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TITLE:
Symmetry Difference Electrical Impedance Tomography – A novel modality for anomaly detection

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Symmetry Difference Electrical Impedance Tomography – A novel modality for anomaly detection

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Abstract- Objective: The theoretical basis, experimental implementation, and proof of concept of a novel Electrical Impedance Tomography (EIT) imaging technique, called Symmetry Difference EIT, is described. This technique is applicable in situations where there is inherent symmetry in the region being imaged. Methods: The sample scenario of the human head is used to describe the technique. The head is largely symmetrical across the sagittal plane. A unilateral lesion such as a haemorrhage or region of ischaemia distorts that symmetry. This distortion may be visualised using EIT. Measurement sets from a ring of electrodes placed on the boundary in both clockwise and counter-clockwise orientations are compared to detect the anomaly. Computer simulations featuring a hemispherical model of the head and brain are used initially to demonstrate the theory. Then, a more complex numerical model with anatomically accurate finite element models (FEMs) is used to expand on the concept with a more realistic scenario. Finally, tank experiments are performed with phantom lesions to validate the technique in the real world. Results: Deviations from normal symmetry, due to the presence of lesions, are detectable using this new modality. The ease of detection improves with larger lesions and those far from the plane of symmetry. Quantitative metrics, as well as an image, help to robustly detect and identify both the presence of an abnormality and the cause (haemorrhagic or ischaemic lesion in the scenarios tested) or indeed indicate where no detection is possible. Conclusion: Symmetry Difference EIT is a valuable new modality that is applicable to cases where the ‘normal’ features symmetry across a plane. Significantly, a change in the region of interest is not required and hence this technique may be suited to static or quasi-static cases where time difference EIT cannot be used.

Key Words – Biomedical Imaging, Electrical Impedance Tomography, Reconstruction Algorithm

1. INTRODUCTION

Electrical Impedance Tomography (EIT) is an imaging technique which typically features a ring of electrodes placed around the area of the body of interest. Alternating current, usually of frequency 1 kHz – 1 MHz, is injected between two of the electrodes, and the voltage is measured between the remaining electrode pairs. The current stimulation is then moved to another injecting electrode pair and the voltage recordings repeated until a complete frame of measurements is taken according to a specific pattern and protocol. In this work, a ‘channel’ refers to an individual measurement within a complete frame. The voltage responses to the electrical stimulation are a function of the electrical conductivity (σ) of the region enclosed by the electrode ring. Hence it is possible to build a conductivity map of the region that translates into an image [1], [2].
EIT suffers from low spatial resolution and high sensitivity to noise. However, it is low-cost, non-invasive, hazard-free, and has high temporal resolution. As such, it is an active area of research [3] for a variety of biomedical applications. Currently there are three main EIT modalities: time difference EIT (tdEIT), absolute EIT (aEIT), and frequency difference EIT (fdEIT). In tdEIT, two frames are taken at different time points and the difference between them can be used to detect a change in the region. Therefore, tdEIT is not useful if there is a static region of interest. Absolute EIT attempts to reconstruct an image from a single set of measurements. However, due to the high sensitivity of this technique to errors, it has not found much success to date. Frequency difference EIT may be used to image an area if there are differences in the response of the tissues to electrical stimulation at different frequencies [4].

This paper proposes a new modality for EIT called Symmetry Difference EIT (sdEIT). This modality is a novel approach to address the challenge of imaging static scenes. The modality is applicable where there is a natural plane of symmetry in the region of interest, for example, in the head, where the sagittal plane is the border between the near mirror images of the left and right side. In the normal patient, the two sides are nearly symmetric within the spatial resolution of EIT; however, if there is a unilateral lesion (i.e., an abnormality) present, then the symmetry is disrupted. It is this disruption in symmetry that sdEIT attempts to detect.

Application of the sdEIT technique comprises two distinct steps, both resulting in an image and quantitative metrics:

(i) Detection of Deviation from Normal Symmetry:
A ring of electrodes is placed across the plane of symmetry such that the electrodes, when assigned as clockwise and then counter-clockwise orientations, result in symmetrically equal but opposite configurations. Measurement frames from each of these are used to generate a difference image. The presence of a unilateral lesion ideally results in an image detecting the lesion as well as a confounding anti-lesion imaged, the latter having opposite conductivity and position to the true lesion. A quantitative metric, percentage symmetry, objectively evaluates the difference image to decide if a lesion is detected.

(ii) Disambiguation:
A simulated model of the normal, the “pseudo normal”, is generated using a priori information. A measurement frame from this pseudo normal model is used to create a difference image (called the “pseudo normal difference image”) with one of the measurement frames from (i). This image along with the applied robust quantitative metrics, are used to disambiguate which of the two equal but opposite lesions is the truth (or indeed return a result that indicates disambiguation is not possible).

The proposed technique is reliant on an aggregate approach, with the outcomes from (i) and (ii) combined to strengthen the overall outcome. In this work, the comprehensive results, including image and metrics from both (i) and (ii), are reported for select illustrative examples, with only the metrics reported for others for brevity.

This paper describes sdEIT using the example of stroke as a model. Hence, the head is the region of interest and the goal is two-fold: first, to detect the presence of a haemorrhagic or ischaemic lesion, and second, to identify which type of lesion it is. Stroke treatment needs a definitive aetiology of either haemorrhagic or ischaemic to initiate treatment [5], [6]. These two lesion types are, respectively, more electrically conductive and less electrically conductive compared to brain parenchyma [7]. Hence for a haemorrhage, the confounding symmetrical mirror image would appear as an ischaemic lesion and vice-versa. Thus, there is a need for both steps in sdEIT, as the first detects and abnormality while the second disambiguates between the true lesion and the false mirror image. Significantly, this technique could allow for successful EIT detection of static or quasi-static lesions such as those in stroke that cannot be detected using fdEIT or aEIT.
The layout of this paper is as follows. Section 2 introduces sdEIT by illustrating the steps involved in applying the modality to a simple numerical head model. Then, Section 3 presents application of the technique to anatomically accurate FEMs, with a variety of lesions of different sizes, locations, and types. These test scenarios demonstrate the value of using the robust quantitative metrics along with images. The performance of sdEIT is also examined in noisy scenarios, and when the FEMs are inaccurate. Next, Section 4 details the experimental validation of sdEIT with tank measurements. These tank experiments feature a model of brain tissue with dielectrically accurate haemorrhagic and ischaemic phantoms of differing sizes placed in various locations. Section 5 highlights the significance and limitations of this new modality for EIT; while Section 6 concludes the paper.

