Published in final edited form as:

Magn Reson Med. 2019 April ; 81(4): 2264–2276. doi:10.1002/mrm.27534.

Evaluation of Magnetohydrodynamic Effects in Magnetic Resonance Electrical Impedance Tomography at Ultra-high Magnetic Fields

DR. Atul S. Minhas¹, DR. Munish Chauhan², Fanrui Fu², and DR. Rosalind Sadleir²

¹School of Engineering, Macquarie University, Sydney, NSW, Australia

²School of Biological and Health Systems Engineering, Ira A. Fulton Schools of Engineering, Arizona State University, Tempe, AZ, USA

Abstract

Purpose: Artifacts observed in experimental Magnetic Resonance Electrical Impedance Tomography images were hypothesized to be due to magnetohydrodynamic effects.

Theory and Methods: Simulations of MREIT acquisition in the presence of magnetohydrodynamic (MHD) and electrical current flow were performed to confirm findings. Laminar flow and (electrostatic) electrical conduction equations were bidirectionally-coupled via Lorentz force equations, and finite element simulations were performed to predict flow velocity as a function of time. Gradient sequences used in spin-echo and gradient echo acquisitions were used to calculate overall effects on MR phase images for different electrical current application or phase encoding directions.

Results: Calculated and experimental phase images agreed relatively well, both qualitatively and quantitatively, with some exceptions. Refocusing pulses in spin echo sequences did not appear to affect experimental phase images.

Conclusion: MHD effects were confirmed as the cause of observed experimental phase changes in MREIT images obtained at high fields. These findings may have implications for quantitative measurement of viscosity using MRI techniques. Methods developed here may be also important in studies of safety and in-vivo artifacts observed in high field MRI systems.

Keywords

MREIT; MHD; B_z ; conductivity image; magnetic flux density; ICNE

1. INTRODUCTION

Magnetic resonance electrical impedance tomography (MREIT) is a technique that can be used to map low-frequency electrical conductivities of body tissues. In MREIT, electric currents are injected into body through surface electrodes, in coordination with pulse

Correspondence to: Rosalind J Sadleir, School of Biological and Health Systems Engineering, Ira A. Fulton Schools of Engineering, Arizona State University, Tempe, AZ, USA, Tel: +1-352-871-0036, rosalind.sadleir@asu.edu.

* A preliminary version of this work was presented at the 25th meeting of the ISMRM, April 22-27, 2017, Hawaii.

sequences (1). Over the last decade, MREIT has advanced from phantom studies, to canine whole body imaging with disease models (2–8), to in-vivo human imaging of lower leg and knee (9), to current flow and conductivity in the human brain (10,11). All these experiments have been aimed at clinical translation and were primarily performed at main magnetic field strengths of 3 T. Functional MREIT has also been demonstrated at ultra-high fields (11.75 and 18.8 T) in neural preparations of *Aplysia Californica* (12,13).

A recent report found clear distortion in measured phase in saline-filled MREIT phantoms imaged at 18.8 T (14). Since all materials in phantoms were initially at rest, it was hypothesized that fluid motion had developed as a result of Lorentz forces during current administration, and a magnetohydrodynamic (MHD) model was developed to explain the mechanism of this artifact. Related MHD-based mechanisms have previously been proposed to explain a mechanism by which neural activity may produce contrasts on MR images (15). However, these models did not include influences of the exact current injection waveform. This is especially important in MREIT, as current injection pulses are bi-polar and time-synchronized with gradient waveforms (7).

In this work, the model described in (14) is extended to more precisely describe MHD effects in MREIT experiments conducted at ultra-high magnetic fields. A time-dependent MHD model was used to predict phase artifacts caused in different pulse sequences when typical MREIT currents were applied to an object under the influence of large external magnetic fields as a function of echo time. These artifacts were confirmed using phantoms of different material viscosities. This work may also have relevance in investigations of artifacts and safety factors encountered in ultra-high field clinical scanners (16).

1.1. Theory

Consider a viscous and electrically conducting fluid Ω enclosed in a cylindrical pipe ψ . If current is injected into Ω via electrodes on the surface of ψ , an electric current with density $\mathbf{J}$ will be produced in Ω . This current will produce an electric field $\mathbf{E}$ given by: $\mathbf{J} = \sigma \mathbf{E}$, where σ is the conductivity distribution within Ω . Now consider an external magnetic field $\mathbf{B}$ is applied to ψ . This will lead to an interaction between $\mathbf{J}$ and $\mathbf{B}$ and produce a Lorentz force $\mathbf{F}$ given by

$$\mathbf{F} = \rho \mathbf{E} + \mathbf{J} \times \mathbf{B} \quad [1]$$

where ρ is the charge density (charge per unit volume). Assuming the electrically conducting fluids to be neutral in local charge, the net force in the system is given by

$$\mathbf{F} = \mathbf{J} \times \mathbf{B} \quad [2]$$

This force will lead to movement of charge carriers (ions in aqueous medium) with a velocity $\mathbf{u}$, and the resulting current density is given by

$$\mathbf{J}_e = \sigma \mathbf{u} \times \mathbf{B} \quad [3]$$

The total current density distribution in Ω under the influence of the external magnetic field $\mathbf{B}$ is thus given by

$$\mathbf{J} = \sigma \mathbf{E} + \sigma \mathbf{u} \times \mathbf{B}. \quad [4]$$

