Chapter 6

Internal Electrode Sensitivity

This sensitivity analysis work has been presented in part at: the 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC 2020) (Stowe and Adler, 2020).

6.1 Introduction

Currently the most common implementations of EIT in biomedical applications measure voltages and inject currents from the body surface using one or two planes of electrodes. Internal electrodes are not used clinically despite promising simulation studies that have shown large improvements in reconstruction accuracy and internal sensitivity in 2D (Nasehi Tehrani *et al.*, 2012a; Nasehi Tehrani *et al.*, 2012b). In practice, EIT images with internal electrodes are challenging to interpret as the measurements are prone to significant differences due to probe positioning (Czaplik *et al.*, 2014).

As discussed in chapter 3, one of the main challenges in perfusion imaging is the large difference in amplitude between the ventilation and cardiac signals. When using external electrodes, the respiratory amplitude is significantly larger than the cardiac component. Techniques such as breath holds, induced apnoea (Leathard *et al.*, 1994; Stowe *et al.*, 2019), or injection of a contrast agent (Frerichs *et al.*, 2002) can reduce the impact of the respiratory signal, but they are not feasible for long-term or continuous monitoring. Other methods such as averaging a large number of signals together have been used (Eyüboğlu *et al.*, 1989; Vonk-Noordegraaf *et al.*, 1998), but as discussed by Deibele *et al.* (2008) these do not allow real-time monitoring and may miss sudden changes in perfusion that are of interest. Filtering techniques have been implemented to help isolate the cardiac component of the signal, but there is also occasionally overlap between the carsiosynchronous component and harmonics of the ventilation signal which makes signal separation more challenging (Leathard *et al.*, 1994; Zadehkoochak *et al.*, 1992).

Low sensitivity in central regions relative to the boundary limits the clinical applications of EIT, reducing the ability to accurately reconstruct and identify impedance changes due to the heart.

Internal electrodes have been proposed several times as a method to sustainably increase sensitivity in central regions of the chest and improve EIT reconstruction accuracy (Czaplik *et al.*, 2014; Nasehi Tehrani *et al.*, 2012b; Nguyen *et al.*, 2020; Pilkington *et al.*, 1989; Schuessler and Bates, 1995). Past research in 2D identified a sixfold increase in the cardiac frequency component of the EIT signal when 2 of 16 total electrodes were placed in the esophagus or trachea (Czaplik *et al.*, 2014).

It is not clear whether the identified increase in cardiac-frequency amplitude stems from pulsatile (motion-based), changes or whether these changes represent perfusion, however internal electrodes in 2D have been shown to increase sensitivity to these cardiosynchronous signals.

There is potential for clinical use of internal electrodes to monitor ventilation, perfusion and hemodynamic changes in the intensive-care unit (ICU), where patients typically have breathing and feeding tubes in place.

EIT applications in development include mechanical ventilation guidance and monitoring (Frerichs *et al.*, 2017), perfusion monitoring (Frerichs *et al.*, 2002; Smit *et al.*, 2003), blood pressure monitoring (Proença *et al.*, 2017; Solà *et al.*, 2011), and cardiovascular output (Braun *et al.*, 2018). For all of these uses of EIT, internal sensitivity in the centre of a model could provide increased accuracy. In an intensive-care environment where feeding and breathing tubes are used internal electrodes could provide several advantages without additional invasiveness. It has also been suggested that internal electrodes may replace electrodes on the back, which are challenging to place in critically ill patients that cannot be safely or easily moved (Czaplik *et al.*, 2014).

Especially while monitoring perfusion where the main challenge has been the small amplitude of the cardiac signal from the surface electrodes (Nguyen *et al.*, 2012), internal electrodes offer potential for significant improvement. This chapter presents a 3D EIT configuration with internal electrodes that can be used to maintain a high sensitivity in regions with large pulsatile components in the centre of a model. An electrode injection pattern to increase internal sensitivity is also compared to the standard measurement and injection pattern used in 3D.

The sensitivity benefits of internal electrode imaging in 3D are assessed in simulation to determine the feasibility of using internal electrodes to improve perfusion monitoring. This chapter provides proof of principle for internal electrode configurations in 3D to improve EIT sensitivity.