2. INTRODUCTION TO SYMMETRY DIFFERENCE EIT

In this section, sdEIT is introduced through a basic example of a large lesion far from the line of symmetry using a simple head model with no added noise. This example is meant to guide the reader through introduction and application of sdEIT. Numerical modelling and simulations were largely performed using MATLAB [8] with the EIDORS open source software package [9], with other packages noted where relevant.

The sdEIT technique involves use of a precise electrode layout, followed by two post-processing steps, each of which are described over three subsections in this section, directly after a description of the simple numerical model.

2.1 Simplified Numerical Head Model

A simplified numerical model of the human head was created using the meshing tool Netgen [10] in conjunction with EIDORS [11]. The model is based on two concentric spheres, the outer of diameter 160 mm which approximates the diameter of the head [12], and the inner placed at a depth of 10 mm, an average scalp-cortex distance [13]. The resulting outer layer was modelled as an aggregate of all tissues external to the brain while the inner layer was modelled as an aggregate of the tissues comprising the brain. Based on previous work, electrical conductivity values of 0.1 S/m and 0.3 S/m were assigned to the outer and brain layers respectively [7]. Spherical target lesions, modelling haemorrhage and ischaemia, were also meshed in Netgen for placement in the brain layer. The conductivity was set at 0.7 S/m for haemorrhagic lesions and at 0.1 S/m for ischaemic lesions [14]. In this initial study, a single haemorrhagic target replicating a 30 ml lesion was placed far from the line of symmetry. The choice of 30 ml was based on research indicating that an intracerebral haemorrhage of volume at or above 30 ml is an indicator of increased mortality [15].

Next, a ring of 16 electrodes was placed around the model at a height approximately half way between the apex and base of the outer hemisphere. The electrodes were placed symmetrically across the sagittal plane, which is the natural line of symmetry for the head. The electrodes were modelled as having a diameter of 12 mm, which is a typical commercially available size EEG electrode [16].

The “normal” model of the head, lacking lesions, was used to generate an inverse model using the GREIT algorithm [17]. Although designed for use in lung applications of EIT, the GREIT approach worked well in this initial development study of sdEIT and was chosen in part due to the extensive information on it provided on the EIDORS website [18]. The stimulation and measurement protocol used, based on empirical results, was a pair drive with a “skip 2” pattern [4]. The simplified numerical model is shown as part of Fig. 1.

2.2 Electrode Layout for sdEIT
In sdEIT, two measurement frames, from rings of electrodes in different orientations, are
differenced to generate an image. The electrodes are arranged around a plane of symmetry such
that in a 16 electrode ring, electrode #1 is the symmetric partner of #16, #2 partnered with #15,
and so on. In one frame the electrode stimulation and measurement pattern run in a clockwise
orientation while in the next the pattern is run counter-clockwise. The setup of the clockwise
and counter-clockwise orientations of the single electrode ring is shown in Fig. 1. The layout
ensures that the scene observed by a given channel is the same in either the clockwise or
counter-clockwise case with the measurement vectors produced from the two orientations the
mirror image of each other across a plane of symmetry. This layout enables the measurements
recorded between these symmetric partner channels to be compared. This comparison assumes
that the setup for each electrode and its partner is the same, i.e., that the electrodes are identical
in every way and the region they observe is effectively the same. This set of assumptions may
not be valid in more challenging test cases but are an acceptable simplification for this initial
simple proof of concept work.

If there is no abnormality in the region of interest, then a difference image produced from
differencing the two measurement vectors should be theoretically empty. The case of a
haemorrhagic lesion on the right-hand side, in the plane of the electrodes, is shown in the
middle illustration of Fig. 1. It is noted that the lesion is near to electrode #4 in the clockwise
setup and near electrode #13 in the counter-clockwise orientation. The first part of sdEIT is to
detect this lesion, present as a mismatch in the two measurement vectors.

![Fig. 1. Left: Symmetry Difference EIT electrode layout on a numerical model of the head (transparent) and brain (burgundy)
where the natural plane of symmetry, the sagittal plane, is shown as a green dashed line. The view is from the top down with
front, left (L) and right (R) sides of the head marked. The clockwise electrode orientation (red numbered electrodes) and
counter-clockwise electrode orientation (green numbered electrodes) are shown. Centre: A spherical haemorrhagic lesion
inside the (now transparent) brain layer. The lesion is near to the clockwise orientation electrode #4, which is the same as
counter-clockwise orientation electrode #13. Right: The stimulation/measurement pattern of a sample channel. The injection
pair is shown in light colour, while the measurement pair is in a heavier tone. The clockwise orientation channel is in red while
the corresponding counter-clockwise orientation channel is in green. The two respective channels are symmetric partners.

2.3 Step 1: Detection of Deviation from Normal Symmetry & Related Quantitative Metrics

A 30 ml simulated haemorrhage sphere is positioned close to clockwise electrode #4
(counter-clockwise electrode #13). Measurement vectors from the counter-clockwise (taken as
the reference) and clockwise (taken as the update) orientations are produced. The GREIT
inverse model is used to reconstruct a difference image from the vectors. This image is rendered
as a slice through the electrode plane and is shown in Fig. 2. A symmetrical image is produced
with a red (conducting) lesion seen near electrode 4 as expected, but also the opposite, blue
(non-conducting) lesion seen near electrode 13. Hence the symmetry difference image shows
either a haemorrhage near electrode #4 or an “anti-haemorrhage” near electrode #13. Fig. 2
also shows a surface plot of the symmetry difference image. The surface plot shows the intensity of the differences in the z-axis (arbitrary units).

![Surface plot of the symmetry difference image. The z-axis of the surface plot shows the intensity values of the differences detected (arbitrary units).](image)

Fig. 2. Left: Symmetry difference image showing a conductive target near electrode #4 and a non-conductive target near electrode #13. Right: Surface plot of the symmetry difference image. The z-axis of the surface plot shows the intensity values of the differences detected (arbitrary units). It is noticed that the topology is dominated by the symmetrical peak and trough caused by the presence of the lesion.

