

fEITER – a new EIT instrument for functional brain imaging

**J L Davidson¹, P Wright¹, S T Ahsan¹, R L Robinson¹, C J D Pomfrett²
and H McCann¹**

¹ School of Electrical and Electronic Engineering, University of Manchester, UK

² School of Medicine, University of Manchester, UK

E-mail: j.davidson-2@manchester.ac.uk

Abstract. We report on human tests of the new EIT-based system fEITER (*functional Electrical Impedance Tomography of Evoked Responses*), targeted principally at functional brain imaging. It is designed and built to medical standard BS EN 60601-1:2006 and clinical trials have been approved by the MHRA in the UK. fEITER integrates an EIT sub-system with an evoked response sub-system capable of providing visual, auditory or other stimuli, and the timing of each stimulus is recorded within the EIT data to a resolution of 500 microseconds. The EIT sub-system operates at 100 frames per second using 20 polar/near-polar current patterns distributed among 32 scalp electrodes that are arranged in a 3-dimensional array on the subject. Presently, current injection is fixed in firmware at 1 mA pk-pk and 10 kHz. Performance testing on inanimate subjects has shown voltage measurement SNR better than 75 dB, at 100 frames per second. We describe the fEITER system and give example topographic results for a human subject under no-stimulus (i.e. reference) conditions and on application of auditory stimuli. The system's excellent noise properties and temporal resolution show clearly the influence of basic physiological phenomena on the EIT voltages. In response to stimulus presentation, the voltage data contain fast components (~100 ms) and components that persist for many seconds.

1. Introduction

Electrical Impedance Tomography (EIT) is a candidate technique for functional brain imaging through its sensitivity to conductivity changes within the subject. Most notably, this has been demonstrated over relatively long time-scales (tens of seconds) by Holder and co-workers at University College London (UCL), who attribute their measurements to the haemodynamic response to neural activity [e.g. 1]. Such early studies demonstrated the imaging capability of EIT using relatively modest frame rates. More recently, the same group recorded impedance changes with scalp electrodes during visual Evoked Response (ER) experiments using slow square wave current injection [2], claiming to detect fast neural activity through voltages measured on a small number of electrode sites and with averaging of repeated stimuli. The detection of sub-second neural activity associated with ER experiments using EIT was also reported in 2003-2006 during a pilot study [e.g. 3] at the University of Manchester (UoM) using an adapted industrial process tomography instrument. The pilot study motivated the development of an EIT system specifically designed for functional brain imaging which delivers high SNR at fast frame rates and is suitable for use in a clinical environment.

In this paper, we report on the development of the instrument called fEITER (functional Electrical Impedance Tomography of Evoked Responses). fEITER captures EIT data at 100 frames per second (fps) and is presently being used in a clinical trial (ISRCTN93596854) at Manchester Royal Infirmary.

2. The fEITER system

The fEITER system implements four key specification targets. Firstly, image reconstruction of 1% impedance changes in the brain due to neural function requires measurement sensitivity in the order of 80 dB [4]. Secondly, to probe the temporal domain of neural function, a frame rate of 100 fps is required. Thirdly, the complete system must comply with the principles of medical standard BS EN 60601-1:2006 and be suitable for use in both the Operating Room (OR) and Intensive Care Unit (ICU). Finally, the system must withstand the processes of electrosurgery and defibrillation which may be present within the OR. The system (Figure 1) is based on 32 voltage measurement channels and 20 near-polar sinusoidal current patterns per frame of data, and comprises of separate headbox and base unit assemblages joined by power and data cables. A CED μ 1401 integrated into the base unit provides randomized stimulus trains to evoke a neurological responses using, e.g. audible clicks.