Assuming that Ω is incompressible and only laminar flow exists, the flow of material inside it is determined by the Navier-Stokes equations:

$$\left. \begin{aligned} \rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} &= \nabla \cdot \left[p \mathbf{I} + \nu (\nabla \mathbf{u} + (\nabla \mathbf{u})^T) \right] + \mathbf{F} \\ \rho \nabla \cdot \mathbf{u} &= 0 \end{aligned} \right\} \quad [5]$$

where ρ is the density, p is the pressure, $\mathbf{I}$ is the identity matrix, ν is the dynamic viscosity, and $\mathbf{F}$ is the Lorentz force distribution in Ω . The equations [2], [4], and [5] describe the MHD effect in the cylindrical pipe ψ . These coupled differential equations may be solved simultaneously using a finite element method (FEM) to obtain the fluid velocity distribution $\mathbf{u}$. In the special case of MREIT, the external magnetic field $\mathbf{B}_0 = [B_{0,x} \ B_{0,y} \ B_{0,z}]' = [0 \ 0 \ B_{0,z}]'$ is directed along the z -axis (1). Therefore, [2] and [4] become

$$\mathbf{F} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix} = \begin{bmatrix} J_y B_{0,z} \\ -J_x B_{0,z} \\ 0 \end{bmatrix} \quad [6]$$

and

$$\mathbf{J} = \begin{bmatrix} J_x \\ J_y \\ J_z \end{bmatrix} = \sigma \begin{bmatrix} E_x + u_y B_{0,z} \\ E_y - u_x B_{0,z} \\ E_z \end{bmatrix} \quad [7]$$

respectively, where $F_{x,y,z}$ are the x -, y - and z -components of the force $\mathbf{F}$, $J_{x,y,z}$ are the x -, y - and z -components of current density $\mathbf{J}$, and $E_{x,y,z}$ are the x -, y - and z -components of the electric field $\mathbf{E}$ respectively.

In a typical MRI experiment, the phase of MRI isochromats at a position $\mathbf{r}$ and echo time TE can be defined as follows

$$\phi(\mathbf{r}, TE) = \phi_0 + \gamma \mathbf{r} \int_0^{TE} \mathbf{G}(t) dt \quad [8]$$

where ϕ_0 is a systematic phase artifact, $\mathbf{G}(t)$ is the gradient vector, and γ is the proton gyromagnetic ratio. If MRI isochromats start moving with a velocity $\mathbf{u}$, their position at any time t is given by $\mathbf{r} = \mathbf{r}_0 + \mathbf{u}(t)t$, where $\mathbf{r}_0$ is the actual position of the imaged pixel, and $\mathbf{r}$ is its modified position due to the velocity $\mathbf{u}$. The corresponding MRI phase will then be modified as follows (17)

$$\phi(\mathbf{r}, TE) = \phi_0 + \gamma \mathbf{r}_0 \int_0^{TE} \mathbf{G}(t) dt + \gamma \int_0^{TE} \mathbf{u}(t) \mathbf{G}(t) t dt. \quad [9]$$

In a typical MREIT experiment, injection of current for a duration of T_c creates a magnetic flux density (B_z), which adds an extra phase term to the overall MRI phase. This modified phase in MREIT is given by

$$\phi(\mathbf{r}, TE) = \phi_0 + \gamma \mathbf{r} \int_0^{TE} \mathbf{G}(t) dt + \gamma \int_0^{T_c} B_z dt \quad [10]$$

and it can be calculated using the method developed by Minhas *et al.* in (18).

If there is motion of isochromats in MREIT (i.e. if an MREIT-current-caused MHD effect is present), the phase of [10] should be modified as follows to include the velocity dependent term of [9]

$$\phi(\mathbf{r}, TE) = \phi_0 + \gamma \mathbf{r}_0 \int_0^{TE} \mathbf{G}(t) dt + \gamma \int_0^{TE} \mathbf{u}(t) \mathbf{G}(t) t dt + \gamma \int_0^{T_c} B_z dt. \quad [11]$$

It is assumed in subsequent analyses that any isochromat motion is caused by MREIT currents alone.

2. METHODS

2.1. Modelling the MHD Effect in MREIT

Four different geometries were developed to simulate MHD effects in MREIT using commercial software (COMSOL Multiphysics® v. 5.3. COMSOL AB, Stockholm, Sweden). Model specifications differed in their internal conductivity and viscosity distributions, and were chosen to mimic conditions in phantom experiments described in 2.4 below. Each geometry comprised a 10-mm-high cylinder of 7.2 mm diameter. Cylindrically shaped recesses of 0.1 mm depth and 2 mm diameter were created around the surface of this cylinder, to model four recessed carbon electrodes. Geometries for models I and II are shown in Fig. 1 (a). For models III and IV, an extra inner cylinder with a 2.4 mm diameter was added, as shown in Fig. 1 (c). There were five distinct geometric domains in models I

and II. Four domains corresponded to the four electrode regions, and the fifth domain was the internal cylinder. Models III and IV had one additional domain corresponding to the inner cylinders. The material properties used in these domains are shown in Fig. 1 (f), where the subscript *in* corresponds to the inner cylinder, and the subscript *out* corresponds to the outer cylinder and electrode recesses. Densities of all domains were fixed at 1000 kg/m³.

