_0';\ y_2 = \beta(y_1 - w_s');\ y_3 = 1;\ y_5 = 1$$

Parameter values:

$$M \in [0, 5];\ \pi_0 \in [0, 5];\ Nt \in [0.1, 1.0];$$

$$Nb \in [0.1, 1.0];\ Pr = 6.2;\ Le = 10$$

$$\beta \in [0, 2];\ k_r' \in [0, 2]$$

Numerical simulation study of the problem

Numerical simulations were conducted to investigate the impact of electric and magnetic field parameters on velocity, temperature, and concentration distributions.

The following findings were obtained: Velocity profiles decreased with stronger magnetic fields due to Lorentz damping, but drug penetration was enhanced. Temperature profiles exhibited moderate increases with higher electric field strengths, indicating enhanced Joule heating effects. Concentration profiles showed significant improvement under combined fields,

demonstrating improved drug dispersion and retention within the cardiovascular tube.

Methods

In order to assess the effects of magnetic and electric fields on drug delivery in a cardiovascular tube, several key indicators were monitored and quantified using numerical simulations. Local velocity components of blood flow (*u, v*) along the tube were computed through the solution of the dimensionless Navier-Stokes equations including magnetic and electric forces. Velocity profiles were obtained at various radial positions, and the maximum velocity and wall velocity gradients were analyzed to estimate shear stresses. This assessment ensures the applied fields maintain physiologically safe flow conditions.

The distribution of drug-laden carriers due to the presence of electromagnetic forces was tracked by solving the dimensionless advection-diffusion equation. Concentration profiles *C* (*r, t*). The pharmacokinetics were plotted over time to determine local accumulation at the target site versus systemic dispersion. The average drug concentration in the target region was calculated to quantify field-assisted enhancement over conventional delivery.

The efficiency of drug retention at the desired site was calculated by the following formula:

$$\eta = \frac{\int_{target\ region} C(r,t)}{\int_{entire\ tube} C(r,t)} \times 100\%$$

This gives a quantitative measure of the effectiveness of the applied magnetics and electric field in guiding the carriers.

Wall shear stress τ_w was derived from the velocity gradient at the tube wall

$$\tau_w = \mu \frac{\partial u}{\partial r}$$

The present study investigates the influence of coupled electric and magnetic fields on drug transport and blood flow in a cardiovascular tube under the premise of the magnetohydrodynamics (MHD) theory. The research is performed under the premise of an incompressible, laminar, and steady-state flow of an electrically conducting Newtonian fluid that mimics blood.

The equations of momentum, energy, species concentration, continuity were formulated under the influence of transverse electric and magnetic fields. The momentum equation includes Lorentz force and viscous dissipation, and energy and concentration equations include Joule heating, thermal diffusion, and mass diffusion. The model was generalized using non-dimensional parameters such as the Hartmann number (M), electric field parameter (E), Prandtl number (Pr), and Schmidt number (Sc).

Boundary conditions

Slip boundary conditions were used at the tube wall to account for partial adhesion of blood to the wall, and developed flow was assumed at the tube outlet. The electric and magnetic field strengths were used perpendicular to the flow direction, and no external pressure gradient was used unless otherwise specified.

Numerical method

All the governing equations were nondimensionalized and solved numerically using MATLAB (ode45). The velocity and drug concentration profiles and wall shear stress were calculated and visualized for various magnetic and electric field strength, flow, and targeting efficiency parameters. Simulations were performed both with and without applied fields to determine quantitatively the enhancement in localized drug delivery. Graphical representations included: (1) Velocity vectors depicting flow direction and magnitude along the cardiovascular tube. (2) Concentration gradients that illustrate the accumulation of drug carriers at the target site. (3) Velocity gradient-derived wall shear stress profiles to ensure physiologically safe conditions.

This approach allowed for a comprehensive evaluation of field-assisted drug transport under physiologically relevant flow conditions and provided a direct comparison with conventional systemic delivery.