6.2 Methods

6.2.1 Tank model

To analyze the sensitivity changes due to different electrode configurations finite element models (FEMs) of a cylindrical tank were created with each of the tested electrode configurations. Figure 6.1 shows the four different configurations that were tested: a 2D electrode ring of 32 electrodes; a 3D configuration of 2 layers of 16 electrodes (3D(a)); a second 3D configuration of 2 layers of 15 electrodes plus 2 central internal electrodes inline with the electrode planes (3D(b)); and a final 3D configuration of 2 layers of 14 electrodes with 4 central internal electrodes evenly spaced between the electrode planes (3D(c)).

The tank in the simulations has a height of 2 m, radius of 1 m, and the electrode radius is 0.05 m for both the round external electrodes and the spherical internal electrodes. In the 3D configurations, the plane separation is 0.5 m and in all configurations the radial spacing between electrodes is equal. The background conductivity of the tank was 1 S/m and the conductivity of the target was 10 S/m.

When reconstructing images a conductive target was added to the tank centred

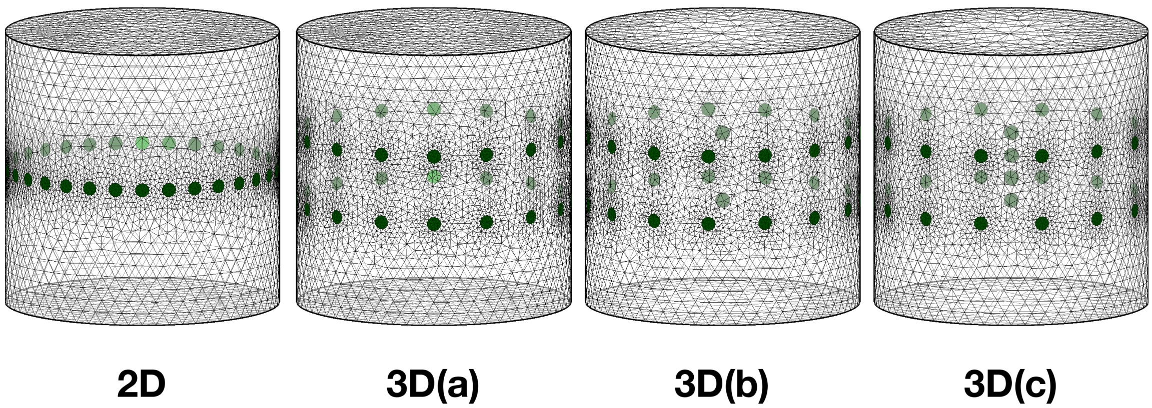

Figure 6.1: 4 configurations of electrodes were tested: 2D) a single ring of 32 electrodes; 3D(a) 2 rows of 16 external electrodes; 3D(b) 2 rows of 15 external electrodes with 2 internal electrodes; and 3D(c) 2 rows of 14 external electrodes and 4 internal electrodes.

at a height of 1 m at the midpoint of the tank radius. The target object radius is 0.4 m.

6.2.2 Image reconstruction

To generate EIT images from voltage measurements, the 3D GREIT reconstruction algorithm was used (Grychtol *et al.*, 2016). A spherical conductive target with a radius of 20 percent of the tank radius was placed midway between the centre and boundary of the tank, in a region with typically low sensitivity. The inverse problem hyperparameter was selected so that in all instances the amount of measurement noise that propagated from the measurements into the final images was equal.

6.2.3 Sensitivitiy calculation

The sensitivity is then calculated from the jacobian (J) of the reconstruction matrix as:

$$S = \frac{\sqrt{\sum_i \vec{J}_{ij}^2}}{V_i} \tag{6.1}$$

where V_i is the volume of each respective voxel.

6.2.4 Current injection and measurement

For this analysis external electrodes are placed in a “square” pattern (Grychtol *et al.*, 2016) and the internal electrodes are placed from top to bottom.

The current injection pattern used in this analysis was the typical “skip 4” injection pattern that has been shown to yield a good sensitivity distribution in 3D EIT (Grychtol *et al.*, 2016). A new stimulation and measurement pattern is also used in a model with two internal electrodes that increases the number of measurements on the internal probe. The stimulation pattern is consistent with the skip 4 pattern, but for the measurements alternating stimulations and measurements are replaced with measurements to the internal probe.