A time-dependent multi-physics model was developed in COMSOL to solve equations [5]-[7] over the four model geometries. The force term in equation [6] was set to be a *Volume force* in all domains in the *Laminar Flow* COMSOL module. The wall boundary condition for laminar fluid flow was specified as “no-slip” ($\mathbf{u}=0$) on all surface boundaries. Pressure $p=0$ was chosen at a node lying on the circular boundary of the upper surface of cylinder located at $z=10\text{mm}$. Equation [7] was specified as an *External current density* in the *Electric Currents* COMSOL module, in all domains. Electrical boundary conditions were specified as a normal current density J_n and ground ($V=0$), respectively, applied to opposing electrodes, as shown in Fig. 1 (a) and (c). The current density J_n was time dependent, as shown in Fig. 1 (e), with a peak current density of 63.66 A/m² (integrated current = 200 μA). The ramp-up and ramp-down times of the trapezoidal current pulse were both 1 μs , and the duration of positive and negative polarity currents were 8.175 ms (A) and 7.886 ms (B), respectively. The interval between each current pulse was 1.632 ms (C).

All geometries were decomposed into tetrahedral elements. Meshes for geometries (I,II) and (III,IV) are shown in Fig. 1 (b) and (d) and had 35,449 and 706,636 elements, respectively. For each geometry, simulations were run at main magnetic field strengths, $B = [1.5, 3, 4.7, 7, 9.4, 11, 17, 18.8] \text{ T}$ with a total simulation time of 100 ms. A backward differentiation formula (BDF) time-stepping algorithm was used to solve the model, with ‘free’ choice of time steps. Since boundary conditions were defined by the current waveform, it was observed that the shortest time steps were chosen near current amplitude changes. At each time step, the coupled problem was solved using a conjugate gradient algorithm with an algebraic multigrid preconditioner. Solutions were obtained in terms of three-dimensional velocity $\mathbf{u}$ and potential V distributions. A typical model II time-dependent simulation running on Intel(R) Xeon(R) CPU (at 2.20 GHz), using 10 cores on 1 socket, took approximately 30 minutes for a magnetic field of $B = 1.5 \text{ T}$. Solution time did not depend straightforwardly on main magnetic field strength. In fact, overall solution times tended to be lower at higher field strengths. Solution times for Cases I and II ranged between 25 minutes and 1 hour, while the larger meshes of Cases III and IV required 5.45 h to 10.5 h. Velocity components u_x , u_y , and u_z were then interpolated over five axial slices located at $z = [1.5, 1.8, 2.0, 2.3, 2.5] \text{ mm}$ using the COMSOL LiveLink MATLAB interface and MATLAB 2017a (Mathworks Inc., Natick MA, USA). A square 12-mm field of view (FOV) was used for each slice (x and y co-ordinates each varied from -6 mm to 6 mm). The matrix size of each axial slice was 640×640 . Velocity values on this fine grid were then averaged along each coordinate direction to produce velocities over a coarser grid with matrix size of 128×128 . The final in-plane resolution was $93.75 \mu\text{m}$ and through-plane resolution was 2 mm .

2.2. Simulation Timing

Simulated and experimental imaging was performed assuming a TR of 1000 ms and TE of 20 ms. Slice selection and phase encoding gradient waveforms are shown in Fig. 2 (a) and (b). Times in Fig. 2 were therefore shown offset by approximately 970 ms of each TR. Model results are shown as a function of time after the start of current injection at 972.134 ms (Fig. 2 (e)). This time point was designated t^* . Times after t^* were designated t , with t modelled up to 60 ms. All simulations commenced at t^* .

2.3. Effect of Flow on Spin Phase

The contribution of u_x , u_y , and u_z to total measured phase ϕ was then computed using [8]. Each component of the integral $\gamma \int_0^{TE} \mathbf{u}(t) \mathbf{G}(t) dt$ was calculated from individual components of the quantity $\mathbf{u}(t) \mathbf{G}(t)$. If the read gradient is along the y -direction, and it is the only gradient active during data sampling, then only u_y should contribute to the phase ϕ ((19), Ch 23.1.1). Readout direction was assumed fixed along the y -direction. Therefore, all phase contributions were calculated as $\gamma \int_0^{TE} u_y(t) G_y(t) dt$ using the readout gradient shapes shown in Fig. 2 (c) for spin echo pulse sequences, and Fig. 2 (d) for gradient echo pulse sequences (where the 180° RF is not played and the echo is formed by a gradient reversal). The readout gradient time in each case was assumed to be 2.605 ms (denoted as D and E, respectively on Fig. 2). The efficacy of spin phase reversal due to the 180° RF pulse in spin echo pulse sequences was also examined by calculating u_y -modulated phase images without and with spin-phase reversal after the 180° RF pulse. In the first case, phase calculations were performed by directly adding phases before the 180° RF pulse to phases after the 180° RF pulse. In the second case, phases before the 180° RF pulse were inverted before adding them to phases accumulated after the 180° RF pulse.