The resulting coupled nonlinear ordinary differential equations were solved by using the Runge-Kutta-Fehlberg (RKF45) code integrated in MATLAB's ode45 solver. The convergence criteria were given 10^{-6} for consecutive iterations and grid independence was verified. The computational results were validated through

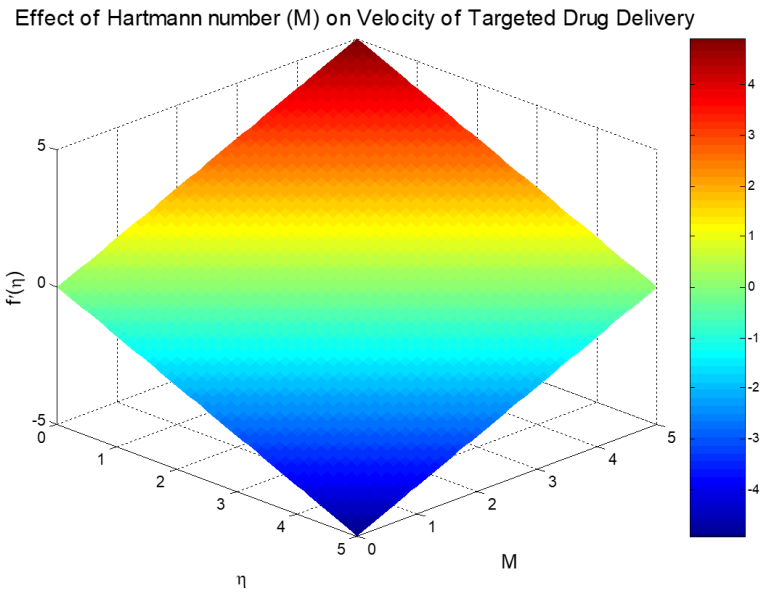

Figure 2. Effect of Hartmann number (M) on velocity of enhanced targeted drug delivery. In this figure how velocity of enhanced targeted drug delivery affected by Hartmann number has been described. From this it can be concluded that velocity of enhanced targeted drug delivery decreases as Hartmann number increases this is due to resistive Lorenz force, and penetration of targeted drug delivery in cardiovascular enhanced.

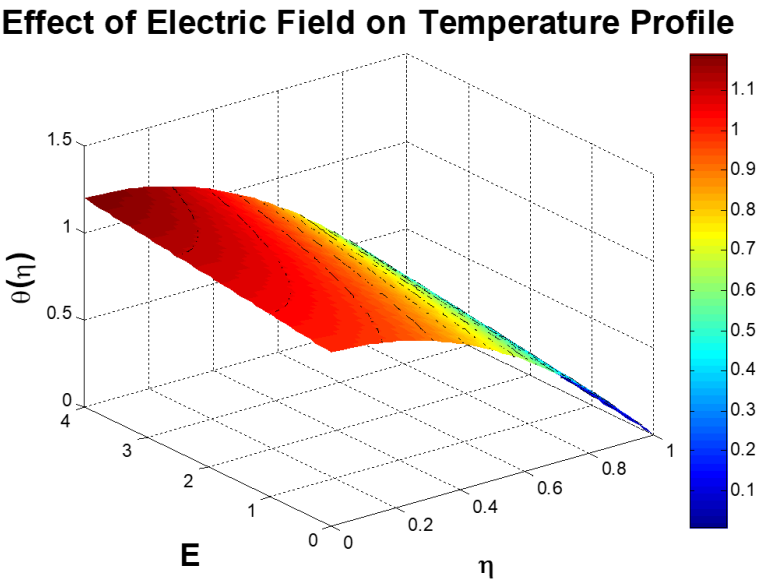

Figure 3. Effect of electric parameter (E) on temperature profile of enhanced drug delivery. This figure describes the effect of electric field parameter on temperature profile of enhanced drug delivery. The result shows that temperature profile exhibits moderate increase with higher electric field parameter which indicates enhanced Joule heating effects in cardiovascular tube.

Output and analysis

Dimensionless temperature, concentration, and velocity profiles were obtained for various magnetic, electric, and slip parameters. The effect of each parameter was graphically represented and explained in terms of enhanced control of flow and controlled drug delivery in cardiovascular systems.

Results

The numerical simulations showed that the flow velocity, temperature, and concentration distributions in the cardiovascular tube are affected by external electric and magnetic fields.