This results in the same number of measurements, but many more measurements use the internal probe. This new stimulation pattern is described in figure 6.2. All measurements are made between the top and bottom plane of electrodes.

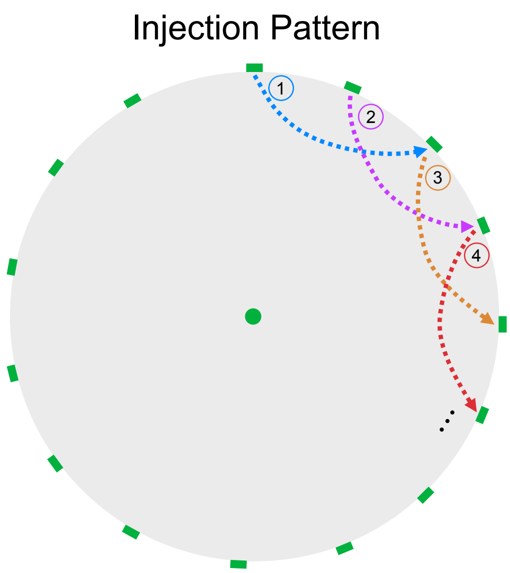

Figure 6.2: A proposed current injection and measurement pattern for EIT imaging with 2 internal electrodes. The injection pattern is a typical "skip 4 " pattern injecting between every 5$^{\text{th}}$ electrode in a square electrode layout and the measurement pattern replaces every 2$^{\text{nd}}$ measurement in the typical method with a measurement between the internal probe and external rings. Note: this figure does not differentiate between upper and lower electrode planes, but all injections and measurements are done between the 2 planes.

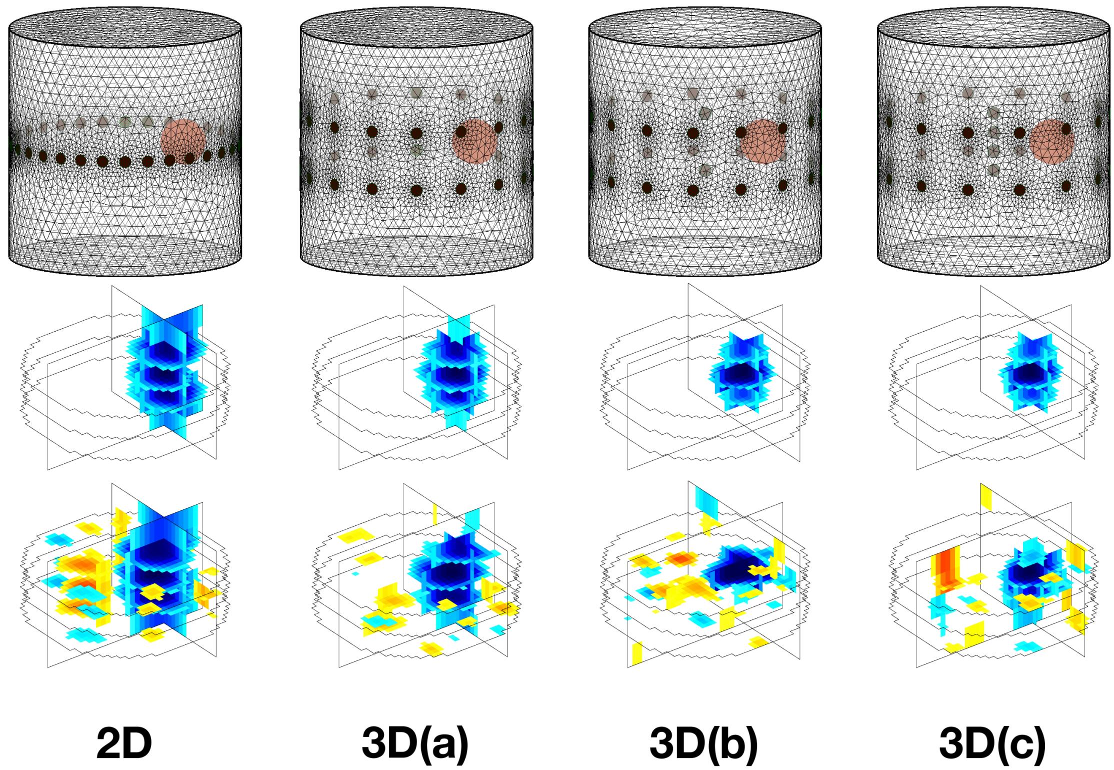

Figure 6.3: The top row shows reconstructions with no additive noise, and the second row shows reconstructions on measurements with 5dB of additive noise.

