A phantom for assessing the performance of EIT systems

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This paper describes a phantom built from 340 precision resistors on a printed circuit board (PCB) representing a circular homogeneous medium. Compared to other phantoms in the literature, this phantom generates very realistic signals while preserving the ability to produce localized perturbations for testing the imaging capabilities of an EIT system. Equivalent electrical models of the Ag/AgCl electrode impedances were integrated to the phantom. Parameters of the electrode models were fitted from impedance curves measured with an impedance analyzer. The technique used to build this phantom is general and applicable to phantoms of arbitrary shape and conductivity distribution. Assessing the performance of EIT systems usually requires a phantom for validation, calibration or comparison purposes. We describe some tests that can be performed with our phantom to measure signal-to-noise ratio, accuracy and modelling accuracy for every measurement of an EIT data frame. These tests were performed on four EIT systems: two of our own systems and two others that were made available to us. The performance of EIT systems is a function of frame rate, operating frequency, applied current intensity, measurement strategies and inter-modulation distortion when performing simultaneous measurements at several frequencies.

1 Introduction

Assessing the performance of EIT systems is often required for validation, calibration and comparison purposes. EIT systems suitable for *in vivo* imaging are complex systems requiring several closely interacting hardware and software parts. Modifications made to any part of the system have to be experimentally validated in order to confirm any expected benefit to the performance of the whole system. Calibration has to be performed periodically to account for components whose performance varies over time and to ensure the system is accurate whenever it is used. Objective comparison of EIT results from multiple centres requires a standard calibration approach for the EIT equipment used at each centre. In order to fully appreciate descriptions of hardware performance in the literature, it would be useful to have clearly defined objective criteria for comparison purposes. Since no standard has been defined, performance results are often published using different methodologies or, worse, without any description of the methodology. Because it is difficult to assess the performance of EIT systems *in vivo*, phantoms are usually preferred.

Two types of phantoms are described in the literature: physical and mesh phantoms. The former consist of a liquid or solid conductive medium that can be imaged by an EIT system using surface electrodes. The conductive medium usually consists of a conductive gel or a saline inside which are inserted targets whose conductivity contrasts with that of the medium. Mesh phantoms are composed of impedance elements interconnected in a particular topology. Resistors [1] [2], combinations of capacitors and resistors [3] [4] and active elements [4] [5] have been used as impedance elements. Three topologies have been described: the Cardiff phantom [1], the Göttingen phantom [2] and the wheel phantom [3]. While physical phantoms generate more realistic signals, mesh phantoms provide predictable, stable and reproducible signals. Mesh phantoms are therefore better suited for objectively assessing the performance of EIT systems in a reproducible manner.

This paper presents a phantom built with 340 precision resistors on a 192 by 192 mm PCB. This phantom is designed to approximate a circular homogeneous medium but the method is general and can be used to design phantoms of arbitrary shape and conductivity distribution [6]. The phantom also incorporates an equivalent electrical model of the electrodes. Signals from this phantom are compared to signals produced by other phantoms described in the literature.

This phantom can be used to assess the performance of an EIT system by measuring signal-to-noise ratio, accuracy and modelling accuracy for every measurement of an EIT data frame. These tests were performed on four EIT systems: two of our own systems and two others that were made available to us.

2 Methods

We have developed an algorithm based on a finite element method (FEM) for automatically producing phantoms of arbitrary shape and conductivity distribution [6]. The desired medium shape is first divided in triangular elements inside which the conductivity is constant and the voltage distribution is linear. We then compute the global admittance matrix using the FEM method. From this admittance matrix, a resistive mesh phantom equivalent to the desired medium shape and conductivity distribution can be designed. Such a mesh is built using the same triangulation as the FEM model where each side of every triangle corresponds to a resistor component and every computing node of the FEM model corresponds to a circuit node. The resistor component values are then extracted from the global admittance matrix. The resulting mesh phantom approximates the real continuous medium with the same accuracy as the FEM model. In practice, however, this accuracy is slightly reduced by the fact that we are using standard 0.1% precision resistors. Theoretical signals obtained from this phantom can be easily calculated from the nominal values of the resistors using circuit analysis techniques.

Using this method, we have built a phantom representing a circular homogeneous medium (Fig. 1). This phantom includes 340 0.1% precision resistors (17 different nominal values ranging from 51 to 3300 Ω), 17 snap-on connectors (including the ground connection) and 12 switches that can be used to short-circuit individual resistors to produce localized conductivity perturbations.