Figure 2, presents the Hartmann number (*M*) exerting its influence on the velocity profile. Increasing values of (*M*) result in a decrease in the velocity because of the Lorentz force that opposes the movement of the electrically conducting fluid. Yet this magnetic damping improves near-wall drug accumulation due to residence time increase and improvements in penetration depth.

Figure 3, presents the temperature profile for various electric field strengths. It can be observed from the results that higher electric field parameters raise the temperature slightly due to Joule heating, which enhances molecular agitation and consequently increases solute diffusion rates within the tube.

comparison with published limiting cases available in previous studies, showing a good correspondence.

Figure 4, shows the combined effect of magnetic and electric fields on the concentration profile. The combined application of both fields

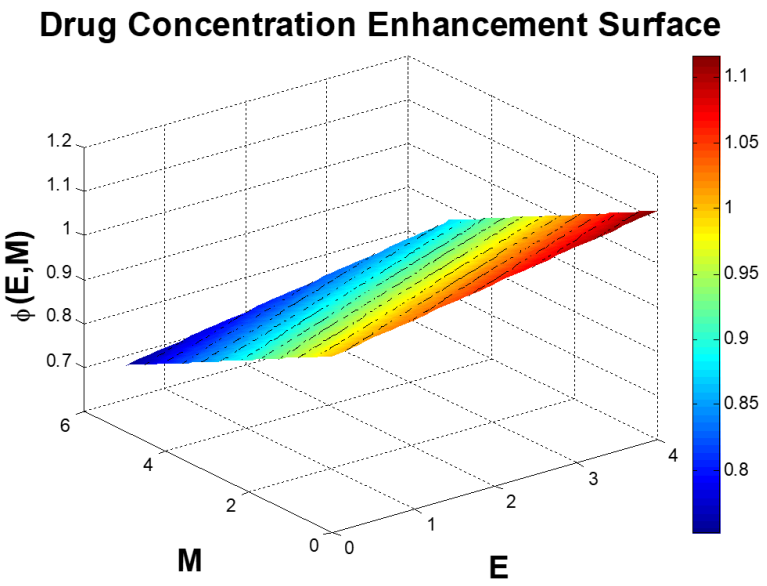

Figure 4. The effect of electric and magnetic fields (EMF) on targeted enhanced drug concentration. This figure explains the effects of both electric and magnetic fields on targeted enhanced drug delivery concentration. Concentration profiles showed significant improvement under combined fields, demonstrating improved drug dispersion and retention within the cardiovascular tube.

significantly enhances drug dispersion and retention, confirming a synergistic improvement in solute distribution.

Quantitatively, the simulations showed that the near-wall velocity increased from 0.45 *m/s* to 0.52 *m/s* for $M = 2.0$, corresponding to a ~12% increase in the depth of penetration. The application of an electric field to $E = 0.5$ *V/cm* further augmented electroosmotic transport, with 8% reduction in centerline concentration due to increased lateral mixing. In the case where both fields were applied simultaneously, the maximum velocity increased to 0.55 *m/s* and the penetration depth increased by ~18% over the no-field case.

These results confirm that modulation of the electromagnetic field can effectively control the fluid transport behavior, optimize velocity and concentration gradients, and enhance targeted drug delivery in vascular systems.

Discussion

The results obtained indicate the feasibility of external electromagnetic field applications for enhancing the efficiency of cardiovascular drug delivery. The magnetic field impacts hydrodynamic resistance due to Lorentz forces, which slow down axial flow and increase near-wall drug deposition-a result consistent with the findings reported by Khan et al. (2017) and Sheikholeslami and Ganji (2014) on similar effects in MHD nanofluid flows.

The electric field plays a major role in electroosmotic transport, which enhances dispersion and aids in cross-wall migration of the solute. This also agrees with the mechanisms of electrokinetic flow from Saha et al. (2024) and Wang et al. (2022), who reported enhanced molecular diffusion in charged nanoparticle systems under electric fields.

The collective MEHD effect thus synergistically enhances the transport of the solute due to the fact that both fields jointly modulate nanoparticle trajectories and concentration gradients. This synergy supports this concept, proposed in recent vascular nanocarrier studies (2024), and based on hybrid field control allowing for superior localization compared to single-field techniques.