6.3 Results

Reconstructions of the conductive object with and without additive noise are shown in figure 6.3. With and without additive measurement noise, all models are able to reconstruct the target object accurately. Measurements with internal electrodes appear to reconstruct the target closer to the actual size.

Figure 6.4 show internal sensitivity distribution changes when using two and four internal electrodes compared to the typical 2D and 3D configurations with only external electrodes. The highest central sensitivity can be seen when using four

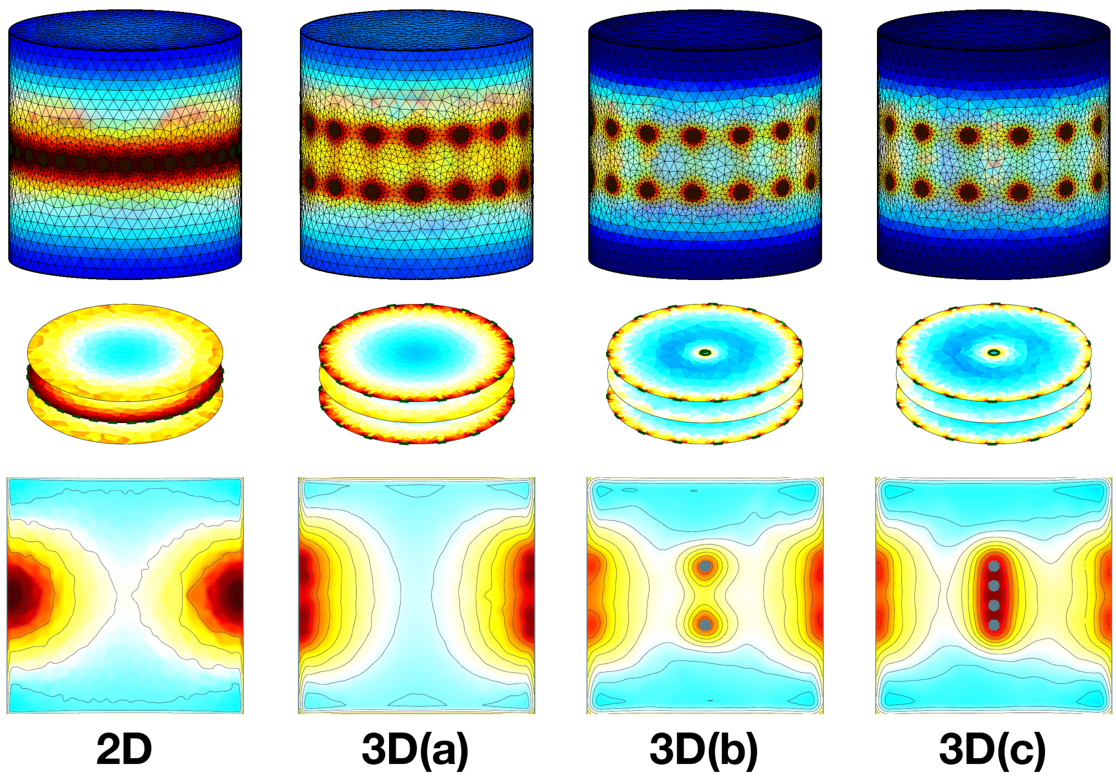

Figure 6.4: Sensitivity distributions for electrode patterns from left to right: A single 2D electrode plane; 2 electrode planes of 16 electrodes each; 2 internal electrodes and 2 external electrode rings of 15 electrodes; 4 internal electrodes arranged between 2 planes of 14 external electrodes

internal electrodes. This electrode configuration also gives a higher sensitivity in between the internal electrodes and the tank boundary.