To quantitatively assess the symmetry difference image, thresholding is performed to create a binary image with the top and bottom 10% of pixels by intensity assigned as ‘1’ and all others ‘0’. Thresholding is performed to focus the extreme regions of difference which is where any potential lesion will be. The quantitative metric of percentage symmetry (PS) is applied to the image, defined as:

- **Percentage Symmetry**: With the midline as the symmetrical border, the left (LHS) and right hand side (RHS) pixels labelled ‘1’ have their locations compared to each other relative to the border. If every pixel on the LHS has a corresponding pixel on the RHS, the score is 1, indicating perfect symmetry. If no pixels on one side have a partner in the same location on the other side, then the image is perfectly asymmetric with a score of -1.

 Ideally, the symmetry difference image, with a lesion present, would give a high PS (near 1). In this example, the PS score was 0.85. If the PS score is low then sdEIT should be deemed incapable of detecting a lesion in that particular case.

The percentage symmetry is also low if there is, in fact, no lesion present. A symmetry difference image and surface plot of a scene with no lesion present, which should ideally have no difference, is found to produce an image with differences, as seen in Fig. 3. However, the surface plot of the normal is effectively low-magnitude noise, and demonstrates poor symmetry (PS = 0.14). In the case of a true lesion, as seen in Fig. 2, a peak and symmetric trough pair dominate the topology, giving a percentage symmetry score approaching 1 with the magnitude of the differences being dramatically larger than in the normal case. Theoretically the normal image should be empty (i.e., noise-free and constant zero magnitude) but in practice this is not achievable due to the inevitable presence of noise from imperfect modelling and software. The FEM models are imperfect. A higher resolution model reduces these imperfections but increases computational time. In the case of the anatomically accurate head and brain models described later, the assumption of symmetry is an approximation. However, this assumption will be an inevitable source of noise. The electrode modelling is imperfect with the size, shape and location of the electrodes limited by the resolution of the FEM. Finally, the inability of the
software to create infinitely precise measurements for the clockwise and counter-clockwise electrode layouts is also an unavoidable source of noise. Despite these deviations from the ideal scenario, the normal case is clearly differentiable from the case in which a lesion is present, both from examination of the image itself and the PS metric.

![Symmetry Difference Image](image)

Fig. 3. Symmetry Difference Image of the normal case (no lesion present) is shown on the left with a surface plot of the 64 x 64 grid shown on the right. The z-axis of the surface plot shows the intensity values of the differences detected (arbitrary units). The topology is chaotic and of low intensity as compared to the case where a lesion is present and dominates the topology, as shown in the surface plot in Fig. 2. The percentage symmetry metric of 0.14 in the normal case suggests that a lesion is not likely to be present.

It is noteworthy that, in the lesion case, the anti-haemorrhage detected is not the same as an ischaemic sphere of the same size as the haemorrhagic sphere, since a greater contrast exists between the background brain parenchyma electrical conductivity (0.3 S/m) and haemorrhage (0.7 S/m) than exists between the former and an ischaemic lesion (0.1 S/m). Hence the magnitude of the red and opposite blue regions produced on the images are greater for the case of a haemorrhage than would be the case for an equivalent ischaemic lesion. However, this cannot be used to disambiguate and correctly identify the lesion as being a haemorrhage. A larger ischaemic sphere could also have produced this same result, with the increase in lesion size compensating for the lower contrast. Hence, another approach is required to disambiguate the true lesion as being a haemorrhage or a larger (relative to the haemorrhage) ischaemic lesion. This comprises step 2 of the sdEIT technique.

2.4 Step 2: Disambiguation & Related Quantitative Metrics

Step 2 involves creating an approximate measurement vector of the normal head from a model developed from *a priori* information along with a measurement vector taken with the lesion present. This approximate vector is used to generate a “pseudo normal difference image”, i.e., an artificially fabricated time difference image of the lesion relative to the normal. This artificial construction of a normal measurement vector is needed since a true normal measurement vector in stroke patients is rarely available. The image produced from this step will not be perfect, but is sufficient, when used in conjunction with the symmetry difference image from the previous section along with quantitative metrics, to disambiguate the lesion type and location.

First, a forward model of the normal head is produced as accurately as possible using *a priori* information, which is trivial in this case as the computer model of the head and brain are known exactly. In a real case, a patient specific mesh is required for better reconstructions [19], [20]; but recent work suggests a generic mesh maybe sufficient for good reconstruction in applications such as stroke [21]. A measurement vector from this *a priori* model with the
electrodes in the clockwise orientation can be produced to approximate the normal case, and used with the clockwise measurement vector with the lesion present to produce a simple difference image. This image should detect the location and nature of the lesion if the model used to generate the normal was sufficiently accurate.

However, in order to generate a high quality normal vector frame, it is found that the accuracy must be very high in terms of anatomy and assigned conductivity. In more realistic cases this may be not possible. As the clockwise measurement vector with the lesion present is largely normal except for the presence of a lesion, the normal measurement vector can be scaled using the measurement vector with the lesion present to result in a more robust normal measurement vector. The scaling technique borrows from that used in fdEIT [22]. Hence, the normal measurement vector (\(v_{\text{normal}}\)) is adjusted by scaling its values according to the curve of best fit between \(v_{\text{normal}}\) and the clockwise measurement vector (\(v_{\text{lesion}}\)).

Then, the pseudo normal difference image is generated using the scaled \(v_{\text{normal}}\) and \(v_{\text{lesion}}\) as input data. ROIs, as described in the previous section, are generated, and compared to those from the symmetry difference image. The true lesion is a haemorrhage, which should be commonly located in both images. The confounding regions will not be the same in both images due to the difference in how the images were produced. The resulting images are shown in Fig. 4. Three quantitative metrics are applied to the high and low intensity ROIs from both images:

- **Centroid Difference (CD):** The centroid (centre of gravity) of the ROIs on each image is calculated, then the Euclidian distance between them determined. This distance is measured in pixels, with each image being a 64 x 64 square pixel grid. If the ROIs from the two images are similar than this distance should be small, ideally 0.

- **F1 score:** This metric measures the accuracy of the image and represents the harmonic mean of precision and recall [23], [24]. The ROIs from the pseudo normal difference image are taken as the expected pixels and the symmetry difference image result the actual. The F1 score ranges from 0 – 1. If ROIs from the two images are similar than the F1 score should approach 1, if dissimilar the result will be close to 0.

- **Mean Intensity Difference (MID):** The mean intensity of the pixels in the respective ROIs are calculated. The difference between them is divided by the mean intensity in the pseudo normal difference image to normalise the result from 0 – 1, where 0 indicates the mean intensities are identical. The mean intensity difference is ideally 0 for the true target and 1 for the false target.