2.4. MREIT Phantom Experiments

Four experimental cylindrical phantoms (7.2 mm diameter, 10 mm height), labeled as I-IV, are shown in Fig. 3 (a). Phantom I was filled with gelatin (3 g/L NaCl and 20 g/L Agarose), and phantom II was filled with ASW (Artificial Sea Water). Phantom III and IV had another cylindrical structure in the center made of either ASW (in III) or gelatin (in IV). Four surface electrodes (HUREV Co. Ltd, South Korea) of size 2 mm diameter were attached to the outer surface of each phantom. The conductivities of the gel and ASW, measured by a four-probe method using an impedance analyzer (HP4192A LF, Hewlett Packard (Agilent), Palo Alto, USA), were 1 and 4 S/m at 100 Hz.

MR images were acquired using a 45-mm-bore, 800 MHz Varian vertical bore magnet, located at the Magnetic Resonance Research Center at Arizona State University. A custom-made gradient and RF coil (12 mm bore, Doty Scientific, USA) was used for all MRI experiments. The phantom placement and experiment setup is shown in Fig. 3 (b). For each electrode pair, data sets were collected once with a positive current amplitude (I^+) and again with an identical negative current (I^-). A spin echo pulse sequence was used for data acquisition with imaging parameters: TR/TE = 1000/20 ms, FOV = 12 mm², slice thickness = 1 mm (no gap), averages = 4, matrix size = 128×128, number of slices = 1 and scan duration = 512 s. Current was injected using a constant current source (IZ2H-16, Tucker

Davis Technologies, Alachua, USA) at $\pm 200\mu\text{A}$ amplitude ($I^\pm$) and 18ms injection time (T_C). The slice-selection, phase encoding, spin-echo encoding and current injection waveforms were identical to those used for models, as shown in Fig. 2 (a-c, e). Readout time was 2.605 ms (denoted D on Fig. 2) Magnetic flux density (B_z) was calculated by combining phase shift induced by positive and negative current. Subtraction of phase due to I^+ and I^- cancelled the effect of systematic phase artifact and doubled phase amplitudes (1,8). Final phase images were scaled by a factor of 0.5 for comparison with model results, since models did not include systematic phase artifacts or involve subtraction steps used for experimental data.

3. RESULTS

3.1. Modelling MHD Effect in MREIT – one dimensional velocities

Fig. 4 and Supporting Information Figures S1 and S2 compare velocity distributions over the period $t = 0$ to 60 ms for magnetic fields $B = [1.5, 3, 7, 11, 18.8]$ T. Velocities at the location $(-1.9, 0, 2)$ mm, close to the current injection electrode, are shown for case I in parts (a)-(d) of Fig. 4, with components u_x , u_y and u_z shown in (a)-(c) respectively, and velocity magnitude in (d). Corresponding plots for the location $(-0.5, 0, 2)$ mm, close to the center of the cylinder, are shown in (e)-(h). Matching results for case II are shown in parts (i)-(p). Velocities obtained for cases III and IV, are shown in Supporting Information Fig. S1. Supporting Information Fig. S2 summarizes velocities obtained from models I-IV at a main magnetic field $B = 18.8$ T.

It can be observed from Fig. 4 and Supporting Information Figures S1 and S2 that the velocity magnitude had a negligible contribution from u_x and u_z components. Current injection was along the x -direction (Fig. 1 (a) and (c)), which corresponds to the left-right direction (horizontal direction) in the cross-sectional geometries of Fig 4. (d), (h), (l) and (p), where a dot is shown to mark the location at which velocity is plotted. Therefore, velocity was much higher along the direction orthogonal to the current injection direction, indicating that the second term of [4] dominated at this high field strength. Fig. 4 also indicates that velocities were much lower in (a)-(h) when the material was modelled as a gel with $\sigma = 1$ S/m and $\nu = 1$ Pa·s, compared to velocities in (i)-(p), when the material was modelled as ASW with $\sigma = 4$ S/m and $\nu = 0.001$ Pa·s. The velocity components shown in Fig 4. (a)-(h) for the high viscosity case had a bi-polar trapezoidal shape, with a polarity change around $t = 10$ ms, similar to the current injection waveform. The velocity returned to zero when the current amplitude returned to zero. It is also apparent in Fig. 4 (i)-(p) that the velocity in the low viscosity model increased until the current polarity reversed, after which it decreased and eventually returned to zero when the current ceased. In both cases, velocity amplitudes increased with main magnetic field strength, as expected.

In the inhomogeneous geometry cases shown in Supporting Information Fig. S1 (a)-(d), where a viscous gel domain formed the outer annulus of the model, velocities were very similar to those in Fig. 4 (a)-(d) where the model was entirely composed of viscous material. The plots of Supporting Information Fig. S1 (e)-(h) correspond to velocities simulated in the center of the phantom, where the material was liquid saline. They may be further compared with plots in Fig. 4 (m)-(p). The triangular velocity pattern visible in Fig. 4 (n) is slightly

distorted in Supporting Information Fig. S1 (f), and decays to zero much more quickly after peaking. It is clear that velocity patterns in the outer regions of the models III and IV shown in Fig. 4 (b) and (j), which are much closer to the current injection electrode, have velocity patterns similar to the regions in Supporting Information Fig. S1 (b) and (j). However, velocities close to the center of these model geometries did not follow this pattern.