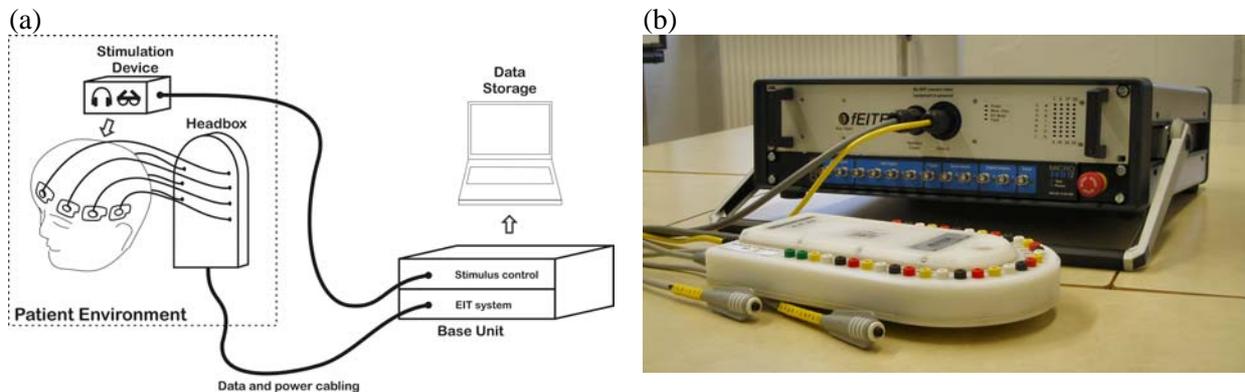


Figure 1. The fEITER system; (a) high-level schematic and (b) photograph showing the base and headbox units in the background and foreground respectively.

The EIT sub-system is a class II medical device and provides at least 5 kV galvanic isolation thereby allowing connection to both the CED μ 1401 and a battery powered data collection laptop without the need of external separation devices. The patient-applied part (headbox) of the sub-system is controlled by a local FPGA (Field Programmable Gate Array, Xilinx Virtex-4 SX35) that provides Direct Digital Synthesis (DDS) to drive high-precision current sources and carries out Phase Sensitive Demodulation (PSD) of the EIT measured voltages. The headbox uses two constant-current sources [5] which can be switched via CMOS switches between any combination of drive and receive electrodes. Presently, the injected current is fixed by hardware to 1 mA pk-pk, and firmware sets the frequency of the current to 10 kHz. The current is approximately one third of the maximum permitted auxiliary current of 1 mA rms at 10 kHz as defined by the medical standard BS EN 60601-1:2006. Both the driven and received currents, and their waveform symmetry properties, are sensed by resistors in the headbox and monitored in real-time by firmware in the FPGA, to ensure that compliance with the standard is actively enforced. Parallel voltage measurements are captured between all pairs of adjacent electrodes by 16-bit ADCs running at 500 ksamples/s. The base unit of the EIT sub-system performs a serial-to-parallel conversion of incoming data from the headbox using a local Xilinx CPLD (Xilinx XC95144 family). The resultant parallel 8 bits of data are read at 500 kHz by a National Instruments USB DAQCard-6221 controlled using LabVIEW. Numerous tests with saline-filled tank tests have been carried out in order to assess the performance of the EIT sub-system, showing a precision around 80 dB in the acquired voltage measurements at 100 fps [6].