These metrics complement visual analysis of the images and objectively help identify the true target. The metrics should be considered collectively when deciding on the lesion type. The results of this simple head model case are listed in Table 1. As can be seen from Table 1, it is probable that the high intensity ROIs in the two images (from Fig. 4) match, while the low intensity ROIs do not have any similarity. Hence, in this case, the decision based on these metrics is that the high intensity ROI, i.e. the conductive lesion near electrode #4, is the true target, which is correct.
Fig. 4. Thresholded images where the top and bottom 10% (by intensity) of pixels are kept. The intensities are mapped to a 0 – 256 scale which is also shown next to the figures. Left: Symmetry difference image thresholded. From this the potential targets of a conductive target near electrode #4 or non-conductive target near electrode #13 are isolated. Right: Pseudo normal difference image. The largest high intensity and low intensity regions of interest in both images are compared quantitatively to assess if the high conductivity or low conductivity targets match. It is evident that the true lesion is the high intensity target near electrode #4.

Table 1. Results of the Quantitative Metrics applied to the top (high intensity) and bottom (low intensity) regions of interest compared from the two images.

<table>
<thead>
<tr>
<th>Metric</th>
<th>High Intensity ROI Analysis</th>
<th>Low Intensity ROI Analysis</th>
<th>Ideal Match for True Target</th>
<th>Ideal Result for False Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centroid Difference</td>
<td>2.25 pixels</td>
<td>15.5 pixels</td>
<td>0.0 pixels</td>
<td>&gt;&gt; 0 pixels</td>
</tr>
<tr>
<td>F1 Score</td>
<td>0.84</td>
<td>0.07</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Mean Intensity Difference</td>
<td>0.05</td>
<td>0.67</td>
<td>0.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

3. MORE COMPLEX SIMULATIONS AND TEST CASES

In this section, sdEIT is applied to a comprehensive set of test cases. An anatomically accurate computer generated finite element model (FEM) of the head and brain is developed, with spherical lesions of 4 different sizes placed in 5 different locations using 5 different levels of simulated noise. These experiments are representative examples to demonstrate where the technique works best and where it breaks down. The ‘result’ of sdEIT comprises the two images (symmetry difference and pseudo normal difference) as well as the metrics, with all considered in reaching an outcome. However, the metrics alone give a robust summary of the result, and therefore in most of the results reported only metrics are reported for brevity.

3.1 Numerical Model

An anatomically accurate head model was developed from stereolithography (STL) files of a human head [25] and brain [26]. The STL files were orientated using Blender [27] before being imported into EIDORS and meshed into a FEM using Netgen [10] and Gmsh [28]. When creating the FEM, a ring of 16 electrodes were placed on the surface symmetrically across the sagittal plane, with the mesh refined in the area of the electrodes [29]. The electrodes could be assigned in either clockwise or counter-clockwise orientation when taking measurements. The final FEM comprised 263,000 elements in a 2-layer model, with this number of elements being a compromise between level of refinement and computation time. As this study is intended as initial proof of concept work, the numerical model was kept relatively simple, as a 2-layer model with the outer layer an aggregate of scalp, skull and the cerebrospinal fluid layer of the meninges, and the inner layer an aggregate of the tissues of the brain. However, this simplification should not affect the underlying thrust of the symmetrical comparison, as the technique can be applied to any symmetric region regardless of number of layers or heterogeneities. The outer elements were assigned a conductivity value of 0.1 S/m with the brain elements assigned as 0.3 S/m as explained in Section 2 above [7]. The model is shown in Fig. 5.

Spherical lesions of volume 2 ml, 10 ml, 20 ml and 30 ml were created as STL files in Blender. These volumes were chosen to replicate volumes typically seen in intracerebral haemorrhage where a median volume of 10 ml and mean of 17 ml is typical [30], while a volume of 30 ml is often the threshold before the prognosis deteriorates [15]. The selection of a sphere as the shape is a simplification; intracerebral haemorrhages for example may be more ellipsoidal [31]. The lesions were assigned conductivity values of 0.7 S/m when mimicking
haemorrhage [7] and 0.1 S/m when mimicking an ischaemic lesion [14]. The spherical lesions were positioned in five unique locations within the brain layer, in the plane of the electrode ring: (1) near electrode #4 (electrode #13 on counter-clockwise orientation); (2) far from electrode #4 (electrode #13 on counter-clockwise orientation); (3) near electrode #8 (electrode #9 on counter-clockwise orientation); (4) far from electrode #8 (electrode #9 on counter-clockwise orientation); (5) midway from the sagittal plane and electrode #13 (electrode #4 on counter-clockwise orientation). A sample of these lesions demonstrating the sizes and locations are shown in Fig. 5. Further, in the subsequent results sections locations of lesions are with reference to Fig. 5.

Symmetry difference imaging is expected to perform best far from the plane of symmetry. A lesion near to or on the plane of symmetry would result in similar clockwise and counter-clockwise measurement sets since the two orientations overlap upon the plane. Such a lesion would hence be harder to detect. Therefore, position (1) was expected to be the easiest lesion location to detect, with (4) being the most challenging. Further it was expected that larger lesions would be easier to robustly detect. Haemorrhagic lesions, since the contrast between blood and brain is greater than that between ischaemia and brain, were also thought to be easier to identify. The choice of this set of scenarios allows all these hypotheses be tested at different simulated noise levels: no noise, 10 dB SNR, 20 dB SNR, 40 dB SNR and 80 dB SNR. The next section reports performance of sdEIT in these scenarios.

3.2 Numerical Results & Discussion

Scenario 1: Small Lesion versus Large Lesion

Table 2 reports the metrics from the separate cases of a 2 ml and 20 ml haemorrhage positioned at (5), at 40 dB SNR. Both lesions are strongly detected in the symmetry difference image as indicated by the positive PS scores of 0.92 and 0.48 for the 20 ml and 10 ml lesions, respectively. The disambiguation metrics, calculated from comparison of the symmetry difference image and the pseudo normal difference image, strongly favour the high intensity
ROI (haemorrhage) in both cases, with the CD, F1 score, and MID much closer to the expected case for a true match (near 0.0, 1.0 and 0.0 respectively) as compared to the low intensity ROI analysis.