These results show the expected increased sensitivity in the central regions of the model. To further improve internal sensitivity a new measurement pattern is proposed that uses more measurements between the internal probe and peripheral electrodes. The sensitivity of the proposed pattern was compared to the sensitivity profile of the same configuration using the basic "skip 4" injection pattern. Using this injection pattern results show a further increase in sensitivity in the internal regions without increasing the measurement acquisition time. The sensitivity distribution for the new injection pattern is pictured in Figure 6.5.

6.3.1 Sensitivity in an ovine model

A sensitivity comparison was also computed for an ovine model with different electrode configurations and is shown below in figure 6.6. Due to the location of the esophagus in adult sheep and the distance from the heart adding internal electrodes resulted in a minimal sensitivity decrease in the heart region of the model (<1%), but there is a significant sensitivity increase in the area immediately surrounding the probe.

6.4 Discussion

Based on the simulations presented in this chapter internal electrodes were able to increase the sensitivity in the central regions of the model significantly. Reconstruction in 3D with GREIT was able to accurately reconstruct the location of an object in 3D with both two and four internal electrodes in the presence of 5 dB measurement noise.

These results align with findings from Nasehi Tehrani *et al.* (2012) who demonstrated that internal electrodes in 2D result in a higher reconstruction accuracy and a much higher internal sensitivity relative to external configurations.

The presented data validates that the benefits of internal electrodes seen in 2D are also realizable in 3D, but there is more work required to quantify and validate the