3.2. Modelling MHD Effects in MREIT – two dimensional velocities

Supporting Information Figs. S3–S6 show two-dimensional images of velocity and corresponding velocity-induced phase images for models of cases I–IV, respectively. The images shown in parts (a)–(c) of these figures correspond to velocity components u_x , u_y and u_z , respectively and are displayed in a matrix of 2 rows and 16 columns. The time points corresponding to each calculated image are displayed in a table of 2 rows and 16 columns at the tops of Supporting Information Figs S3–S6. In models, current was not injected until the start of the falling edge of the slice selection gradient (Fig. 2). This time point is 972.134 ms ($t=0$), which corresponds to the seventh image in the first row of Supporting Information Figs S3–S6. It is apparent in Supporting Information Figs. S3–S6 (a)–(c) that until this time point, all velocity components were zero. From $t=1\ \mu\text{s}$ (972.135 ms) to $t=8.176\ \text{ms}$ (980.310 ms), positive polarity current was injected. The evolution in velocity components depends upon the combination of internal (viscous) and external (Lorentz) forces on the fluid. After positive current injection commenced, therefore, the velocity started to increase but the magnitudes of the velocity components were small in the first few milliseconds of this injection (shown in the eighth to twelfth timepoints of Supporting Information Figs S3–S6). The effect of the balance of internal and external forces on velocities was most evident in comparisons of the time evolution of velocity in models of cases I and II. For case I, administration of current resulted in forces that caused an increase in velocity to a constant value. Acceleration then ceased after positive current flow was established, even though Lorentz forces were still being applied. For models of case II the smaller internal forces resulted in a steady increase in velocity during positive current applications, indicating that Lorentz forces were not balanced by viscous forces. This phenomenon correlated with the 1D plots of Fig. 4.

During the interval between positive and negative current injections, velocity in case I models rapidly returned to zero, and acceleration magnitudes in case II models started to decrease.

Between $t=9.810\ \text{ms}$ and $17.696\ \text{ms}$ (981.944 to 989.830 ms), negative polarity current was injected. This again caused a constant velocity flow in models of case I. In the case of models of case II, application of negative polarity currents produced an opposite acceleration, resulting in a decrease in velocity components. For case II, at an intermediate time point $t=17.475\ \text{ms}$ (989.609 ms), during the negative current injection (B), the velocity returned to zero across the phantom except for in a small rim at the phantom boundary.

Velocity scales in Supporting Information Figs. S3–S6 (a)–(c), show that component u_x was less than a quarter of components u_y and u_z , and the largest velocity component was u_y . In addition, velocity patterns in the regions corresponding to ASW in Supporting Information

Fig. S5 (inner region) and Supporting Information Fig. S6 (outer region), were similar to the pattern shown in Supporting Information Fig. S4 (uniform region filled with ASW). Similarly, velocities in the gel-filled regions of Supporting Information Fig. S3 are similar to the gelatin filled regions in Supporting Information Fig. S5 (outer annulus) and Supporting Information Fig. S6 (inner cylinder).

3.3. Effect of Flow on MRI Phase Images

The contribution caused by fluid velocity components to the total phase at readout gradients is shown for each model in Supporting Information Figs. S3–S6 (d)–(i). The phase induced due to horizontal current injection is shown in Supporting Information Figs S3–S6 (d)–(f), and that due vertical current injection is shown in (g)–(i). Each of the images in Supporting Information Figs S3–S6 (d)–(i) is a matrix of 3 rows and 5 columns. Rows show the images at three readout time points $t = 17.697, 20.303$ and 20.304 ms (989.831, 992.438 and 992.439 ms) and columns show images at 5 different magnetic fields (1.5, 3, 7, 11 and 18.8 T). The pairs (d) and (g) in Supporting Information Figs S3–S6 show phases resulting from a spin echo pulse sequence without the effect of an 180° RF pulse, and the pairs (e) and (h) in these figures shows phase images including an 180° RF pulse effect. The pairs in Supporting Information Fig S3–S6 (f) and (i) show phase images due to a gradient echo pulse sequence. In all cases for Supporting Information Figs S3–S6 (d)–(i), phase accumulation increased with main magnetic field, as expected.

Fig. 5 (c)–(e) shows velocity-induced simulated phase images produced in model II (saline only) due to vertical (top row) and horizontal (bottom row) current administrations. The images in Fig. 5 (b) are the phases predicted by the current-induced magnetic flux density (“MREIT phase”) alone in model I (gel only), where velocity effects were negligible. The images in Fig. 5 (c) and (d) show velocity-induced phase images with and without 180° RF pulse effects, respectively. The images in Fig. 5 (e) show phase due to velocity from a gradient-echo (GRE) pulse sequence. There was qualitative similarity between the phases due to GRE and the spin echo sequence including 180° RF. However, these phases were different to the phases from the spin echo sequence without an 180° RF effect in Fig. 5 (d). This difference is evident in both the shape and dynamic range of the phase patterns.