Table 2. sdEIT Quantitative Metrics for the separate cases of a 2 ml and 20 ml haemorrhage positioned at (5) at 40 dB SNR.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Case 1: 2 ml Haemorrhage</th>
<th>Case 2: 20 ml Haemorrhage</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) PS</td>
<td>0.48</td>
<td>0.92</td>
</tr>
<tr>
<td>(ii) Disambiguation Metrics</td>
<td>High Intensity</td>
<td>Low Intensity</td>
</tr>
<tr>
<td>CD</td>
<td>2.4 pixels</td>
<td>24.5 pixels</td>
</tr>
<tr>
<td>F1 Score</td>
<td>0.84</td>
<td>0.0</td>
</tr>
<tr>
<td>MID</td>
<td>0.03</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Scenario 2: Near Exterior Lesion versus Near Midline Lesion

In Table 3, the results of a 10 ml haemorrhagic lesion placed at position (1), near the exterior, and at position (4), near the midline, are presented. Both cases had an SNR of 20 dB. For the lesion near the exterior the PS is high (0.56) and the disambiguation metrics clearly identify the high intensity (red) ROI as the true lesion. When the lesion is near the midline, however, the percentage symmetry is -0.29 which indicates the inability of the method to detect a lesion. The analysis should be terminated at this point, but the disambiguation step, if also applied, fails also, with no clear difference in the metrics from either the high or low ROI. This example demonstrates the challenge in detecting lesions near the line of symmetry.

Table 3. sdEIT Quantitative Metrics for the separate cases of a 10 ml haemorrhage at 20 dB SNR positioned at (1), near the exterior, or at (4), near the midline.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Case 1: Near Exterior</th>
<th>Case 2: Near Midline</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) PS</td>
<td>0.56</td>
<td>-0.29</td>
</tr>
<tr>
<td>(ii) Disambiguation Metrics</td>
<td>High Intensity</td>
<td>Low Intensity</td>
</tr>
<tr>
<td>CD</td>
<td>2.3 pixels</td>
<td>26.5 pixels</td>
</tr>
<tr>
<td>F1 Score</td>
<td>0.86</td>
<td>0.0</td>
</tr>
<tr>
<td>MID</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Scenario 3: Haemorrhagic Lesion versus Ischaemic Lesion

The contrast between brain (0.3 S/m) and an ischaemic lesion (0.1 S/m) is less than that between brain and haemorrhage (0.7 S/m), implying a haemorrhagic lesion should be more readily detectable than the equivalent ischaemic lesion. In Table 4, the sdEIT metrics for a 20 ml lesion of each type positioned at (5) with 40 dB SNR, are presented. The results show that the true lesion is equally well detected in both cases, with the high ROI being favoured in the case of the haemorrhage and the low ROI being favoured for the ischaemic case.

Table 4. sdEIT Quantitative Metrics for the separate cases of a 20 ml lesion at 40 dB SNR positioned at (5), modelled as either a haemorrhage or an ischaemic lesion.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Case 1: Haemorrhage</th>
<th>Case 2: Ischaemia</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) PS</td>
<td>0.91</td>
<td>0.78</td>
</tr>
</tbody>
</table>
Surface plots of the symmetry difference image are shown in Fig. 6. These plots demonstrate that the haemorrhagic lesion results in a greater peak and trough than that produced by the ischaemic lesion, which is expected since there is a greater contrast for a hemorrhage with respect to the brain. It follows that a haemorrhage will be more readily detected than an ischaemia when approaching the limit of detection for the method (smaller lesion size, increased distance from the exterior, low SNR). This is demonstrated by considering the metrics from the case of a 10 ml haemorrhagic lesion at position (1) at 20 dB SNR as shown in Table 3, and the equivalent ischaemic lesion at position (3), also near the exterior, at 20 dB SNR as shown in Table 5. The haemorrhage is detectable and differentiable, but for the ischaemic lesion both detection and differentiation are just possible, with the metrics demonstrating the difficulty in doing so.

![Surface plots of the Symmetry Difference images resulting from a haemorrhagic lesion (left) and ischaemic lesion (right) both of 20 ml, located at position (5) with 40 dB SNR. The magnitude of the peak and trough corresponding to the haemorrhage and anti-haemorrhage lesion is 1669 (arbitrary units), while for the ischaemic lesion this value is 1372 (arbitrary units). Hence the haemorrhagic lesion is easier to detect, however, the ischaemic lesion is still detectable.](image)

**Scenario 4: Variations in SNR**

Decreasing the SNR increases the noise in the measurement vectors, and thus may decrease the performance in sDEIT. This expectation is confirmed in Table 5, with results shown for a 10 ml ischaemic lesion placed at position (3) under conditions of 80 dB SNR, 20 dB SNR and 10 dB SNR. At 80 dB SNR, the lesion is clearly detected and disambiguated. The PS is high with disambiguation metrics showing a clear bias towards the low intensity ROI (the low CD and high F1 scores are much closer to the ideal of 0 pixels and 1.0 respectively than the corresponding metrics from the high intensity ROI analysis). In this case, the MID results are practically the same for both rendering the metric of no value. It is emphasised that the metrics should be considered collectively when deciding on the result (ideally along with a visual analysis of the images). Hence the failure of one metric should not lead to a conclusion that disambiguation is not possible: good contrast in the F1 metric should lead to a decision in favour of the low intensity ROI being the true lesion.

At 20 dB SNR the lesion is barely detectable. The PS of 0.03 indicates this is likely a case on the limit of detection. The subsequent disambiguation metrics show a slight favouring of the low intensity ROI, as evidenced by the marginally higher F1 score for the low intensity lesion. However, it is suggested that this case be classified as inconclusive, due to the low PS.
score and marginal difference in F1 scores. At 10 dB SNR, the lesion is not detectable at all. The percentage symmetry of -0.42 indicates extremely poor symmetry, confirming that detection of the lesion in this scenario is beyond the limits of sdEIT.

Typical existing EIT systems report SNR values typically of the order 80 dB and above [32]. Indeed, a system developed specifically for use in EIT in neurological applications including lesion diagnosis in stroke reported a SNR of 77.5 dB [32]. The strong performance of sdEIT at both 80 dB and 40 dB indicates that the modality be promising for use in real world experiments.

