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In vitro localisation of intracranial haematoma using electrical impedance tomography semi-array

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ABSTRACT

Electrical Impedance Tomography is a non-invasive and portable method that has good potential as an alternative to the conventional modalities for early detection of intracranial haematomas in high risk patients. Early diagnosis can reduce treatment delays and most significantly can impact patient outcomes. Two eight-electrode layouts, a standard ring full array (FA) and a semi-array (SA), were investigated for their ability to detect, localise and quantify simulated intracranial haematomas *in vitro* on ovine models for the purpose of early diagnosis. SA layout speeds up electrode application and avoids the need to move and lift the patient's head. Haematomas were simulated using gel samples with the same conductivity as blood. Both layouts, FA and SA, could detect the presence of haematomas at any location within the skull. The mean of the relative radial position error with respect to the brain radius was 7% for FA and 6% for SA, for haematomas close to the electrodes, and 11% for SA for haematomas far from the electrodes at the back of the head. Size estimation was not as good; the worst size estimation error for FA being around 30% while the best for SA was 50% for simulated haematomas close to the electrodes.

1. Introduction

Head injury is the main cause of death among young adults and children and may become the third greatest global death cause by 2020, due to the substantial number of associated deaths and cases of disability [1]. The UK National Confidential Enquiry into Patient, Outcome and Death (NCEPOD) reported that more than half of the patients that required neurosurgical advice were taken to hospitals with no on-site neurosurgical provision and only 14% of patients requiring secondary transfer to a neurosurgical centre had access to neurosurgical treatment within four hours [2]. Patients treated in a non-neurosurgical centre had a 26% increase in mortality and a 2.15-fold increase in the risk of death compared to patients treated at a neurosurgical centre [3]. First responders need more information on the neurological condition of their patient. In particular, they require information on potentially evolving haematomas which may need prompt and rapid action. This information is vital for proper triage, and to ensure the best possible decisions are made for the patient's welfare.

Haematomas expand and increase the intracranial pressure on the brain. A growing haematoma will cause severe and even permanent damage to the delicate tissue of the brain, morbidity, and eventual death of the patient [4]. Haematomas are classified based on their location. Epidural haematomas form between the skull and the dura-mater. They occur because of trauma and a tear in an artery, often to the temple, where the middle meningeal artery is located. Subdural haematomas occur because of trauma and a tear in veins beneath the dura-mater in the brain. A subdural haematoma is very close to the brain and may cause a serious problem. Intracerebral Haematomas, occur within the brain parenchyma itself due to bleeding from trauma or uncontrolled high blood pressure. The development of the haematoma from benign to symptomatic can be sudden, and a patient can change from lucid to a state of rapid neurological deterioration over a very short-period of time [5]. It is well known that the time from injury-to-diagnosis-to-treatment is a key factor in patient outcome, and must be minimised for a patient to make a full recovery.

Electrical Impedance Tomography (EIT) reconstructs cross-sectional images of the conductivity distribution of the internal components of the brain, based on non-invasive voltage measurements through an array of electrodes on its boundary. Blood has a high electrical conductivity contrast relative to other cranial tissues and thus its appearance can be detected and monitored using EIT [6].

Head injuries and haematoma are often accompanied by other traumatic injuries that can be aggravated by unnecessary movement, including the placing of electrodes around the head. Therefore, it is desirable to develop methods that do not involve

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applying electrodes at the back of the head. Placement of the electrodes on the anterior of the head avoids exacerbating existing injuries and removes the need to lift the patient. However, good localisation of a haematoma is hampered by eliminating the electrodes at the back of the head. To conquer the quality reduction of the images and to minimise these errors, several reconstruction strategies have been proposed previously [7]. The purpose of this study is to evaluate the performance of EIT, using optimised eight-electrode configurations. This includes an investigation of the different configurations to evaluate their ability to detect and localise anomalies similar to haematoma in the human head, for the purpose of early diagnosis. Using the minimum number of electrodes is always desirable in clinical applications since it may also speed up the electrode setup process in emergency cases. The proposed electrode configurations are evaluated for the detection and localisation of simulated haematomas *in vitro* using an ovine model. Intracerebral haematoma detection has been considered in previous studies using EIT [8]. Epidural and subdural haematomas are considered in this study since their location can represent the worst case with respect to the SA configuration.

2. Methods

In EIT, the process is divided into a forward problem and an inverse problem. To reconstruct the conductivity distribution images through the EIT inverse problem the forward problem on a prototype model has to be solved. For general cases, a numerical method such as finite element analysis is required to implement the model and solve the forward problem. Initially, a simple forward model based on a circular shape with a homogenous conductivity distribution may be used to calculate the sensitivity matrices [9]. Better results are obtained if the forward model exactly matches the object in terms of internal conductivity distribution and external geometry. In principle, an incorrect estimate of boundary shape will introduce artefacts and reduce the quality of the reconstructed images. However, more realistic models need to be used carefully since inaccurate prior information may yield images worse than those reconstructed with a simple forward model [10]. In practice, it is difficult to specify an accurate model for an individual head because head geometry varies from patient to patient.