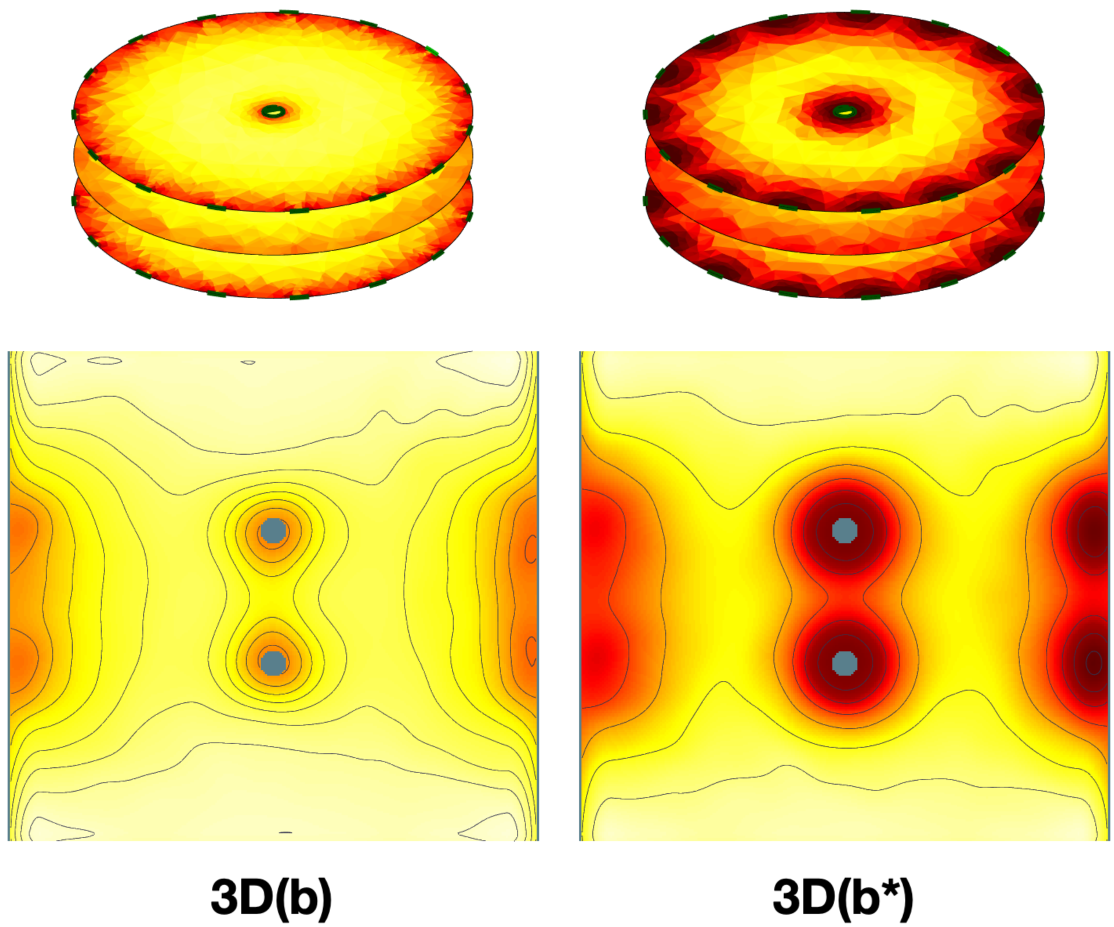

Figure 6.5: A comparison between the sensitivity distributions for a typical "skip 4" injection pattern pictured on the left (3D(b)) and the modified injection and measurement pattern on the right (3D(b*)).

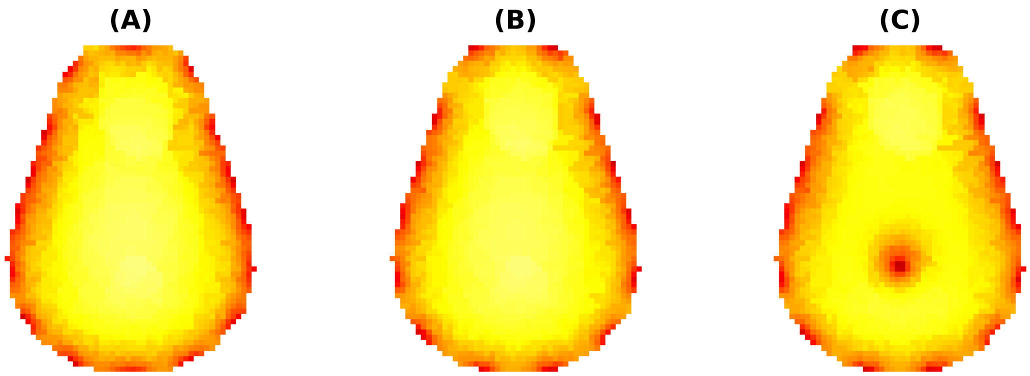

Figure 6.6: Sensitivity distribution averaged across 10 evenly spaced layers between the electrode planes in the lamb model for: A) 32 external electrodes B) 28 external electrodes c) 28 external electrodes and 4 internal electrodes.

improvements in real-world settings. Additionally reconstructions on a static target with a static electrode probe are relatively simple. It has been shown that electrode motion and boundary deformation are major contributing factors to error in EIT recordings (Boyle and Adler, 2011; Grychtol *et al.*, 2012), and this has been presented as an additional concern when using internal electrodes that there is currently no solution for (Nguyen *et al.*, 2020). The following chapter explores this source of error in more detail and provides a solution to correct for internal motion.

While the modified current injection pattern increased sensitivity in central regions of the model, it is not likely feasible for real-world use. The majority of commercially available EIT systems use fixed stimulation and measurement spacing and would not be able to accommodate this type of measurement. Additionally if movement of the internal probe is one of the main sources of artefacts when using internal electrodes, it is possible that using the probe for more measurements will not improve the reconstructed image.

Sensitively modelling in an ovine model showed a large increase in sensitivity surrounding the internal probe, but no improvement in sensitivity in the heart region. The ovine model is very different to the human model where the heart is much closer to the esophagus. The ovine model may be sufficient to analyze the feasibility of internal electrodes for ventilation and lung perfusion imaging, but may not be comparable to data collected in humans due to the difference in physiology.

These results serve as a starting point for 3D EIT, demonstrating that sensitivity increases in the centre of the model when using internal electrodes. Four internal electrodes gave the largest increase in internal sensitivity. The next chapter elaborates on the benefit of internal electrodes demonstrating reconstruction accuracy in simulations.

6.5 Summary

Reconstructions using the GREIT algorithm with internal electrodes on an esophageal probe were able to give increased sensitivity in internal regions. This shows promise for increased sensitivity to cardiosynchronous signals and may allow better isolation of pulsatile motion related to perfusion. The following chapter further investigates the impact of motion on internal electrodes.