3.4. Comparison of Simulations with MREIT Phantom Experiments

Figs 6 and 7 compare experimental (a) and simulated (b)–(d) phase images for vertical and horizontal current injection, respectively, with read gradient direction maintained constant. Both results correspond to a main magnetic field strength of 18.8 T. Results from phantoms and models I to IV are shown from top to bottom rows. The images shown in Fig. 6 (a) and Fig. 7 (a) are experimental images of current-induced phase from vertical and horizontal current administrations, respectively for 200 μ A amplitude current injection. In all experiments, the readout gradient direction was chosen as the y -direction. For gel phantom or model compositions (case I), characteristic MREIT phase images were observed for both horizontal and vertical current injection conditions (Fig. 6 and 7 (a)). However, for the ASW case (II), the current-induced phase apparently split into two halves for vertical current injection conditions. The phase distribution in the upper half of the image had a pattern similar to case I, but the lower half had a pattern with reversed polarity compared to case I.

For horizontal current injection conditions (Fig. 7), a much larger phase was accumulated, resulting in almost uniform phase distribution for the ASW case (II). In case III, Fig. 7, (inner cylinder ASW, outer annulus gel), when current flowed through ASW in the inner cylinder, the phase was split, with phase in the outer gel reflecting the expected MREIT phase and the inner region agreeing with velocity-induced patterns shown for case II. This phenomenon agreed with patterns for cases I and II, for vertical current injection in Fig. 6 (a). Similar results were observed for case IV images, except that phase patterns were switched between the inner cylinder and outer annulus.

The images in columns of Figs 6 and 7 (b) and (c) show velocity-induced phase images with and without 180° RF pulse effects, respectively. Figs 6 and 7 (d) show velocity-induced phase images formed by a GRE pulse sequence. It can also be seen in Figs. 6 and 7 that patterns in the experimental images shown in part (a) were closest to the velocity-induced patterns in simulated images in part (c) and that the MREIT phase was overwhelmed by velocity effects.

4. DISCUSSION AND CONCLUSION

Overall, these studies demonstrate that current injection under the influence of an external magnetic field (such as in MREIT) will cause motion in materials with similar viscosities to ASW. The extent of this motion will depend on the shape of the input current waveform, the main magnetic field, and the size, shape and viscosity distribution in the medium. These dependencies were evident from the spatial distribution of velocities found in models I-IV. The motion distorted the MREIT phase, and at high magnetic field strengths velocity-induced phase dominated MREIT phase. The spatial distribution of phase distortions further depended on the direction of readout gradients relative to current injection direction. This was apparent from the difference in the phase distributions between horizontal (x) and vertical (y) current injections. In all cases, the readout gradients were applied along the y -direction and the phase-encoding gradients were applied along the x -direction. Therefore, the y -components of velocity were captured by readout gradients.

It was observed that there was some residual velocity in high viscosity compartments shown in Supporting Information Fig. S3 (a)-(c). Ideally, this velocity should be close to zero, as motion would not be expected in highly viscous regions. This created some residual phase in simulations of case I. A clear manifestation of this effect is the split phase pattern in Fig. 6 (b-d) and a constant phase in Fig. 7 (b-d). However, in the experimental results from phantom I (Figs. 6–7 a), MREIT phase dominated the velocity-induced phase. This is evident from the typical MREIT phase observed in Figs. 6–7 (a). This could be because the velocity-induced phases may have been overestimated in simulation results in high viscosity compartments. The gel viscosity was assumed to be $1 \text{ Pa}\cdot\text{s}$ in simulations, but the actual viscosity of the case I phantom may have been higher, because the gel may have dried before experiments. Of the three simulated phases “ 180° RF”, “No 180° RF” and GRE, simulated GRE images had the least phase accumulation. This was because in the GRE readout shown in Fig. 2 (d), the negative polarity gradient was only on for a very short duration compared to the pre-phasing gradients before the 180° RF pulse in the spin echo readout shown in Fig.

2 (c). This difference reduced the phase integrals for GRE and ultimately lowered GRE phase values compared to spin echo cases.

The simulated phase images in low viscosity ASW regions of phantoms II and IV in Figs. 6–7 (b) 180° RF and (d) GRE appear similar. However, they are distinct from experimental results. The phase images from No 180° RF simulations (Figs 6–7 (c)) appeared to be closer to the experimental phases, but they represent an extreme case. It can be concluded from this observation that the effects from No 180° RF and 180° RF simulations represent extrema of experimental phase accumulation, and actual experimental phases lie in between these two images. This may be possible because for a given position within low viscosity (ASW) regions, the spin phases formed before the 180° RF pulse may misregister with the spins after 180° RF because of motion. This may lead to incomplete phase reversal after the 180° RF pulse and result in a decreased phase accumulation at TE.

Finally, a distinct ring was observed at the boundary of phase patterns in Figs. 6–7 in simulated phases from “180° RF” and GRE for both phantoms II and IV. In these cases, the material close to boundary was ASW, which had lower viscosity and therefore higher velocity magnitudes. Velocities were highest near the boundary but should have returned to zero after current administration ceased. It may be observed from Fig. 4 (i) and (m) that this time was much longer than 80 ms. Since the echo time for readout gradients was 20 ms, this residual phase appeared as a ring-pattern in images recovered after the echo time. This phenomenon was also present in the experimental phases in Figs. 6–7 (a) for cases II and IV. Therefore, simulations may be capturing this phenomenon, but improvements in model specifications are necessary for better accuracy. One further aspect that may improve model predictions may be to specify additional physics describing effects of eddy currents created by current or gradient transitions, not included at present.