Table 5. sdEIT Quantitative Metrics for the separate cases of a 10 ml ischaemic lesion at position (3) at 80 dB, 20 dB and 10 dB SNR

<table>
<thead>
<tr>
<th>Metric</th>
<th>Case 1: 80 dB SNR</th>
<th>Case 2: 20 dB SNR</th>
<th>Case 3: 10 dB SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) PS</td>
<td>0.83</td>
<td>0.03</td>
<td>-0.42</td>
</tr>
<tr>
<td>(ii) Disambiguation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metrics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td>13.1 pixels</td>
<td>6.2 pixels</td>
<td>13.1 pixels</td>
</tr>
<tr>
<td>F1 Score</td>
<td>0.18</td>
<td>0.63</td>
<td>0.38</td>
</tr>
<tr>
<td>MID</td>
<td>0.24</td>
<td>0.20</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Scenario 5: Non-ideal Modelling in Creation of the Simulated Normal

Creation of a good forward model of the normal, lesion free head is the first part of step 2 of sdEIT. As EIT is inherently sensitive to modelling errors, there is a need to keep the forward model of high quality. This section investigates the effect of non-ideal models using the case of a 20 ml haemorrhagic lesion, with no noise, at position (5).

Table 6 reports the sdEIT results, in the first row for the ideal forward model, and in following rows for non-ideal models. As Step 1 of the sdEIT process does not require use of the forward model of the normal head, the resulting PS metric has the same value for both ideal and non-ideal models. In the second row case, a grossly asymmetric brain is used, in the third row case the brain is symmetric but reduced in volume by 10%. In the fourth row case, the outer layer conductivity is set to 1 S/m and the brain set to 3 S/m, while in the fifth row case the outer is set to 2 S/m with the brain set to 4 S/m. The correct conductivity values modelled for the outer layer is 0.1 S/m and that of the brain layer is 0.3 S/m. Hence, in the case of the fourth row, the values are incorrect, but the ratio is correct; while in the fifth row case both the values and ratio of conductivity are incorrect. It is seen from analysis of the results reported in Table 6 that having good a priori information to construct a forward model in terms of anatomical detail (in this case a two-layer model) and ratio of conductivities between the layers is vital to achieving clear disambiguation between ischaemic and haemorrhagic targets. Poor anatomical detail appears to affect the results more than incorrect ratio of conductivities.
Table 6. sdEIT Quantitative Metrics and pseudo normal difference image for various forward models. In all cases the scenario is that of a 20 ml haemorrhage. The first row shows the complete sdEIT result with the ideal forward model. Subsequent rows only show the output from step 2 (the output of step 1 will be the same as in the first row), for various non-ideal forward models.

<table>
<thead>
<tr>
<th>Metric:</th>
<th>Case 1: Ideal Forward Model</th>
<th>Symmetry Difference Image</th>
<th>Pseudo Normal Diff. Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) PS</td>
<td>0.88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(ii) Disambiguation Metrics</td>
<td>High Intensity ROI Analysis</td>
<td>Low Intensity ROI Analysis</td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td>0.5 pixels</td>
<td>17.4 pixels</td>
<td></td>
</tr>
<tr>
<td>F1 Score</td>
<td>0.93</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>MID</td>
<td>0.01</td>
<td>0.57</td>
<td></td>
</tr>
</tbody>
</table>

Case 2: Grossly Asymmetric Brain

<table>
<thead>
<tr>
<th>Disambiguation Metrics</th>
<th>High Intensity ROI Analysis</th>
<th>Low Intensity ROI Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>7.0 pixels</td>
<td>10.9 pixels</td>
</tr>
<tr>
<td>F1 Score</td>
<td>0.59</td>
<td>0.31</td>
</tr>
<tr>
<td>MID</td>
<td>0.19</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Case 3: Brain shrunk in volume by 10 %

<table>
<thead>
<tr>
<th>Disambiguation Metrics</th>
<th>High Intensity ROI Analysis</th>
<th>Low Intensity ROI Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>8.5 pixels</td>
<td>9.6 pixels</td>
</tr>
<tr>
<td>F1 Score</td>
<td>0.48</td>
<td>0.42</td>
</tr>
<tr>
<td>MID</td>
<td>0.49</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Case 4: Correct Brain, Incorrect Conductivities but Correct Ratio

<table>
<thead>
<tr>
<th>Disambiguation Metrics</th>
<th>High Intensity ROI Analysis</th>
<th>Low Intensity ROI Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>1.8 pixels</td>
<td>11.5 pixels</td>
</tr>
<tr>
<td>F1 Score</td>
<td>0.89</td>
<td>0.37</td>
</tr>
<tr>
<td>MID</td>
<td>0.0</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Case 5: Correct Brain, Incorrect Conductivities and Incorrect Ratio

<table>
<thead>
<tr>
<th>Disambiguation Metrics</th>
<th>High Intensity ROI Analysis</th>
<th>Low Intensity ROI Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>CD</td>
<td>7.1 pixels</td>
<td>17.9 pixels</td>
</tr>
<tr>
<td>F1 Score</td>
<td>0.62</td>
<td>0.0</td>
</tr>
<tr>
<td>MID</td>
<td>0.19</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Scenario 6: Challenging Lesion Models

In this section, the performance of sdEIT is assessed in two additional cases: that of a lesion out of the plane of the electrode ring and that of multiple simultaneous lesions.

In Table 7, the metrics for the case of a 20 ml haemorrhage at position (5) but raised out of the plane in the ‘z’ axis is shown for 80 dB SNR. The lesion is readily detected with sdEIT. Although the easiest detection scenario occurs when the lesion is in the electrode plane, a lesion out of the plane can still affect measurements. Any theoretical device based on a ring pattern of electrodes could be envisioned as consisting of a series of rings, at different levels in the ‘z’
axis. Such a device, by conducting readings at each level should result in any lesion present being in at least one of the planes under study, and hence maximally detected.

Furthermore, it is possible that multiple lesions could be present simultaneously. The clinical condition used to motivate this study, stroke, does sometimes feature multiple lesions both in haemorrhagic and ischaemic cases [33], [34]. Table 7 reports the metrics from the case of two haemorrhagic lesions, 10 ml at position (1) and 20 ml at position (5) at 80 dB SNR. The larger of the lesions is detected by sdEIT, as expected, since the algorithm employs thresholds to isolate the extreme intensity regions of interest. Therefore, in the metrics the high intensity ROI is favoured.

Table 7. sdEIT Quantitative Metrics for the two challenging lesion cases: Lesion out of the electrode plane and multiple simultaneous lesions.

