The Feasibility of Fast Neural Magnetic Detection Electrical Impedance Tomography: A Modelling Study

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***Abstract*—Magnetic Detection Electrical Impedance Tomography (MDEIT) is a possible method to non-invasively image fast neural activity in the human brain by injecting current with scalp electrodes and measuring the change in the magnetic field due to neural activity. A modelling study was performed on an anatomically realistic head model, assessing the SNR and reconstructed image quality for MDEIT and EIT with 3 different realistic noise cases. EIT produced a larger SNR than MDEIT for 2 out of the 3 noise cases. However, MDEIT was found to reconstruct images with a significantly lower error for all the reconstruction cases considered (P<0.001).**

***Index Terms*—Neural imaging, Magnetometry**

I. Introduction

A. Background

There is currently no well-established technique capable of imaging functional neural activity non-invasively throughout the human brain with a mm and ms spatiotemporal resolution. Electrical Impedance Tomography is a functional imaging technique which works by injecting a constant current through pairs of surface electrodes on a body of interest and measuring the change in voltage due to an internal change in impedance [1]. By repeating this for many injection and measurement pairs of electrodes, an image of the impedance change can be reconstructed. In the case of neural imaging, the local change in impedance due to action potentials is measured with electrodes and an image of the neural activity is reconstructed. Gilad, 2009 measured the impedance change from the scalp in humans and concluded that the signal-to-noise ratio (SNR) was too small for practicable imaging with scalp electrodes [2]. The best resolution of fast neural EIT has been the imaging of cortical activity in the rat brain with a resolution of 2ms and 200μm with an array of electrodes placed on the surface of the brain [3].

MDEIT is a technique akin to EIT; the same protocol of current injection is performed and the external magnetic field is measured with magnetometers instead of the boundary voltage, the change in the magnetic field is then used to reconstruct an image [4]. MDEIT with scalp electrodes could provide an increase in SNR and image quality over EIT because the current is attenuated by the presence of the skull, but the magnetic field is not [5].

Optically pumped magnetometers (OPMs) have recently been developed that are capable of sensing magnetic fields of femtoteslas, a sensitivity comparable to that of superconducting quantum interference devices (SQUIDs), which are the gold standard in magnetometry [6]. The small form factor, portability and room-temperature operation of OPMs suggest that they are ideal candidates for MDEIT.

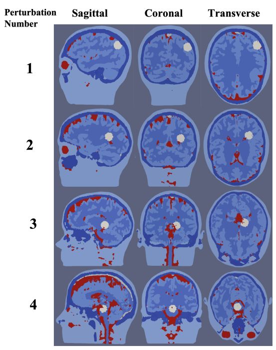
B. Experimental Design

Simulations were performed using a realistic head mesh segmented from MRI and CT scans of a human head (Figure 1b). Four realistic perturbations of 1cm radius and 1% local increase in conductivity, representing neural activity, were modelled at four depths from the surface of the brain (Figure 1a). Image reconstruction was performed using three cases of noise corresponding to realistic noise measured with scalp electrodes, a projected decrease in the noise of the current source and the same current source noise decrease coupled with a 1000-fold increase in the magnetometer sensitivity.

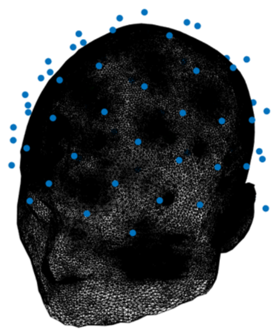
The performance of EIT and MDEIT were assessed and compared using the objective measures of SNR, error in the reconstructed position and error in the reconstructed volume of the perturbation.

The Quspin QZFM Gen-2 magnetometer [7] considered in this had 6.5mm of casing between the edge of the sensor and the point at which the magnetic field is measured. Whilst this is a current limitation to the distance between the scalp and the sensor, it is not a fundamental limitation, so scalp-to-sensor distances between 1mm and 10mm have been considered.

The number of electrodes and magnetometers chosen was aimed to reflect a realistic number that would be used in a real experiment whilst maintaining the same number of EIT and MDEIT measurement positions.



(a) The perturbations considered.



(b) The head FEM and magnetic field sensors considered.

