Simulation and Analysis of Magnetohydrodynamic Effects in High-Field Magnetic Resonance Electrical Impedance Tomography (MREIT)

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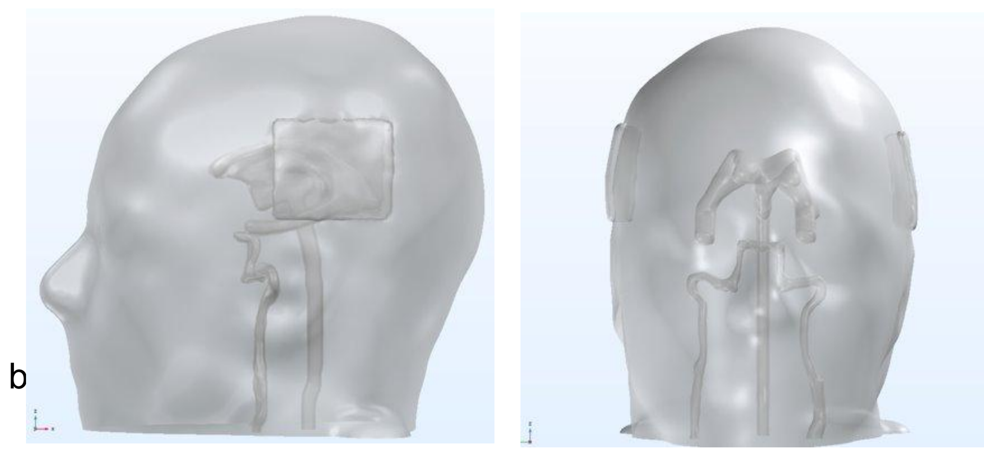
Introduction

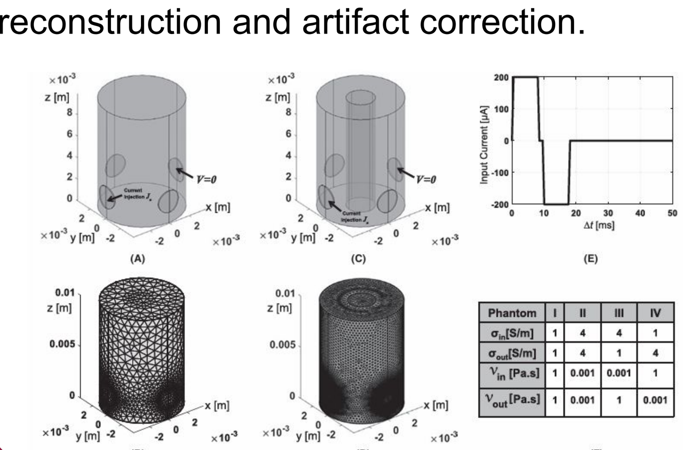
- MRI current injection in conductive fluids (blood, CSF) generates Lorentz-force–driven flow.
- These magnetohydrodynamic (MHD) velocities can alter MRI phase and contribute to image artifacts.
- Understanding the magnitude and timing of induced velocities is essential for predicting artifact severity at high magnetic fields.
- This study uses a COMSOL human head model to quantify MHD-induced blood and CSF velocities across 0–18 T.
- Magnetohydrodynamic (MHD) effects arise when electrical currents interact with strong magnetic fields, producing Lorentz-force–driven fluid motion.
- Minhas et al. demonstrated that unexpected phase artifacts in MREIT experiments were caused b MHD-induced flow rather than instrumentation error .