<table>
<thead>
<tr>
<th>Metric</th>
<th>Case 1: 20 ml Haemorrhage at Position (5) but Raised out of Electrode Plane.</th>
<th>Case 2: Two Haemorrhagic Lesions: 10 ml at position (1), 20 ml at position (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) PS</td>
<td>0.91</td>
<td>0.90</td>
</tr>
<tr>
<td>(ii) Disambiguation Metrics</td>
<td>High Intensity ROI Analysis</td>
<td>Low Intensity ROI Analysis</td>
</tr>
<tr>
<td>CD</td>
<td>1.5 pixels</td>
<td>6.8 pixels</td>
</tr>
<tr>
<td>F1 Score</td>
<td>0.88</td>
<td>0.37</td>
</tr>
<tr>
<td>MID</td>
<td>0.0</td>
<td>0.64</td>
</tr>
</tbody>
</table>

4. TANK EXPERIMENTS

This section reports the experimental implementation of sdEIT in a saline filled tank model used to emulate the brain, with phantom haemorrhagic and ischaemic lesions.

4.1 Experimental Setup

A cylindrical Perspex tank of diameter 250 mm with 32 bolts equidistant and embedded in the tank wall was used. Only the odd numbered bolts were used, giving a 16 member, evenly spaced ring. The Swisstom Pioneer [35] EIT device was used at a frequency of 100 kHz with a 0.5 mA peak to peak current. The choice of 16 electrodes was taken to match the setup of the computer simulations described above. The Swisstom Pioneer provides a 32 channel system, which was used to provide two co-located rings, one in clockwise orientation and the other counter-clockwise, with one electrode from each ring attached to each of the 16 bolts. Measurements could be taken in the usual way and relevant data for each ring extracted later in software.

Roughly spherical haemorrhagic and ischaemic phantom lesions scaled so as to correspond to volumes of 2 ml, 10 ml and 30 ml in an actual brain were made from a solid tissue mimicking material as described in [7]. The haemorrhagic lesions were of conductivity 0.7 S/m and the ischaemic lesions of conductivity 0.1 S/m at 100 kHz [7]. In addition, cuboid shapes (2 cm x 2 cm x 5 cm) of the two phantom types were produced for initial testing of the material and the tank setup. The tank was filled to a depth to completely submerge the electrodes with saline of concentration 0.03 M, which had a conductivity of approximately 0.3 S/m at 100 kHz; thus emulating an aggregate of brain tissues [36]. Each spherical lesion was sequentially placed in the five positions used in the numerical simulations described above in Section 3. For each lesion in each position, 40 s of data was recorded, and the middle 30 s of this data was analysed using the symmetry difference imaging technique. Photos of the setup are shown in Fig. 7, which shows the tank and electrode bolts with co-located red (clockwise) electrodes and black
(counter-clockwise) electrodes. Fig. 7 also shows some of the spherical phantoms as well as cuboid test phantoms and the technique used to position the phantoms in the tank. With symmetry difference imaging, a direct symmetry comparison is made between the left- and right-hand sides of the tank.

![Tank experimental setup. Top left: Tank filled with saline and the two electrode rings (red, clockwise, odd numbered and black, counter-clockwise, even numbered) co-located on the wingnuts of the bolts. Top right: Spherical phantoms used. These phantoms proportionally match 30 ml, 10 ml and 2 ml haemorrhages in a realistic-sized human brain. Bottom left: Wooden sticks are used to suspend a phantom at a fixed point in the tank with the aid of graph paper under the tank. Bottom right: Close up of a cuboid phantom next to bolt 7 (electrode #4 on the clockwise ring; electrode #13 on the counter-clockwise ring).](image)

### 4.2 Experimental Results & Discussion

#### Scenario 1: Small Lesion versus Large Lesion

In Table 8, the metrics for the 2 ml and 30 ml ischaemic lesion placed at the equivalent of position (5) in the tank are shown. The smaller lesion is not detectable, as evidenced by the negative PS score. The larger lesion is detectable as shown by strong PS score and subsequent disambiguation metrics favouring the low intensity ROI.

**Table 8.** sdEIT Quantitative Metrics for the separate cases of a 2 ml and 20 ml ischaemic lesion positioned at (5).

<table>
<thead>
<tr>
<th>Metric</th>
<th>Case 1: 2 ml Ischaemic Lesion</th>
<th>Case 2: 30 ml Ischaemic Lesion</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) PS</td>
<td>-0.39</td>
<td>0.86</td>
</tr>
<tr>
<td>(ii) Disambiguation Metrics</td>
<td>High Intensity ROI Analysis</td>
<td>Low Intensity ROI Analysis</td>
</tr>
<tr>
<td>CD</td>
<td>4.1 pixels</td>
<td>15.5 pixels</td>
</tr>
<tr>
<td>F1 Score</td>
<td>0.63</td>
<td>0.25</td>
</tr>
<tr>
<td>MID</td>
<td>0.07</td>
<td>0.07</td>
</tr>
</tbody>
</table>

#### Scenario 2: Near Exterior Lesion versus Near Midline Lesion

The cases of the 10 ml haemorrhagic lesion positioned near the exterior of the brain at (1), and far from the exterior but near the midline at position (4), are reported in Table 9. In both cases, the lesions are readily identifiable. However, the case at position (1) shows stronger results as demonstrated by the higher relative PS and the disambiguation metrics which heavily favour the high intensity ROI. The increasing distance of the lesion from the electrodes reduces...
the quality of the result, and lesions near the line of symmetry are not as readily detectable with this technique.

Table 9. sdEIT Quantitative Metrics for the separate cases of a 10 ml haemorrhagic lesion positioned at (1), near the exterior, or at (4), near the midline.

<table>
<thead>
<tr>
<th>Metric:</th>
<th>Case 1: Near Exterior</th>
<th>Case 2: Near Midline</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) PS</td>
<td>0.87</td>
<td>0.36</td>
</tr>
<tr>
<td>(ii) Disambiguation Metrics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CD</td>
<td>1.2 pixels</td>
<td>3.0 pixels</td>
</tr>
<tr>
<td></td>
<td>40.2 pixels</td>
<td>34.9 pixels</td>
</tr>
<tr>
<td>F1 Score</td>
<td>0.91</td>
<td>0.75</td>
</tr>
<tr>
<td>MID</td>
<td>0.0</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>0.48</td>
<td>0.52</td>
</tr>
</tbody>
</table>

To summarise, the sdEIT technique works successfully with experiments in the tank with the background medium representative of a homogenous brain and the targets emulating haemorrhagic and ischaemic stroke lesions. The experimental results also confirm those of the simulation and suggest that sdEIT has promise for real-world applications.