Fig. 1: Graphical representations of the head mesh, sensors and perturbations considered.

C. Purpose

The aims of this study were to answer the following questions;

1) How large is the SNR for MDEIT?
   a) Is constant voltage or constant current better for MDEIT?
   b) Does MDEIT have a better SNR than EIT?
   c) What is the significance of sensor-to-scalp distance?
2) Are MDEIT images better than EIT images?
   a) Do accurate images of a conductivity perturbation reconstruct with MDEIT?
   b) What is the quality of the reconstructed MDEIT images and how do they compare to EIT images?

II. Methods

A. Computational Model

A finite element model (FEM) of a realistic human head containing ∼3.2M elements was generated using COMSOL Multiphysics [8]. The FEM comprised seven regions of electrical conductivity corresponding to different tissue types (Table I).

32 electrodes placed in the EEG 10-20 positions on the scalp of the FEM were used for injection and measurement, and an additional 34 electrodes were evenly placed on the scalp for measurement only. 64 tri-axial magnetic field sensors were considered around the FEM in a helmet shape. The distance of the sensors from the scalp was set to 7mm for comparison with EIT and distances of 1mm to 10mm in 1mm intervals were considered to assess the effect of the scalp-to-sensor distance.

Region	Conductivity (Sm^{-1})
White matter	0.150
Grey matter	0.300
Cerebrospinal fluid (CSF)	1.79
Sagittal sinus	0.700
Skull	0.0180
Air	1.00×10^{-4}
Scalp	0.440

TABLE I: The different regions defined by the FEM and their respective conductivity.

Current was injected at 1mA and the current injection protocol was chosen such that the current density was maximised in the brain (white and grey matter) of the model.

Four different spherical conductivity perturbations were considered, each with a volume of 3.86 cm^3 corresponding to a radius of $\sim$ 1cm. The perturbations were modelled as a 1% increase in local conductivity of the grey and white matter to simulate neural action potentials (Table II, Figure 1a).

Images were reconstructed on a hexahedral FEM of $\sim$ 375k elements. The reconstruction algorithm used was 0^{th} order Tikhonov regularisation with simulated noise-based correction. The regularisation parameter λ was found using leave-one-out generalised cross-validation.

Perturbation Number	Perturbation Depth (mm) (3sf)	Perturbation Volume (cm^3)(3sf)
1	7.40	3.86
2	32.8	3.86
3	58.2	3.86
4	83.6	3.86

TABLE II: The impedance perturbations considered in this work. The depth is taken as the distance from the centre of mass of the perturbation to the surface of the brain.

Three different cases for the noise were considered, corresponding to measured noise (noise case 1), realistic reduction in current source noise (noise case 2) and noise case 2 paired with the best possible OPM sensitivity that could be obtained (noise case 3) (Table III) [9]. Calculations were based on 232 measurement averages, corresponding to 1 hour of recording with 31 injection pairs of electrodes and 2 evoked potentials per second.

Noise Case	Magnetic Noise	Electric Noise
1	21.2fT + 3.67×10^{-3}%	0.0880µV + 3.67×10^{-3}%
2	21.2fT + 6.57×10^{-5}%	0.0880µV + 6.57×10^{-5}%
3	0.436fT + 6.57×10^{-5}%	0.0880µV + 6.57×10^{-5}%

TABLE III: The three noise cases considered in this work. Multiplicative noise is expressed as a percentage of the standing field.

B. Data Analysis

The mean of the largest 10% of absolute changes was used to calculate SNR and percentage changes for the magnetic and electric cases. The SNR was defined as the magnitude of the signal divided by the magnitude of the noise.

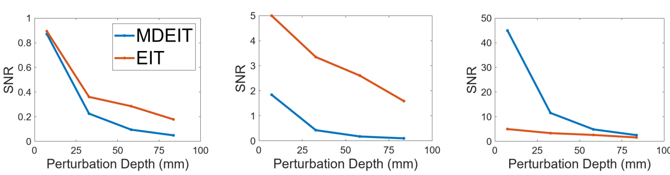
The reconstructed images were submitted to a threshold of 50% of the maximum positive change (full-width half-maximum). The images were assessed on their position and volume error The position error was defined as the difference in position of the centre of mass of the reconstructed image and that of the true perturbation as a percentage of the average mesh dimension. The volume error was defined as the difference in volume between the reconstructed perturbation and the true perturbation as a percentage of the total volume of the FEM. The total error was defined as the position error plus the volume error. Images with a total error of $< 10\%$ were considered to be accurate reconstructions. 100 reconstructions were performed in each case and a mean error was taken. The reconstruction error was compared using repeated measures ANOVA and the multiple comparison test.