2.1. Full and semi-array electrode layouts

In this study, two eight-electrode layout strategies were investigated *in vitro* and compared in terms of their ability to detect and localise intracranial haematomas. The first one was a standard ring layout or full-array (Fig. 1a), where the eight electrodes were placed equally spaced around the head. The second layout was a novel electrode configuration applied to the front of the head. This so-called semi-array (SA) configuration consisted of a set of eight electrodes separated by angle of 36° in a semi-circular profile (Fig. 1b). This layout simplifies the application of the electrodes and avoids the need to move and lift the patient's head. An adjacent current pattern was applied to both layouts, wherein current was applied in turn to pairs of adjacent electrodes, and voltages were measured across other pairs of adjacent electrodes. In the SA, use of this scheme included measurements and current applications between the last-numbered and first electrodes positioned at the end of the array and approximately 108° apart. Both layouts involved 8 current positions and a total of 40 voltage measurements. Experiments were performed on an ovine model using both layouts and the results obtained from the SA layout were compared with data from the standard eight-electrode full-array (FA) layout to determine the ability of the SA to detect and localise intracranial haematomas. Restricting electrodes at the back of the head limits the resolution and thus inferior localisation of the anomaly can be expected, compared to that of the FA layout.

2.2. Data generation

In vitro ovine experiments were performed in conjunction with an eight-electrode EIT system to determine the potential of this configuration to provide good results *in vivo*. To obtain the experimental measurements, a prototype 16-electrode EIT system known as the "EITLboro" rig was used. The structure of this device is presented in Fig. 2. The system is controlled by a microcontroller connected to a PC through a serial port. A graphical user interface was developed using Visual Basic (VB). A sinusoidal current generated by a constant current source was injected through one pair of adjacent electrodes and the corresponding boundary potentials were measured over pairs of the remainder of the neighbouring electrodes using a multiplexer. The input pair of electrodes was switched over all adjacent electrodes pairs and the measurement procedure was repeated for all possible adjacent pairs. The performance of this system was previously evaluated using phantom experiments [11]. The results showed a high level of accuracy with an average accuracy of 93.5% for the system. This EIT system has 16 channels and operates with a temporal resolution of 100 frames per second. For this experiment, a constant current of 1 mA at a frequency of 50 kHz and 8 electrodes were chosen.

2.3. Experimental setup

Five freshly skinned sheep heads (labelled as A, B, C, D and E) were obtained from a local butcher. The locations of the 8 electrodes for each layout were marked in different colours on the skull. Equal distance between electrodes has been considered around the head for the FA and in the anterior of the head for the SA according to the perimeter measurement of each head. Eight Ag/AgCl disk electrodes (Unimed Electrode Supplies Ltd) were fastened to the skull using conductive paste (Unimed Electrode Supplies Ltd) for the FA layout (Fig. 3a). These electrodes were also soldered to the wires to connect to the skull on the interior of the head using conductive paste for the SA layout (Fig. 3b).

A saline solution with the same conductivity as blood (0.67 S/m) was made with a concentration of 0.33% [weight/volume] of sodium chloride in water. In order to localise haematoma *in vitro*, the position of the anomaly has to be known with a good estimation. To simulate a more realistic haematoma in an accurate location, the saline solution was transformed to gel. The saline solution was stirred using a magnetic stir bar at a temperature of 70 °C while agar powder was added to achieve the desired gel concentration (1.9% by weight). Then the solution was poured into a 1 cm diameter tube and allowed to cool at room temperature. The gel sample was removed from the tube and cut into one tenth of the diameter of each brain to simulate pockets of blood. The conductivity of the gel sample was measured and found to be the same as the conductivity of the saline solution. A 2-terminal measurement was performed to measure the gel conductivity and the same gel samples were used on each subject. An AC voltage was applied across the gel at a frequency of 50 kHz at room temperature using a waveform function generator connected in series with a digital multimeter to measure the AC current and voltage across the gel. The circuit was calibrated with multiple known resistances, and the conductivity measurements were compared to published data [12].

All the skulls were cut in approximately half using a bone saw. The top half of the skull was carefully removed and the brain was exposed in order to position the anomalies (Fig. 4). Gel samples were placed superficially on top of the brain lobe and the top half of the skull was replaced. The anomaly was located in different positions along the α, $\alpha\beta$, β, $\beta\gamma$ and γ axes (at $\theta = 0°, 45°, 90°, 135°$