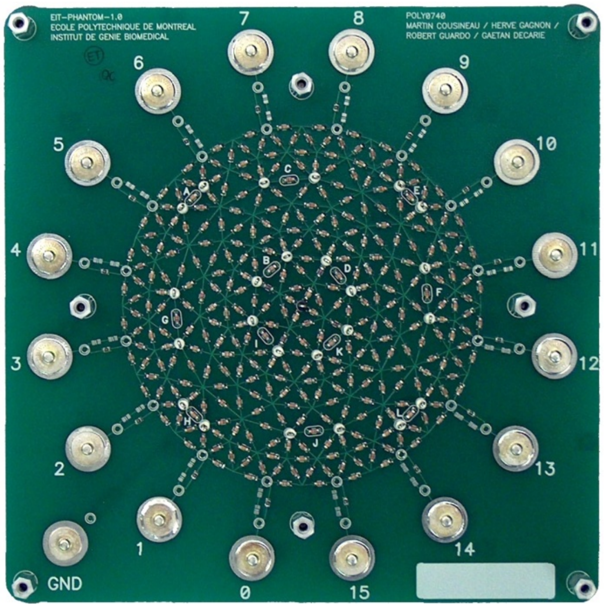

Fig. 1 Top view of the resistor mesh phantom.

Using a 4395A Network/Spectrum/Impedance Analyzer from Agilent Technologies, we measured the impedances of two Ag/AgCl electrodes immersed in a saline solution from 10 Hz to 1 MHz. To remove the contribution of the saline solution to the measured impedances, the measurements were also performed with a saline solution whose conductivity was doubled. An equivalent electrical model composed of a resistor in series with a parallel combination of a resistor and a capacitor was then fitted on the experimental data to reproduce the complex impedance behaviour of the Ag/AgCl electrodes. This equivalent circuit was inserted in series with the 17 snap-on connectors on the phantom PCB.

In order to assess the performance of EIT systems, 1000 data frames each consisting of n measurements are acquired on the mesh phantom. The average and variance signals of the 1000 data frames are then computed.

Signal-to-noise ratio (SNR) is computed using the following formula:

$$\mathrm{SNR}_i = 20\log\frac{|\mathrm{E}[m_i]|}{\sqrt{\mathrm{Var}[m_i]}}$$

where m_i represents the i^{th} measurement, $\mathrm{E}[m_i]$, the average of m_i and $\mathrm{Var}[m_i]$, the variance of m_i.

Accuracy (A) is computed using the following formula:

$$\mathrm{A}_i = \left[1 - \left|\frac{\mathrm{E}[m_i] - m_i^T}{m_i^T}\right|\right] \times 100\%$$

where m_i^T represents the theoretical value for the i^{th} measurement.

Since some reconstruction algorithms account for hardware imperfections in the forward problem formulation [7], modelling accuracy (MA) is defined by the following formula:

$$\mathrm{MA}_i = \left[1 - \left|\frac{\mathrm{E}[m_i] - f_i(\mathbf{m}^T)}{f_i(\mathbf{m}^T)}\right|\right] \times 100\%$$

where $\mathbf{m}^T$ represents the n-length theoretical measurement vector and $f_i(\mathbf{m}^T)$, the i^{th} measurement compensated for any hardware imperfections that are modelled by the forward problem solver.

3 Results

Theoretical EIT signals produced by our phantom have been compared with those produced by the Cardiff phantom, [1], the Göttingen phantom [2] and the wheel phantom [3]. The Cardiff phantom produces signals that are deformed compared to real EIT signals with a maximum measurement error of around 90%. This is mainly due to the fact that this phantom approximates a circular shape with a square mesh.

The Göttingen phantom and the wheel phantom produce EIT signals with a shape that is similar to an actual EIT signal measured on a continuous homogeneous medium with a maximum measurement error of around 45%. Our phantom is able to reproduce EIT signals from a continuous homogeneous medium with a maximum measurement error of 0.2%. This small error is entirely due to the fact that standard 0.1% resistor values were used instead of the computed values.

For testing the imaging capabilities of an EIT system, a phantom must be able to produce localized and controlled conductivity perturbations. Therefore, the phantom with the most impedance elements will be the best candidate to evaluate the position dependent impulse response of an EIT system. For this purpose, the Cardiff phantom is the best with 624 impedance elements, followed by our phantom, the Göttingen phantom and the wheel phantom with respectively 340, 65 and 32 impedance elements.