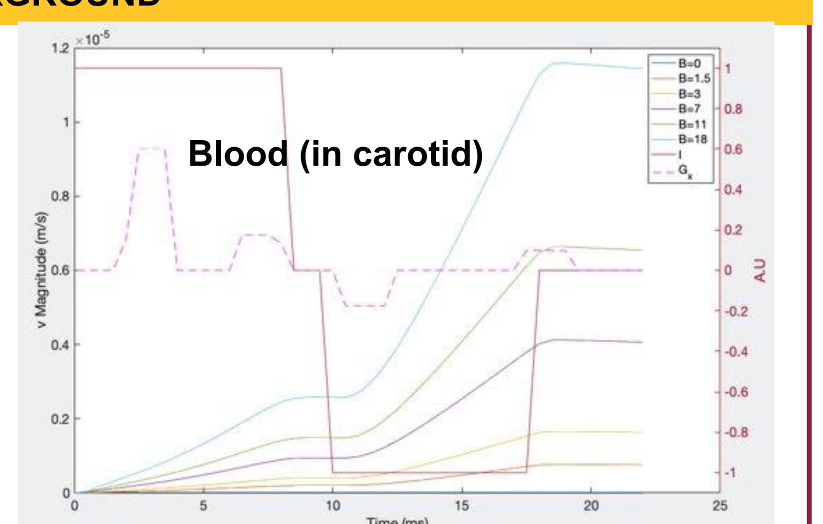


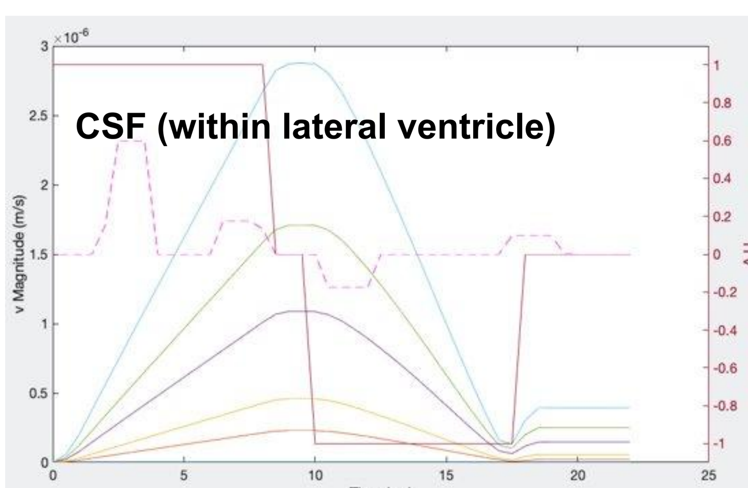
COMSOL Head Model

Background

- MRI sequences coordinate RF pulses with gradients along slice-select, phase-encode, and readout axes.
- Accurate gradient timing is essential for modeling velocity-induced phase.
- The Minhas et al. sequence uses precisely defined Gx and Gy lobes synchronized with current injection.
- Blood and CSF have different flow patterns and conductivities.
- Modeling their MHD response helps understand flow-related artifacts.
- This supports improved conductivity reconstruction and artifact correction.