3. First human tests

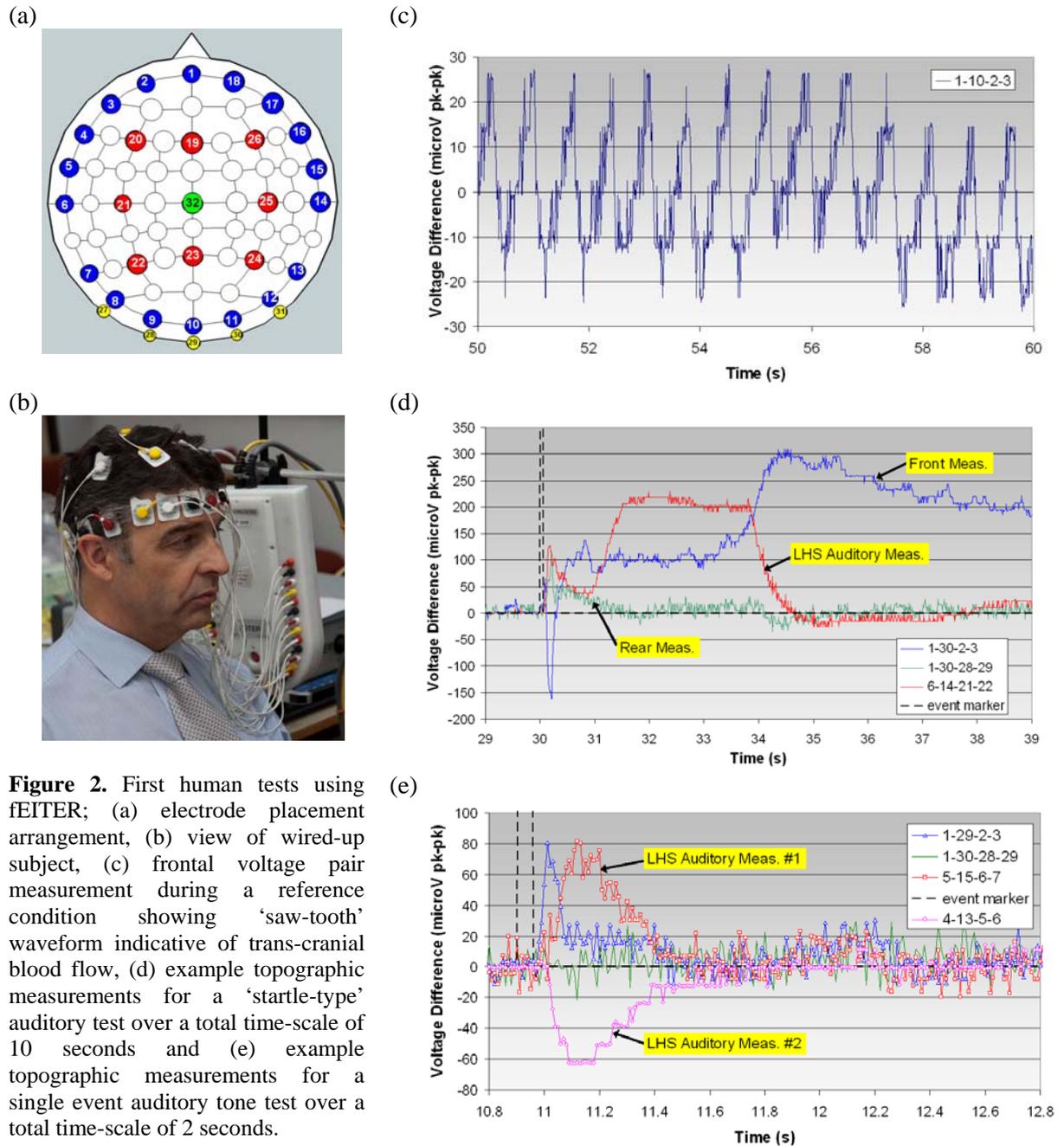


Figure 2. First human tests using fEITER; (a) electrode placement arrangement, (b) view of wired-up subject, (c) frontal voltage pair measurement during a reference condition showing ‘saw-tooth’ waveform indicative of trans-cranial blood flow, (d) example topographic measurements for a ‘startle-type’ auditory test over a total time-scale of 10 seconds and (e) example topographic measurements for a single event auditory tone test over a total time-scale of 2 seconds.

3.1. Methodology

Prior to a comprehensive clinical trial, numerous simple stimuli tests have been carried out with 2 subjects from the experimenter team at UoM with no objection from the local ethics committee. In all tests, the subject was wired up using 32 Ag/AgCl-type Zipprep electrodes (Aspect Medical Systems Inc., USA) for tomographic measurements based on a subset of the International 10-20 EEG System as shown in Figure 2(a). Additionally, a reference electrode was attached below the left ear-lobe. EIT data were captured continuously in 1-minute blocks at 100 fps (546 independent voltage pair measurements per frame) for reference conditions, and before, during and after stimulus presentations.