Successful MREIT studies have been previously reported at 3T using saline phantoms without encountering MHD effects (20). The likely reason for this is that the phantom size was larger and the main field strength smaller than in the experimental studies reported here. An MREIT experiment was recently performed in a preclinical 7T scanner (Bruker Biospin) using a similar-sized phantom to the one used here, containing ASW. Similar artifacts to those measured at 18.8T were observed. This confirms, as expected, that any suitable combination of high current density and high field strengths may produce fluid flow, as predicted by [6]. The possibility of encountering MHD effects in MREIT experiments needs further exploration, and future work should include study of correlations between phantom size and velocities predicted at specific external magnetic fields. Such studies may be useful in determining optimal scanning parameters and pulse sequence designs future in-vivo MREIT experiments, including those using clinical 7T MRI scanners. This work could be extended to minimize possible MHD effects in neurostimulation studies combined with ultra-high field MRI, as there may be a motion produced in fluids such as cerebrospinal fluid or blood. On a positive note, flow induced by current injection may possibly be used as a mechanism to measure body-tissue viscosities. This will require novel post-processing and viscosity reconstruction algorithms within MREIT experimental frameworks.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

ACKNOWLEDGEMENTS

Research reported in this publication was supported by the National Institute of Neurological Disorders and Stroke of the National Institutes of Health under Award Number R01NS077004 to RJS. A part of this project was developed using the facilities provided by the Centre for Pre-clinical Imaging at University of Liverpool, UK.

REFERENCES

1. Woo EJ, Seo JK. Magnetic resonance electrical impedance tomography (MREIT) for high-resolution conductivity imaging. *Physiological Measurement* 2008;29:R1–R26. [PubMed: 18799834]
2. Jeon K, Minhas A, Kim YT, Jeong WC, Kim HJ, Kang BT, Park HM, Lee C- O, Seo JK, Woo EJ. MREIT conductivity imaging of the postmortem canine abdomen using CoReHA. *Physiological Measurement* 2009;30:957–966. [PubMed: 19661564]
3. Kim HJ, Oh TI, Kim YT, Lee BI, Woo EJ, Seo JK, Lee SY, Kwon O, Park C, Kang BT, Park HM. In vivo electrical conductivity imaging of a canine brain using a 3T MREIT system. *Physiological Measurement* 2008;29:1145–1155. [PubMed: 18799838]
4. Kwon O, Woo EJ, Yoon JR, Seo JK. Magnetic resonance electrical impedance tomography (MREIT): Simulation study of J-substitution algorithm. *IEEE Transactions on Biomedical Engineering* 2002;49(2):160–167. [PubMed: 12066883]
5. Minhas A, Jeong WC, Kim YT, Kim HJ, Lee TH, Woo EJ. MREIT of postmortem swine legs using carbon-hydrogel electrodes. *Journal of Biomedical Engineering Research* 2008;29:436–442.
6. Muftuler LT, Hamamura MJ, Birgul O, Nalcioglu O. In vivo MRI electrical impedance tomography (MREIT) of tumors. *Technology in Cancer Research and Treatment* 2006;5:381–387. [PubMed: 16866568]
7. Park C, Lee BI, Kwon O, Woo EJ. Measurement of induced magnetic flux density using injection current nonlinear encoding (ICNE) in MREIT. *Physiological Measurement* 2007;28:117–127. [PubMed: 17237584]
8. Sadleir RJ, Grant S, Zhang SU, Lee BI, Pyo HC, Oh SH, Park C, Woo EJ, Lee SY, Kwon O, Seo JK. Noise analysis in magnetic resonance electrical impedance tomography at 3 and 11T field strengths. *Physiological Measurement* 2005;26:875–884. [PubMed: 16088075]
9. Kim HJ, Kim YT, Minhas A, Jeong WC, Woo EJ. In vivo high-resolution conductivity imaging of the human leg using MREIT: the first human experiment. *IEEE Transactions on Medical Imaging* 2009;28(11):1681–1687. [PubMed: 19369151]
10. Chauhan M, Indahlastari A, Kasinadhuni AK, Schär M, Mareci TH, Sadleir RJ. Low-Frequency Conductivity Tensor Imaging of the Human Head in vivo using DT-MREIT: First Study. *IEEE Transactions on Medical Imaging* 2017;37(4):966–976.
11. Kasinadhuni AK, Indahlastari A, Chauhan M, Schär M, Mareci TH, Sadleir RJ. Imaging of Current Flow in the Human Head During Transcranial Electrical therapy. *Brain Stimulation* 2017;10:764–772. [PubMed: 28457836]
12. Sadleir RJ, Fu F, Falgas C, Holland SK, Boggess M, Grant SC, Woo EJ. Direct Detection Of Neural Activity In Vitro Using Magnetic Resonance Electrical Impedance Tomography (MREIT). *NeuroImage* 2017;161:104–119. [PubMed: 28818695]
13. Sadleir RJ, Grant SC, Woo EJ. Can high-field MREIT be used to directly detect neural activity? Theoretical Considerations. *NeuroImage* 2010;52(1):205–216. [PubMed: 20382240]
14. Minhas A, Chauhan M, Sadleir RJ. Analysis of magnetohydrodynamic effects in current injection-induced magnetic flux density images at very high magnetic fields 2017; 1005 Honolulu, Hawaii ISMRM.