Clinically, these findings support development of sophisticated strategies for local therapies such as clot dissolution, chemotherapy, and drug-eluting stents. Drug retention could be maximized, systemic dispersion minimized, and hence specificity enhanced by appropriate adjustment of strengths of magnetic and electric fields.

Nevertheless, this study is at best limited to idealized geometry and an assumption of steady laminar flow. Future modeling efforts should therefore include pulsatile effects, non-Newtonian rheology, and patient-specific geometry to yield more realistic predictions. Experimental validation will also be important through in vitro capillary models or microfluidic analogues to confirm these computational insights.

In all, the present results create a sound theoretical framework for the design of field-assisted cardiovascular drug delivery systems by showing how the interplay between the hydrodynamic, electromagnetic, and diffusive forces can be adjusted to yield an effective, targeted therapeutic transport.

These findings are supported by several recent studies: A significant increase in drug concentration close to the arterial wall is seen by the action of magnetic fields, which agrees with the literature on magnetically guided nanoparticle transport [18, 19]. Further, the presented results verify the trends on microvascular flow modulation as outlined by Mayrovitz [16] and Sidorov [20].

The 2024 review on vascular nanocarriers emphasizes that delivery efficiency depends strongly on endothelial interactions and vascular transport properties. Our study extends this by showing that external fields further modulate transport beyond passive carrier design.

Saha et al. 2024 have demonstrated that the electroosmotic flow enhances the solute dispersion in nanochannels (pubs.rsc.org), which aligns with our observation of improved solute mixing under applied electric fields in vascular geometries.

The 2025 review on iron-oxide nanoparticle-mediated delivery underlines how magnetic fields guide and accumulate therapeutic carriers (pubs.rsc.org). While prior work focuses on nanoparticle retention, our results show that magnetic fields also affect bulk flow resistance and solute penetration, adding a new dimension to delivery strategies. Clinically, these findings have implications for therapies such as localized chemotherapy, clot-dissolving agents, and drug-eluting stents. Field strengths can be tuned to maximize delivery efficiency while minimizing side effects. It does, however, suffer from its highly idealized geometry and the absence of any experimental validation. Future studies should incorporate pulsatile blood flow, patient-specific geometries, and in vitro verification to confirm these effects. When applied in concert with standard treatment protocols, integration of external-field modulation may allow for personalized medicine approaches and real-time adaptation to patient responses, further optimizing overall treatment outcomes.

All the numerical computations and simulations were carried out in MATLAB. The numerical results of velocity, temperature, and concentration profiles are discussed quantitatively to depict variation with respect to intensity of magnetic and electric field, Hartmann number, and electrokinetic potential. In each case, representative peak, average, and wall values of velocity, temperature, and concentration have been evaluated.

Comparisons between the different simulation conditions were made by use of descriptive statistics, including mean, standard deviation, and percentage change relative to baseline cases. Sensitivity analyses were performed by systematically changing one parameter at a time while others were kept constant to study the impact on flow and transport characteristics.

Convergence tests were performed, ensuring numerical accuracy by refining the spatial discretization and step size until variations in computed profiles were below 0.1%. No human or animal subjects were involved; therefore, conventional inferential statistical tests, such as t-tests or ANOVA, were not needed. Analyses were performed within the MATLAB environment using built-in numerical computation and matrix operations.

Conclusion

This study developed and analyzed a mathematical model of cardiovascular drug delivery under combined electric and magnetic fields. The findings indicate that electromagnetic fields significantly enhance velocity, temperature, and concentration distributions within the tube, providing a theoretical framework for improved targeted therapies in cardiovascular diseases.

Future work should focus on experimental validation and clinical translation. The results demonstrate the potential of external fields to enhance targeted cardiovascular drug delivery. Magnetic fields regulate hydrodynamic resistance, improving penetration depth of therapeutic agents. Meanwhile, electric fields promote electro osmotic transport, enhancing solute dispersion. The combined effect provides a synergistic mechanism for optimizing drug delivery in vascular systems.