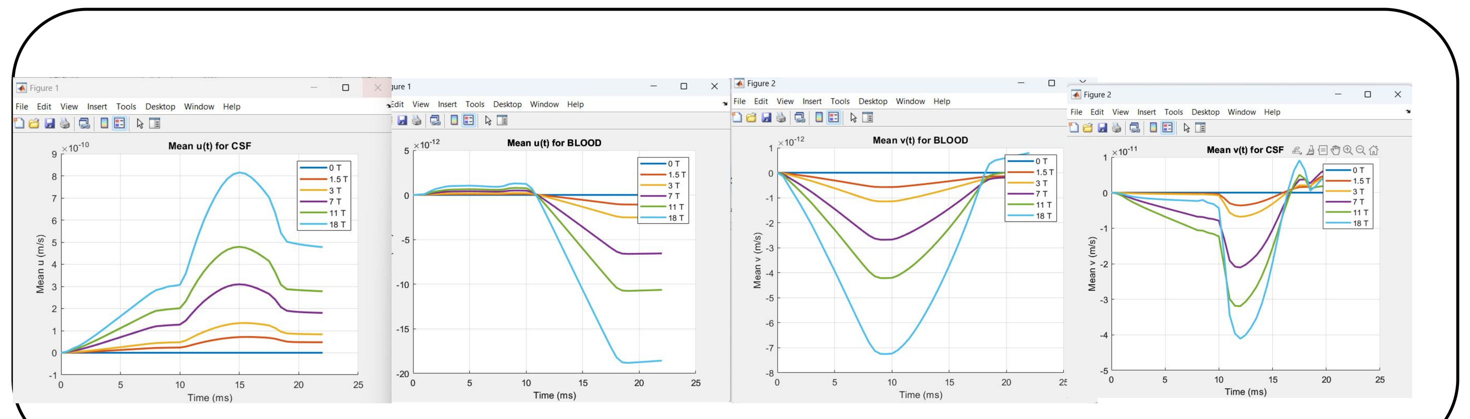
Methods

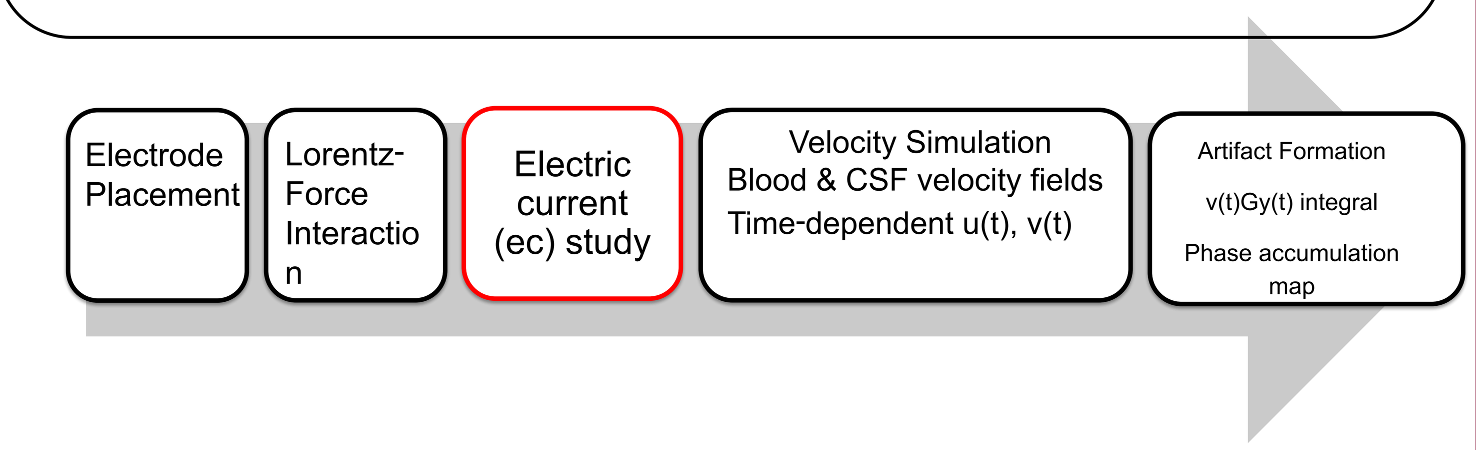
Global parameters were defined and utilized in the simulation.
The parameters *t*0 to *t*4 were employed to create a ramp function, similar to the approach used in Minhas et al. [1].

Name	Expression	Value	Description
t	0 [s]	0 s	Start time
t0	0.000001 [s]	1E-6 s	1st Ramp +ve (Upward)
t1	0.008175 [s]	0.008175 s	+ve current time
t2	0.009809 [s]	0.009809 s	2nd Ramp -ve (down)
t3	0.017695 [s]	0.017695 s	3rd Ramp -ve (down)
t4	0.017697 [s]	0.017697 s	4th Ramp +ve (Upward)
C	+0.987955 [s]	0.98796 s	Correction 1
E	1 [s]	1 s	Correction 2
Ic	0.001 [A]	0.001 A	Input Currenrt
Area	0.003480106 [m^2]	0.0034801 m^2	Area of Input electrode
Jn	Ic/Area	0.28735 A/m^2	Current density
B	1.0[T]	1 T	Magnetic Field

Parameters used in ATULMHD COMSOL model

Methods





T7 and T8 represent electrode placements on the head. Blood and cerebrospinal fluid (CSF) are key regions of interest (ROI) in this study. The material properties for these tissues are defined based on referenced data sources.