5. DISCUSSION

Clinical scenarios that are not time variant have few options for imaging with EIT. Absolute EIT and frequency difference EIT both show promise but have challenges to overcome. This paper proposes another EIT modality to tackle these difficult imaging problems. Symmetry difference EIT (sdEIT) has the potential to develop into a stand-alone technique or as support tool for time static cases. This work comprehensively introduces the technique, describing its implementation and performance in a representative set of numerical models and tank experiments using the stroke clinical model as a vehicle. Essentially, the proposed technique comprises of both producing a symmetry difference image and a pseudo normal difference image, along with associated metrics. By considering all images and metrics together, a confident decision can be made as to whether there is a lesion present or not, along with the nature and location of the lesion if present.

The symmetry difference image alone, if it returns a low Percentage Symmetry score, provides enough information to indicate that no decision can be made with the technique. However, if it returns a high Percentage Symmetry score, then the issue with ambiguity is present – is it a haemorrhage or an ‘anti-haemorrhage’ at the symmetric location? Therefore, the pseudo normal difference image is needed to disambiguate between haemorrhage and ‘anti-haemorrhage’. On the other hand, the pseudo normal difference image alone may be sufficient if it returns a nice ‘clean’ image with one single region of interest (for example the pseudo normal difference image in the bottom row of Table 6). However, even in this case it does not make sense to neglect the information from the symmetry difference image which confirms this region of interest as a likely haemorrhagic lesion at this location. Further, in the case in the third row of Table 6, the pseudo normal difference image taken alone would imply the presence of an ischaemic lesion slightly to the left of centre, which is incorrect. When the corresponding symmetry difference image is also considered (as well as the metrics), the correct decision to make is that symmetry difference EIT fails in this case. Finally, the fourth of Table 6 shows a case where the pseudo normal difference image may be interpreted as indicating a haemorrhage near electrode 13 or an ischaemia near the midline. The symmetry difference image gives the confirmatory evidence of the haemorrhage as the correct lesion present. Hence the proposed technique is reliant on an aggregate approach, with the two images
needed to confirm the results of each other, both visually and quantitatively by the metrics used, to give a final result that a potential user would have confidence in.

This work provides a proof of concept for sdEIT evaluated on a variety of test cases. This study has illustrated cases where sdEIT is successful and cases where it is inconclusive. Better, more robust performance is seen for larger lesions, lesions near the exterior, lesions of higher conductivity contrast, situations where there is a higher SNR and also cases where the simulated normal is modelled well in terms of anatomy and conductivity profile.

It is recognised that there are limitations to the work so far, with many future challenges to overcome. Some of these challenges are now described, starting with study limitations (i.e., those relating to the model, and lesion types/locations), then finishing with those related to sdEIT specifically.

The numerical models are a 2-layer simplified head model and the tank experiments are based on a saline model of the brain. Future numerical and phantom work will necessitate more elaborate models, both in terms of geometry and tissue layers. For example, the scalp is a layer of low conductivity, while the skull acts to dampen current and the layer of cerebrospinal fluid immediately inside the skull shunts current away from the brain [1]. In this study, these three layers are aggregated into one ‘outer layer’ but division into the component parts, and the effect of this, is an important step to more realistic scenarios.

The disambiguation step requires an accurate model of the normal to be successful. It is recognised that creation of a perfect model may not be possible, with the scaling procedure described in section 2.4 designed to partially compensate for this. However, scenario 5 of section 3.2 illustrates that further work is needed to cope with imperfections particularly poor anatomical modelling and perhaps to a lesser extent incorrect conductivity profiling.

A fundamental part of sdEIT is the comparison between symmetrical partner channels from the clockwise and counter-clockwise orientation. In this work, these channels are designed to be as symmetrically equivalent as possible through the use of precise electrodes placement in both the simulation and tank models. More realistic cases will necessitate the need to move away from this ideal and model factors such as imperfect electrode placement and differing and unknown electrode contact impedance. These uncertainties will cause channels to deviate from the ideal. Issues which affect other modalities that attempt to image static scenes are then likely to be introduced [3], [4], [37].

An absolute limitation of sdEIT is that it can only be used in cases where the lesion(s) are unilateral and normally there is inherent symmetry in the region under study. In the case where the background is not normally symmetric, due to asymmetric inhomogeneities or other reasons, this technique should not be used.

6. CONCLUSION

EIT is a promising imaging technique with numerous potential biomedical applications. Many diagnostic situations require imaging of an area where there is no change in the region over a short time, such as in the case of cancer or in the case of stroke where there is a haemorrhagic or ischaemic lesion present. The EIT modalities currently available for use in these cases are limited to frequency difference EIT and absolute EIT. This paper has introduced a novel modality for use in such static or quasi-static scenarios, called symmetry difference EIT (sdEIT). This proposed technique can detect the presence of an abnormality where there is a natural line of symmetry in the region and has been shown to perform best where the abnormality upsetting the symmetry is both large and far from the plane of symmetry.

sdEIT is comprised of two key steps: (i) detection of deviation from normal symmetry and (ii) disambiguation, both of which result in images & metrics. The proposed technique is reliant on an aggregate approach, with the two images outputted from each step needed to confirm the
results of each other, both visually and quantitatively by the metrics used, to give a final result that a potential user would have confidence in.

In this work, we have demonstrated the application of sdEIT to stroke detection through a wide range of realistic numerical scenarios and an experimental tank model of the brain. The case study of stroke is particularly suited as an example for this technique, since the confounding mirror image lesion produced from the first step, from a conductivity point of view, for a haemorrhage is a region of ischaemia and vice-versa. In the example of stroke, the second disambiguation step is absolutely needed to clarify whether the lesion is truly a haemorrhage or an ischaemic area.

It is hoped that symmetry difference EIT will prove a valuable addition to the range of EIT modalities available and further the development of the technology. While this study has demonstrated the concept, in the future improvements can be made to each part of sdEIT (initial setup, modelling, image processing, quantitative metrics and so on) to develop the modality further. The modality could also be improved as a whole, through adding metrics or the application of machine learning.

ACKNOWLEDGMENTS

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