3.2. Example results

A typical result for a frontal measurement during a reference condition over a period of 10s is shown in Figure 2(c). With reference to Figure 2(a), the data correspond to current injection between electrode pair 1 and 10, with differential voltage measurement between electrode pair 2 and 3. A saw-tooth like waveform can be clearly seen, approaching 50 μV pk-pk. The frequency of the waveform is consistent with the heart-rate of the subject during the test, which has been subsequently verified. When the effect of this waveform is taken into account, the rms noise voltages are around 6 μV .

Figure 2(d) shows example topographic data evoked by a sharp bang (release of a party-popper) giving rise to a gross auditory stimulus. The data are for a single trial for 3 measurements corresponding to 1-30-2-3 (forehead), 1-30-28-29 (posterior head) and 6-14-21-22 which is close to the Left-Hand-Side (LHS) auditory cortex. The onset of sound was detected at 30.01s via the CED μ1401 and is shown as the event marker. Clear differences in the latencies and amplitudes in the measurement data can be seen. The data shows both fast components (~ 100 ms) and relatively slower components persisting for several seconds. The signal measured close to the auditory cortex has a very short-term (~ 100 ms) spike, followed by a plateau rising at about 1s and lasting approx. 3s. Haemodynamic (total blood volume) processes in visual cortex have been measured to start at about 1s by Sirotin *et al.* [7] using Intrinsic Signal Optical Imaging (ISOI), but their technique has a temporal resolution of about 130 ms and can't test the fast component of our signal. The frontal measurements are more complex, showing a 3-stage process with the last following after the slow auditory response, but measurements at the rear of the head show a simple decay to baseline after the 100 ms spike.

Figure 2(e) shows topographic data for a single presentation of an auditory tone delivered binaurally to the subject using inner-ear headphones, as part of a 22-event sequence comprising of pseudo-randomly spaced stimuli at 2.5 kHz, each of 50 ms in duration with varying intensities corresponding to a loudness range estimated between 60-90 dB SPL. On the presented time-scale, the temporal spacing (10 ms) of each measured data point can be seen, demonstrating the excellent temporal resolution of fEITER. The latencies of the peak measured signals closest to the auditory cortex are approximately 200 ms from the onset of the presented tone. This has been observed several times using fEITER and is consistent with the neural encoding associated with the late cortical auditory response typically observed using EEG methods in Auditory Evoked Potential (AEP) studies.

4. Conclusions and future work

Initial human tests using fEITER with simple auditory stimuli show the measurement of both fast and slow components in the EIT voltage signals on single event presentations. Image reconstruction of these data is in progress. We aim to improve our understanding and implications of the origin and mechanisms of the observed EIT data changes from more comprehensive tests, including an MHRA approved clinical trial at Manchester Royal Infirmary which is presently underway.

References

- [1] Tidswell A T, Gibson R H, Bayford and D S Holder 2001 Three-dimensional electrical impedance tomography of human brain activity *Neuroimage* **13** 283-294
- [2] Gilad O and Holder D S 2009 Impedance changes recorded with scalp electrodes during visual evoked responses: implications for EIT of fast neural activity *Neuroimage* **47** 514-522
- [3] McCann H *et al* 2006 Sub-second functional imaging by Electrical Impedance Tomography in *Proc. of 28th Annual Int. Conf. of the IEEE EMBS* (New York City, NY, USA) 4269-4272
- [4] Polydorides N, Lionheart W R B and McCann H 2002 Krylov subspace iterative techniques: on detection of brain activity with electrical impedance tomography *IEEE Trans. Med. Imag.*, **21** 596-603
- [5] Rafiei-Naeini M and McCann H 2008 Low-noise current excitation sub-system for medical EIT *Physiol. Meas.* **29**(6) S173-S184
- [6] Davidson J L *et al* 2009 fEITER – a new instrument for OR and ICU applications in *Proc. of 10th International Conference on Biomedical Applications of Electrical Impedance Tomography* (Manchester,UK) Available: <http://www.maths.manchester.ac.uk/eit2009>
- [7] Sirotin Y B *et al* 2009 Spatiotemporal precision and hemodynamic mechanism of optical point spreads in alert primates *Proc. Natl. Acad. Sci.* **106**(43) 18390-18395