Table 1

Tissue	Electrical Conductivity (σ) (S/m)	Relative permittivity (ε_r) (1)	Density (ρ) (Kg/m^3)	Dynamic Viscosity (Pa.s)
T_8	1	1	1	1
T_7	1	1	1	1
Skin	0.43	1	1109	-
Muscles	0.16	1	1090	-
Bone	0.0109	1	1543	-
Fat	0.025	1	911	-
CSF	1.8	1	1007	7.39e-5
Blood	0.67	1	1050	7.72e-4
Sclera_lens	0.5	1	1005	-
Grey Matter	0.1	1	1145	
White Matter	0.38	1	1041	-
References	[3]	[4]	[5]	[6]

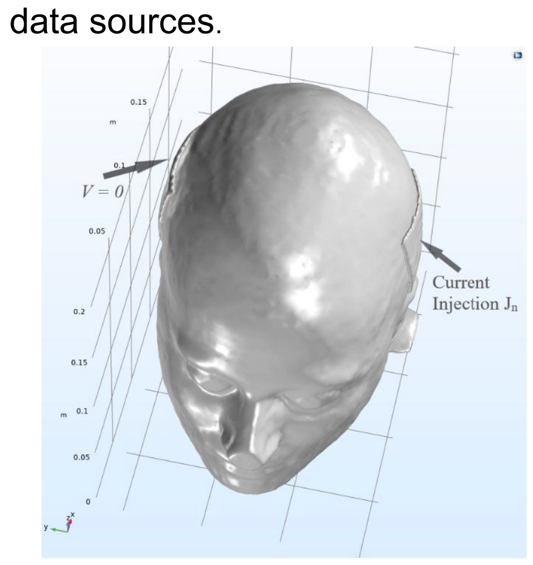
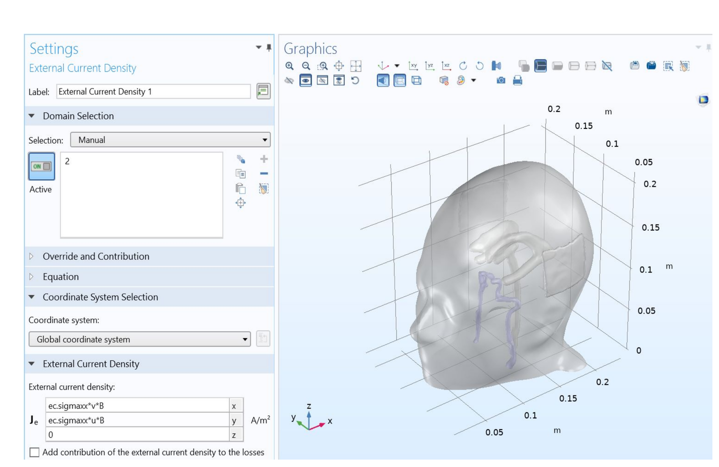


Figure - Electrode with Current Injection and ground marking.

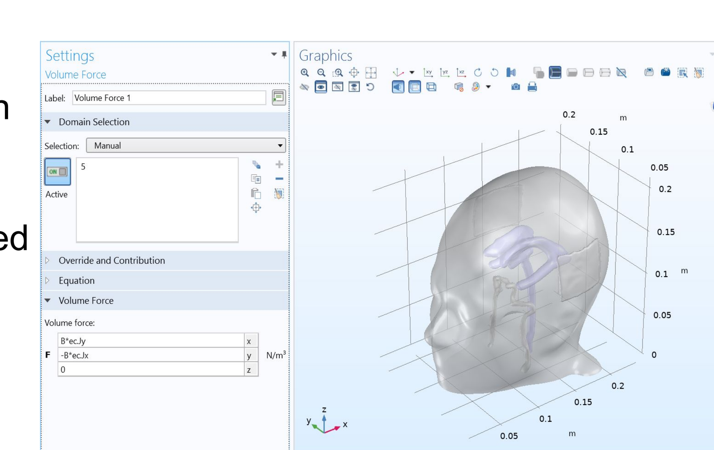
Electric Current (ec) study – ROI – Blood and CSF



External Current Density Applied to Blood & CSF: The simulation shows the distribution of current density within the ROI. The function used defines the smooth transition of current density over time, ensuring accurate modeling of electrical behavior in the ROI.

Laminar Flow (spf) study – ROI – Blood and CSF

- Study Settings
- Parametric Sweep: The study focuses on varying the magnetic field (B) values at 1.5, 3, 7, 11, and 18.8 Tesla.
- The time-dependent analysis is conducted over a range of 0 to 10 milliseconds (saving time at 1 ms)
  - with a relative tolerance of 0.005 (physics-controlled).