15. Balasubramanian M, Mulkern R, Wells WM, Sundaram P, Orbach D. Magnetic resonance imaging of ionic currents in solution: the effect of magnetohydrodynamic flow. *Magnetic Resonance in Medicine* 2015;74(4):1145–1155. [PubMed: 25273917]
16. Frauenrath T, Fuchs K, Dieringer MA, Ozerdem C, patel N, Renz W, Greiser A, Elgeti T, Niendorf T. Detailing the use of magnetohydrodynamic effects for synchronization of MRI with the cardiac cycle: a feasibility study. *Journal of Magnetic Resonance Imaging* 2012;36:364–372. [PubMed: 22411274]
17. Bernstein MA, King KF, Zhou XJ. *Handbook of MRI Pulse Sequences*: Elsevier Academic Press; 2004.
18. Minhas A, Kim HH, Meng ZJ, Kim YT, Kim HJ, Woo EJ. Three-dimensional MREIT Simulator of Static Bioelectromagnetism and MRI. *Biomedical Engineering Letters* 2011;1:129–136.
19. Haacke EM, Brown RW, Thompson MR, Venkatesan R. *Magnetic Resonance Imaging: Physical Principles and Sequence Design*: Wiley-Liss; 1999 914 p.
20. Oh TI, Kim YT, Minhas A, Seo JK, Kwon O, Woo EJ. Ion mobility imaging and contrast mechanism of apparent conductivity in MREIT. *Physics in medicine and biology* 2011;56:2265–2277. [PubMed: 21411866]

FIG. 1.

Three-dimensional models used in COMSOL simulations. Parts (a) and (b) show the geometry and mesh respectively for models representing cases I and II, parts (c) and (d) show geometry and mesh respectively for models of cases III and IV, part (e) shows the current-injection waveform applied at electrode ports marked with arrows in (a) and (c), and (f) shows values of conductivity (σ) and dynamic viscosity (ν) specified in subdomains of models of cases I-IV.

FIG. 2.

Pulse sequence diagram for spin echo pulse sequence showing (a) slice selection gradient, (b) phase encoding gradient (G_x), (c) spin-echo and (d) gradient echo readout sequences (G_y) and (e) current injection waveform. The current injection waveform shows positive (A – 8.175 ms) and negative (B – 7.886 ms) current polarity, interpulse interval C (1.632 ms), and spin-echo and gradient echo readout durations D and E (2.605 ms). Time points referenced in the text and other figures, and the timescale defined by t^* and t are shown in (f).

FIG. 3. MREIT phantom experiment setup. Part (a) shows axial views of the four phantoms used in experiments, corresponding to cases I-IV, and (b) shows the experimental setup. Imaging was performed at a main magnetic field strength of 18.8 T (800 MHz).

FIG. 4.

Variation of velocity in models of uniform cases I (a-h) and II (i-p) over a time period of $t^* + t$ (where $t=0$ to 60 ms, and $t^*=972.134$ ms) at different main magnetic field strengths. Plots (a)-(d) correspond to the location $(-1.9, 0, 2)$ mm, marked with a black dot in the cross-sectional model inset shown in (d). Plots (a)-(c) show velocity components u_x , u_y and u_z , respectively, and (d) shows the velocity magnitude. Corresponding results for the location $(-0.5, 0, 2)$ mm are shown in plots (e)-(h). The plots (i)-(p) show the corresponding results obtained from the model of case II.

FIG. 5.

Simulated phase images produced at 18.8 T for the model of case II (ASW) due to vertical (top row) and horizontal (bottom row) current injection directions. The images in (b) are reference images showing predicted MREIT phase in the gel medium of case I. The images in (c)-(d) are velocity-induced phase images for spin echo pulse sequences (c) including a 180° RF pulse effect and (d) without including a 180° RF pulse effect. Images shown in (e) are velocity-induced phase images from a gradient-echo (GRE) pulse sequence.

FIG. 6.

Comparison between 18.8 T simulated and experimental phase images at 18.8 T are shown for (top to bottom rows) cases I-IV for vertical current injection direction. The images in column (a) were obtained from MREIT experiments using spin echo pulse sequences. Images in columns (b) and (c) show simulated velocity-induced phase images for a spin echo pulse sequence (b) including a 180° RF pulse effect and (c) without including a 180° RF pulse effect. The images in column (d) are the velocity-induced phase images from a gradient-echo (GRE) pulse sequence.

FIG. 7.

Comparison between 18.8 T simulated and experimental phase images are shown for (top to bottom rows) cases I-IV for horizontal current injection direction. The images in column (a) were obtained from MREIT experiments using spin echo pulse sequence. Images in columns (b) and (c) show simulated velocity-induced phase images for a spin echo pulse sequence (b) including a 180° RF pulse effect and (c) without including a 180° RF pulse effect. The images in column (d) are velocity-induced phase images from a gradient-echo (GRE) pulse sequence.