One thousand measurements were acquired on the phantom with two of our EIT systems. Fig. 2 and 3 respectively show performance indicators for our single and multiple frequency systems. Fig. 2 was obtained with the Sheffield protocol at an operating frequency of 50 kHz, a frame rate of 4.71 and a current of 4 $\mathrm{mA_{pp}}$. Fig. 3 was obtained with the Sheffield protocol in single frequency mode at 100 kHz, a frame rate of 5 and a current of 4 $\mathrm{mA_{pp}}$. In Fig. 2, modelling accuracy was obtained by accounting for a low-pass filter which is part of the system design. In Fig. 3, both accuracies are identical since no model is used in the forward problem solver.

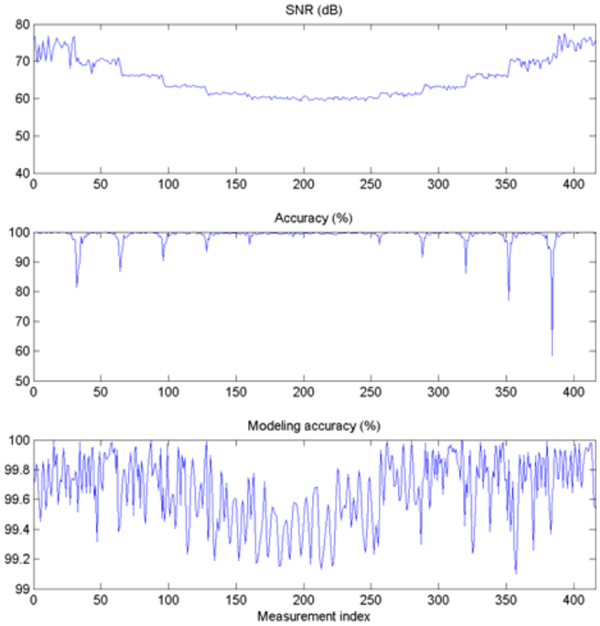

Fig. 2 Performance indicators of our single frequency EIT system.

Performance indicators are affected by several parameters. For instance, by decreasing operating frequency or frame rate, performance indicators improve. They can be further improved by increasing applied current intensity or measurement gain. Measurement strategies also affect performance indicators since they modify the dynamic range and frequency content of EIT signals. For multi-frequency systems, inter-modulation between the measurement frequencies may also adversely affect the performance indicators.

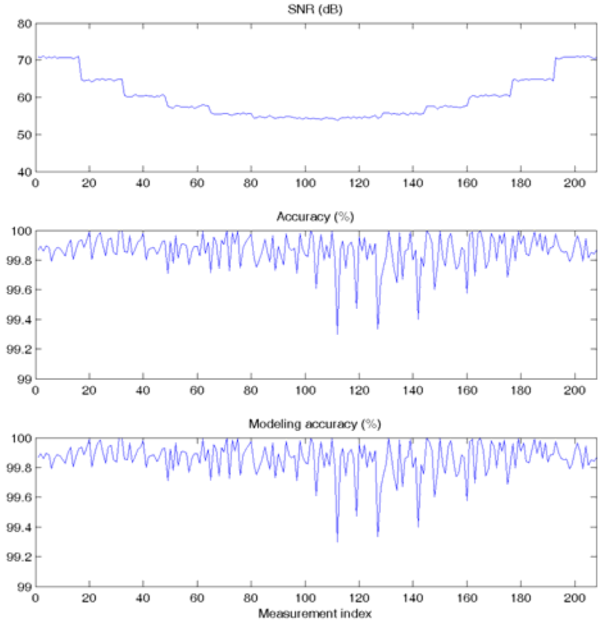

Fig. 3 Performance indicators of our multi-frequency EIT system.

We also have access to two other EIT systems which we are preparing to evaluate. The measurements were unfortunately not completed in time for this submission but will be available to include in the final paper for the conference.

4 Conclusion

Compared to other phantoms in the literature, our phantom generates very realistic signals while preserving the ability to produce localized perturbations for testing the imaging capabilities of an EIT system. Our phantom also incorporates a realistic electrical model of electrode impedances. By using snap-on connectors, performance indicators also include stray effects of electrode leads. Furthermore, phantoms of arbitrary shape and conductivity distributions can be produced using the same methodology.

Three performance indicators that can be computed from measurements made with this phantom have been presented. These performance indicators are functions of the measurement index. It is therefore mandatory to represent them graphically or at least to specify minimum, mean and maximum values rather than mentioning an ambiguous scalar value.

Many factors influence the performance indicators of a system: measurement strategy, operating frequency, frame rate, applied current intensity and inter-modulation distortion. Their values should therefore be specified with all performance indicators to better appreciate their significance.

5 References

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