III. Results

A. Forward Modelling

For constant voltage injection, there was a decrease in SNR of the MDEIT signal of 0.27%, 0.97%, 1.4% and 0.55% for perturbations 1-4 respectively with respect to constant current injection. For noise cases 1 and 2, EIT produced a higher SNR than MDEIT for all perturbations with a mean decrease in SNR of 45% and 84% for each case respectively (Figures 2a and 2b). For noise case 3, EIT produced a lower SNR than MDEIT for all perturbations with a mean decrease in SNR of 310% (Figure 2c).

There was an increase in the SNR of the MDEIT signal of 27%, 20% 18% and 20% when the scalp-to-sensor distance was reduced from 7mm to 1mm for perturbations 1-4 respectively. The mean increase in SNR was 21%.



(a) Noise case 1. (b) Noise case 2. (c) Noise case 3.

Fig. 2: The SNR of the mean of the largest 10% of changes for EIT And MDEIT as a function of perturbation depth in the brain.

B. Inverse Modelling

For noise case 1, EIT had a larger total reconstruction error than MDEIT for all perturbations ($P < 0.001$) with a mean difference of 12% (Figures 3, 4 and 5a). For noise case 2, EIT had a larger total reconstruction error than MDEIT for all perturbations ($P < 0.001$) with a mean difference of 7.1% (Figures 3, 4 and 5b). For noise case 3, EIT had a larger total reconstruction error than MDEIT for all perturbations ($P<0.001$), with a mean difference of 12% (Figures 3, 4 and 5c).

IV. Discussion

A. Summary of Results and Answers to Questions

1) How large is the SNR for MDEIT?: Constant current injection provided a larger SNR than constant voltage injection with a mean decrease of 0.79% for constant voltage.

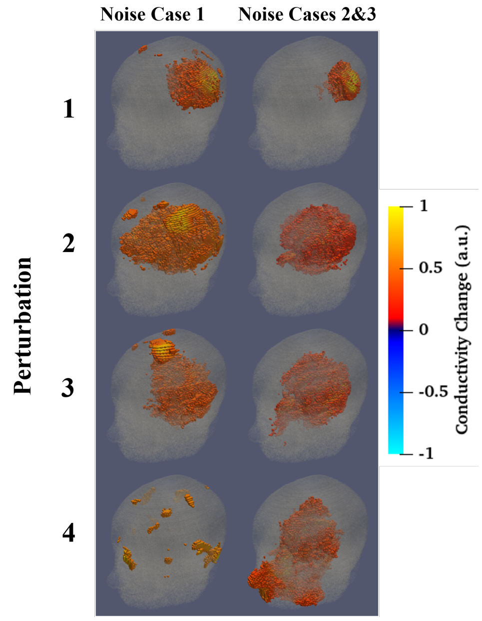


Fig. 3: EIT reconstructions for all perturbations and noise cases.

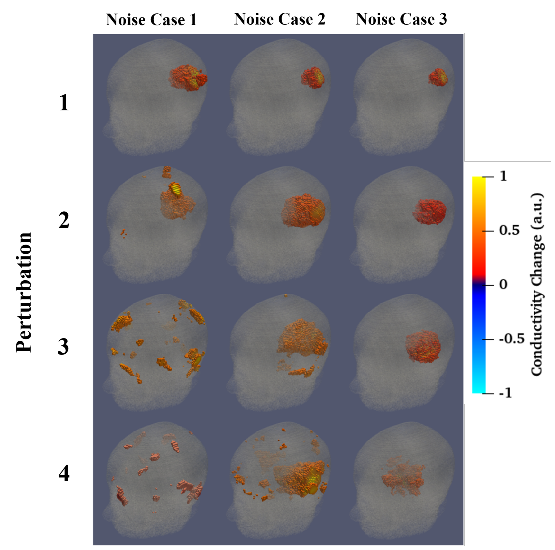


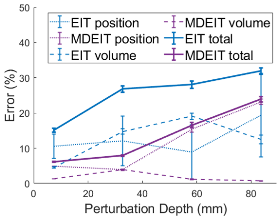
Fig. 4: MDEIT reconstructions for all perturbations and noise cases.

