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A Modified Electrode Configuration for Brain EIT

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Abstract. Electrical impedance tomography (EIT) of the brain holds great promise for long term non-ionizing detection and imaging of blood flow, ischemia, stroke, and even neuronal activity. One of the most difficult challenges with this modality, however, is overcoming the high impedance of the skull, which severely limits current passage through the intracranial space and “washes out” the tissue property images. There are situations, however, in which invasive electrode configurations are appropriate to overcome this limitation. We propose the use of a central and circumferential-electrode configuration to improve detection and localization of edema, hemorrhage, and ischemia within the cranium. Results from a simulation study and a phantom experiment verifying the simulation are shown.

1. Introduction
Electrical Impedance Tomography is an enticing and safe candidate method to image the human body over an extended period of time. However, the method is diffuse by nature as current prefers to follow the most conductive paths (i.e. not necessarily a straight line). This is especially troublesome if one wants to pass current across the cranium for imaging or detecting blood flow, ischemia, stroke, and even neuronal activity within the head. The skin and muscle surrounding the cranium are very conductive. The cranium, however, is insulative. No matter the electrode configuration on the periphery, most current will pass through the outer tissue rather than take the preferable path through the skull and brain. This leaves a less sensitive center region within the image [1, 2, 3].

To overcome the current passage limitation, one can place electrodes invasively within the cranium as demonstrated by Holder et al in his evoked response experiments [4]. Most research shies away from this solution as implanting electrodes in the brain is inherently risky and generally seen as undesirable. There are a few situations, however, in which a centrally-located electrode is an obvious and even desirable choice. One such application includes treatment of traumatic brain injury in which catheters and intracranial pressure (ICP) sensors will be inserted into the brain parenchyma.

It is not difficult to conceive of an ICP sensor or catheter-electrode combination, which could be used to augment present brain-EIT setups. Indeed there are several FDA-approved predicate devices on the market now, two of which include the deep-brain stimulators from Medtronic and impedance-based pressure-volume sensors from Millar. The addition of such an electrode would allow new excitation patterns in both active (current sink/source) and passive sensing modes. In this way one could guarantee more current passage through the cranium to detect worsening injury or even neuronal function by blood flow imaging [4]. This paper will demonstrate our
Figure 1. Image (a) shows the surface of the 159,000 node forward problem mesh. The red sphere in the image is the 100 uL inclusion. Image (b) shows the saline tank setup. Nine electrodes are visible with 8 on the periphery and one in the center. The red catheter has a latex balloon at its tip, which is inflated with 100 uL of fluid.

preliminary look into the use of a centrally-located electrode for brain-based EIT applications through simulation evidence and bench top verification.

2. Methods

2.1. Saline Tank Simulation

The purpose of this simulation is to determine how much a central electrode improves reconstruction of a small 100 uL (roughly one drop of fluid) inclusion within a larger saline 2 liter tank. A 3-dimensional model was created in SolidWorks (Dassault Systmes SolidWorks Corp., Concord, MA.) with a cylinder of diameter 20.3 cm and a depth of 7.6 cm. Eight 3 mm diameter x 7.6 cm high cylindrical electrodes were placed equidistant from one another 8.9 cm radially from the center. A ninth electrode of the same characteristics is placed in the center of the cylinder. Two meshes are created. The first is a 184,000 node homogeneous mesh for the inverse problem. The second is a 159,000-node mesh with well-defined concentric spherical inclusions of differing volumes centered at 3.2 cm radially outward from the center and 3.2 cm from the bottom (see Fig. 1(a)). These are used for the forward problem. The background conductivity is 0.28 S/m (roughly that of brain), and a 100 uL spherical inclusion is set at 0.80 S/m (roughly that of blood) [5]. The forward solution is solved using tetra-polar excitation patterns for all possible combinations of electrodes. Noise is added to the forward problem solution at 1%, 2%, and 5% to simulate systematic and random errors according to the equation

\[ \nu = \frac{\text{std}(d)}{\text{std}(\nu)} \]

where \( \nu \) is a vector of Gaussian distributed random numbers scaled by the standard deviation of the difference \( d = Z_1 - Z_0 \). \( Z_0 \) and \( Z_1 \) are vectors of the electrode impedance measurements for the system with all excitation patterns from the homogeneous and inclusion meshes respectively. Comparisons are made between solutions with and without the central electrode participating. All solutions are computed using NDRM, Dartmouth’s custom finite-element software [6].
2.2. Saline Tank Verification
A saline tank (after which the finite-element simulation is modeled) was constructed to determine the sensitivity a new USB-based EIT system developed at Dartmouth. The system provides the same tetra-polar excitation patterns described above. It is capable of DC to 100kHz excitation frequencies. The drive current is hard-coded to be in line with the IEC 60601-1 guidelines. This experiment uses a frequency of 50 kHz and a current drive of 5 mA. The background conductivity of the saline solution is about 0.1 S/m. A Fogarty catheter (small 1.3 mm diameter catheter with a latex balloon at its tip) is placed into the tank mid-water level at the same location described for the inclusion in the simulation section. It is then inflated with 100 uL of fluid. Figure 1(b) shows the experimental setup. EIT frames are acquired with and without the central electrode at 9 frames per second.

3. Results
3.1. Saline Tank Simulation
The small volume and biological contrast for this simulation were chosen to give us an idea of whether our device is sensitive enough to detect blood flow. The L2-norm was calculated from the difference between the baseline impedance data from the homogeneous background forward problem and that of the forward problem from the inclusion. This yielded 0.15 ohms with the central electrode and 0.13 ohms without. The peak impedance for the homogeneous tank is 100 ohms.

Typical signal-to-noise ratios for this new system ranges between 85 and 95 dB depending upon the current, frequency, and pre-amp scaling. The worst-case scenario would be to use the 85 dB value. This is equivalent to a noise floor at 56 uV. This value is used as a threshold for analysis. Finding all values from a singular-value decomposition of the reconstruction Jacobian greater than this threshold yields 36 values for the central electrode and 28 without. This is an improvement of about 28% over the standard circumferential ring topology. The effects can be seen in Fig. 2 with 5% noise.

3.2. Saline Tank Verification
The difference images are presently reconstructed in 2-dimensions in real-time with minimal averaging. The effect of the Fogarty catheter inflated with 100 uL of fluid is seen in Fig. 3(a) imaged without a central electrode and in Fig. 3(b) with a central electrode. On the same color scale, a peripheral-only electrode topology shows the inclusion with less intense values,
Figure 3. Image (a) shows the 100 uL balloon reconstructed in real-time without using a central electrode. Image (b) shows the same balloon while using the central electrode.

deformed shape (oblung towards the center), and slightly skewed position. On the other hand, the inclusion is readily seen as a tighter region correctly positioned midway between the center and periphery using the central electrode.

4. Conclusion and Future Work

EIT has the potential to be used as a long-term monitor of status in patients with potentially life-threatening brain injuries. We put forth an argument for placement of a centrally located-electrode which is in-line with today’s clinical standard of care for such patients. We demonstrated that such an electrode improves detectability of small inclusions in both simulation and a saline tank phantom. In vivo studies of 1 month-old piglets have begun using a central electrode in a real-time EIT system. Analysis and comparison of this EIT data to CT/MRI data and other physiologic monitors will continue in an effort determine the efficacy of this modality.

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