Results

Overlay of Gradient Waveforms (Gx, Gy) with Simulated Velocity Components u(t)

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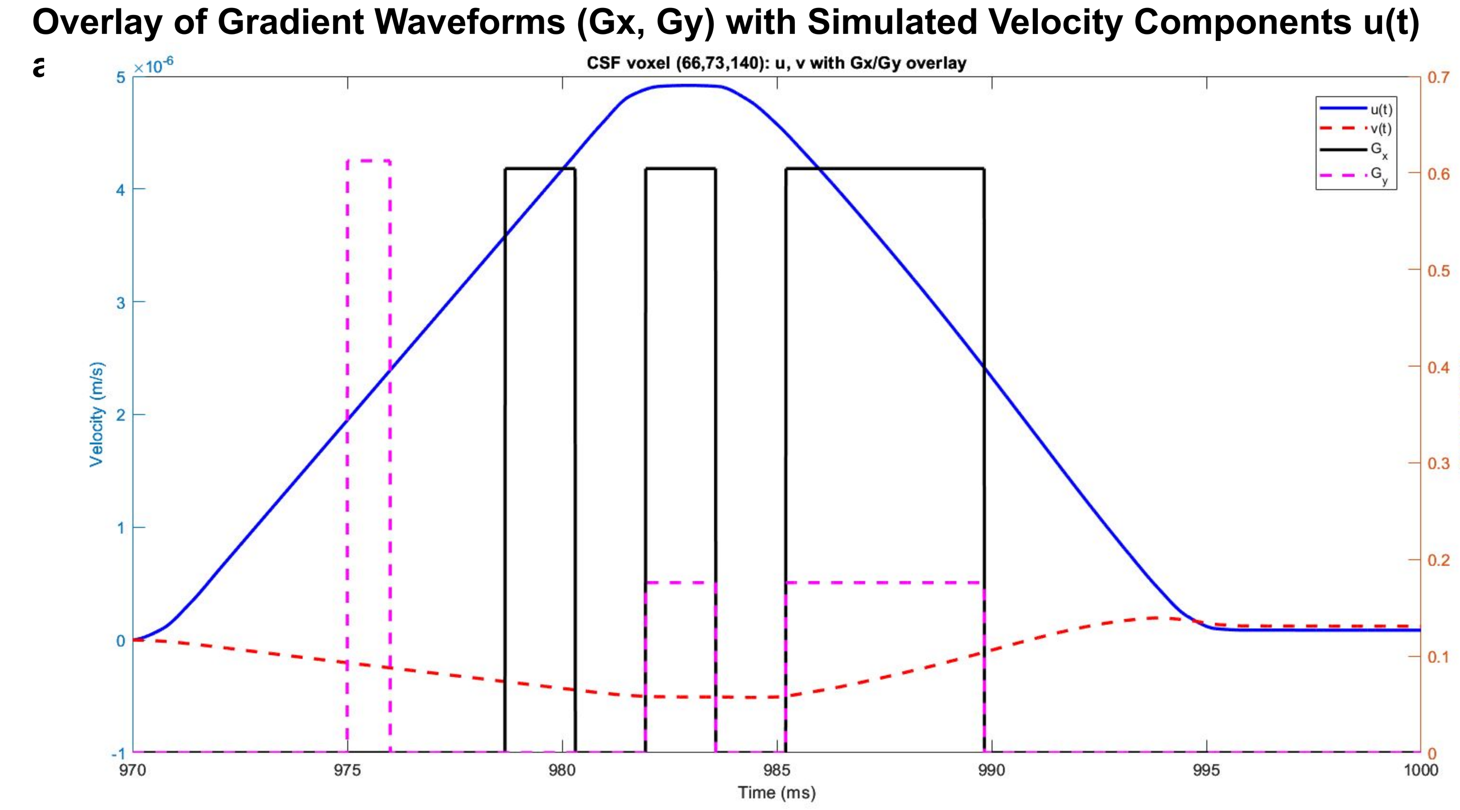
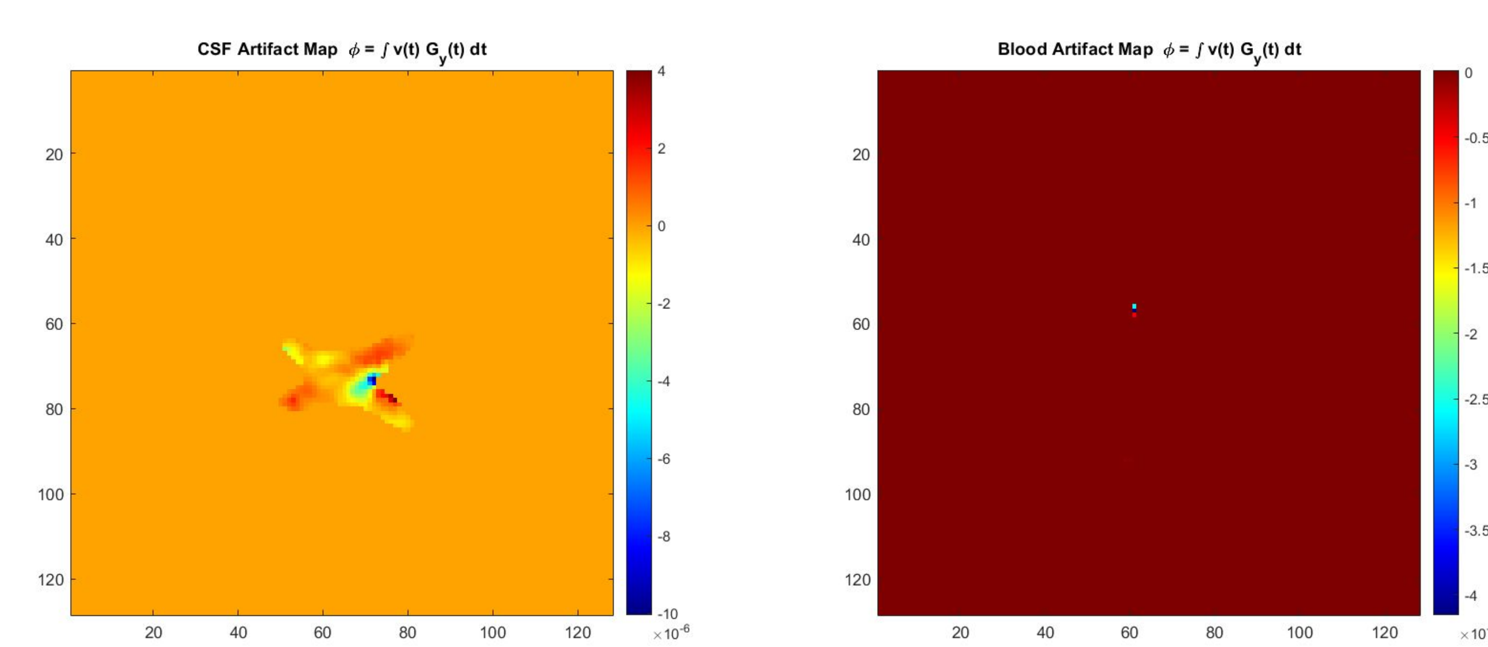


Voxel-Wise Artifact Integral Computed from Simulated Velocity and Gradient Waveforms.



Summary, Conclusions and Future Directions

- MHD-induced velocities increased with field strength and were an order of magnitude higher in CSF than in blood.
- Overlay of velocity components with MRI gradient waveforms confirmed dominant v(t)Gy(t) interaction, consistent with Minhas et al. (2019).
- Artifact integral maps revealed spatially heterogeneous phase accumulation, strongest in conductive CSF regions.
- Results validate that MHD flow contributes directly to high-field MREIT phase distortions.
- The model provides a computational foundation for predicting and mitigating MHD artifacts in future MRI/MREIT studies.

References

[1 Minhas, A. S., et al. "Simulation and Analysis of Magnetohydrodynamic Effects in High-Field Magnetic Resonance Electrical Impedance Tomography (MREIT)." *Magnetic Resonance in Medicine*, vol. 82, no. 6, 2019, pp. 2184–2197.