Given the current state of noise (noise case 1) the SNR for MDEIT varied from 0.87 for the most superficial perturbations to 0.049 for the deepest perturbations. This increased by a factor of approximately $\sim$2 if the multiplicative current source noise was reduced by a factor of 50 (noise case 2) and by a factor of $\sim$45 if the sensor noise was also reduced by a factor of 1000 to the fundamental limit for OPMs (noise case 3).

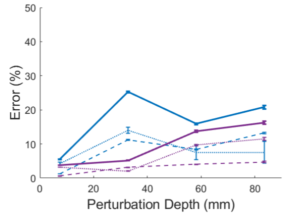
EIT had a higher SNR than MDEIT for noise cases 1 and 2; however, MDEIT had a higher SNR than EIT for noise case 3.

By moving the magnetic field sensors from 7mm to 1mm from the scalp, a 20% increase in SNR was calculated.

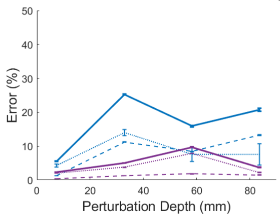
2) Does MDEIT reconstruct better images than EIT?: MDEIT reconstructed accurate images of conductivity per-



(a) Noise case 1.



(b) Noise case 2.



(c) Noise case 3.

Fig. 5: The position, volume and total reconstruction error (mean $\pm$ SE) of the image reconstructions as a function of perturbation depth for three different noise cases. N = 100.

turbations (error $<10\%$) for superficial perturbations in the outer third of the brain, provided the noise is equal to current measured levels or lower (Figure 4).

Overall, MDEIT reconstructed images of a higher quality than EIT for all of the 12 perturbation-noise combinations considered (P<0.001) (Figures 3, 4 and 5).

B. Technical Considerations

For the purposes of this modelling work, the sensitivity of the Quspin Gen-2 QZFM OPM [7] has been used to model triaxial magnetic field sensors with a bandwidth of $\pm$500Hz at a frequency of 1475Hz. In reality, OPMs have a bandwidth of $\sim\pm$200Hz, they are insensitive to frequencies >1400Hz and typically only exhibit a sensitivity of $\simeq$ 10fTHz$^{-\frac{1}{2}}$ when operated in a one-axis measurement mode. This means that the state of current OPM technology is not yet at the standard assumed in this modelling, which should be taken into consideration.

The same model and software (EIDORS) were used for the implementation of the EIT forward and inverse solutions; however, the MDEIT forward problem was solved using EIDORS and custom code and the inverse was solved using COMSOL, which could reduce the quality of the MDEIT images.

C. Conclusion

To conclude, fast neural EIT with scalp electrodes produced a higher SNR than MDEIT for noise cases 1 and 2 and vice versa for noise case 3. However, the SNR of MDEIT can be increased by approximately 20% by moving the sensors to a distance of 1mm from the scalp. Conversely, MDEIT reconstructed images of a higher quality throughout the brain across all perturbations and noise levels considered (P$<$ 0.001), which is supported by qualitative inspection of the images (Figures 3 and 4) and an analysis of the reconstruction error (Figure 5).

The most pertinent conclusion from this work is that even though the SNR is lower for MDEIT, images of better quality are reconstructed. The reason for this could be the larger amount of information ($3\times$) available to the reconstruction algorithm due to the triaxial nature of magnetometry or differences in the degree of mathematical ill-conditioning or rank-deficiency of the inverse problem.

D. Future Work

To further determine whether MDEIT is feasible for fast neural imaging, future work will entail assessing the robustness of EIT and MDEIT reconstructions to errors in electrode position, head geometry and sensor position for realistic noise levels, investigating the effects of image reconstruction with equal information for MDEIT and EIT and performing MDEIT studies *in vivo* in humans with scalp electrodes.

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