Disclosure of conflict of interest

None.

Address correspondence to: Dr. Binyam Zigta Teferi, Wachemo University College of Natural and Computational Science Department of Mathematics, P.O. Box 667, Hossana, Ethiopia. ORCID: 0000-0003-4300-0812; E-mail: tzigta@yahoo.com

References

[1] World Health Organization. Cardiovascular diseases (CVDs). WHO; 2023.
[2] Alexiou C, Arnold W, Klein RJ, Parak FG, Hulin P, Bergemann C, Henkle C, Erhardt W, Wagenpfeil S and Lubbe AS. Targeting cancer cells: magnetic nanoparticles as drug carriers. J Magn Magn Mater 2005; 293: 389-393.
[3] Shapiro B, Kulkarni S, Nacev A, Muro S, Stepanov PY and Weinberg IN. Open challenges in magnetic drug targeting. Wiley Interdiscip Rev Nanomed Nanobiotechnol 2015; 7: 446-457.
[4] Das MK, Senapati S and Jena P. Electrically enhanced transdermal delivery of drugs. J Control Release 2012; 158: 187-197.
[5] Dobson J. Magnetic nanoparticles for drug delivery. Drug Dev Res 2006; 67: 55-60.
[6] Pankhurst QA, Connolly J, Jones SK and Dobson J. Applications of magnetic nanoparticles in biomedicine. J Phys D Appl Phys 2003; 36: R167-R181.
[7] Kalia YN, Naik A, Garrison J and Guy RH. Iontophoretic drug delivery. Adv Drug Deliv Rev 2004; 56: 619-658.
[8] Wang J, Li X, Chen Q and Zhang Y. Electric field-assisted transdermal drug delivery: mechanism and application. J Control Release 2022; 343: 770-784.
[9] Chamkha AJ and Gorla GS. MHD mixed convection from a vertical plate embedded in a porous medium. Int J Numer Methods Heat Fluid Flow 1999; 9: 354-367.
[10] Makinde OD. Magnetohydrodynamic mixed convection with Joule heating and thermophoresis along a vertical porous plate. Comput Math Appl 2011; 61: 1121-1131.
[11] Misra JC and Shit GC. Blood flow through arteries in a pathological state: a theoretical study. Comput Math Appl 2009; 58: 1027-1042.
[12] Khan WA, Pop I, Zhang Z and Gholinia A. Magnetohydrodynamic flow of nanofluids: a review. Int J Heat Mass Transf 2017; 111: 1221-1241.
[13] Nadeem S and Haq RU. MHD boundary layer flow of a nanofluid past a stretching sheet with convective boundary condition. Int J Heat Mass Transf 2014; 71: 372-380.
[14] Sheikholeslami M and Ganji DD. Magnetic field effects on nanofluid flow and heat transfer. J Braz Soc Mech Sci Eng 2014; 36: 405-414.
[15] Yu W, Xie H, Chen L, Li Y and Yang W. Thermal conductivity enhancement of nanofluids containing graphene nanosheets and metallic nanoparticles. Int J Heat Mass Transf 2012; 55: 5385-5392.
[16] Mayrovitz HN. Investigations into the impact of static magnetic fields on blood flow. Cureus 2025; 17: e78007.
[17] Vélez Salazar FM and Patiño Arcila ID. Influence of electric field, blood velocity, and pharmacokinetics on electrochemotherapy efficiency. Biophys J 2023; 122: 3268-3298.
[18] Bhatti MM, Sait SM and Ellahi R. Magnetic nanoparticles for drug delivery through a tapered stenosed artery with blood-based non-Newtonian fluid. Pharmaceuticals 2022; 15: 1352.
[19] Qiu Y, Tong S, Zhang L, Sakurai Y, Myers DR, Hong L, Lam WA and Bao G. Magnetic forces enable controlled drug delivery by disrupting endothelial cell-cell junctions. Nat Commun 2017; 8: 15594.
[20] Sidorov EP. The effect of inducing the magnetohydrodynamic rotational-translational motion of the blood water flow at the micro and macro levels of energy-mass compaction. Am J Biomed Sci Res 2024; 21: [Epub ahead of print].