Conductivity Distribution Measurement at Different Low Frequencies Using a Modular 64 Electrode Electrical Impedance Tomography System

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Abstract— **Electrical Impedance Tomography (EIT) is a technique that is widely spread in applications in biomedical engineering. The purpose of EIT is to use a sinusoidal current rather than the traditional methods of tomography where radiation or ultrasound waves are used. In this work, a system architecture using 64-electrodes applied to a circular liquid setup is implemented as well as a test circuitry to verify the system operation. Moreover, measurements are taken at a low-frequency range and their results are presented and compared.**

Keywords— Electrical Impedance Tomography, Phantom Model, Measurement Frequencies, Conductivity

I. INTRODUCTION

Electrical Impedance Tomography (EIT) is a non-invasive medical imaging technique and is used by applying a sinusoidal current with low amplitude instead of the traditional method of radiation or ultrasound waves [1]. Despite EIT first being proposed in the early 1980s, only recently has it began to find real applications on biomedical technology [1]. Additional uses of electrical impedance tomography are found in geology, archaeology and even in robotics as well as control systems (e.g. control of a robotic hand with imaging) [2].

The main advantages of EIT in comparison to other, more conventional medical imaging techniques, are the relatively low hardware and software costs, its safety, its imaging speed and the convenience towards patients due to the minimal preparation and operating time required [1] [3]. On the other hand, the few disadvantages of EIT are its low resolution and the susceptibility to many external noise sources.

The main concept of EIT is that a sinusoidal current is driven through a cluster of electrodes to a volume under examination, which is translated as a tissue in the biomedical research. Voltages between the electrodes are measured, demodulated and digitized to be used as inputs to an image reconstruction algorithm. The produced image shows the conductivity map of each cross-section area where the measurements are done. The conductivity behaviour of the interior of an object gives useful information about its electric and magnetic properties, from which conclusions can be made regarding the volume's interior structure (possible cavities of liquid, gas or hard tissue).

It is important to note here that biomedical tissues have very unstable conductivity behaviour that depends on a large number of factors. Some of them include the cardiopulmonary function, the blood pressure, the measuring frequency and the electrical noise produced from random internal neuroelectric signals [4]. In order to specify the specific frequency that shows the complete conductivity of a measurement, a sweep of frequencies in performed, commonly ranging from 10kHz to 100kHz. Each frequency gives specific information about the properties of the examined area, due to the mixture of resistive, capacitive and inductive behaviour. Frequencies outside of that range would also be useful for further tissue investigation. DC signal inputs would ideally image the clear resistivity map of the area, however this is not recommended for EIT because of the undesirable polarization that metal electrodes cause. Much higher frequency signals, up to the order of a few MHz would result in valuable information, which is beyond the scope of this work.

In the next section, the system architecture as well as the topology is presented. Furthermore, the measurement protocol and a testing circuitry are briefly described. In section III, after a small introduction to the image reconstruction problem, a phantom circular model that simulates tissues in low frequencies is presented, as well as the results according to the measured frequencies. Finally, the conclusion is discussed.

II. SYSTEM ARCHITECTURE & MEASUREMENT STRATEGY

A. Hardware Implementation

A typical EIT system is comprised of a sinusoidal current source, a Data Acquisition System (DAQ) to measure and record the resulting voltages and a switching circuit sequentially connecting the current source and the DAQ to different pairs of electrodes. The switching circuit is typically built using four analog multiplexers controlled by a micro-controller unit (MCU). Two multiplexers are used for the current injection and the other two for the voltage measurement.

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The hardware system used in this work, that uses 64 electrodes for voltage measurements, is described in detail in [5]. A simplified block diagram of the system is presented in Fig 1. Briefly, the main parts of the system are the following:

- A load independent current source, based on two amplifying stages, which operates as a voltage to current converter and has a signal bandwidth of 10MHz. The source is connected to the inputs of the first two analog multiplexers. The voltage comes from a digital-to-analog converter (DAC) which is programmed from the MCU.
- Two 1-to-64 analog multiplexers that switch the injected current between the electrode pairs and two 64-to-1 analog multiplexers for the voltage measurement. It is important to note here that each analog multiplexer can also act as a demultiplexer. In order to reduce the required logic signals from the MCU, four 8-bit parallel registers were used, one before each multiplexer.
- An output stage that contains a 1st order high pass filter (f_{cut} at 200Hz), to remove the DC offset and a high noise rejection rate instrumentation amplifier (AD8421) that drives the output signal to an analog-to-digital converter (ADC).
- An Arduino Due board, based on the 32-bit ARM ATSAMX8E microcontroller, which is programmed to control the multiplexer switches, the DAC and the serial communication via the PC. It also contains a 12-bit ADC that can perform up to 180ksps.

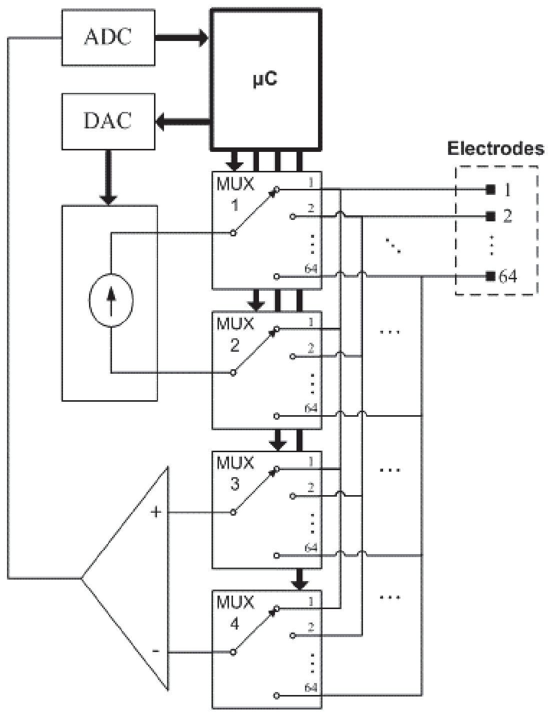

Fig 1: EIT basic System Architecture

B. Measurement Strategy

In this experiment, the measurement pattern used is the adjacent strategy, in which current is applied between a pair of adjacent electrodes and the resulting boundary potential is measured between all other pairs of adjacent electrodes. This is repeated 64 times, which is the number of the electrodes being used and of course the possible current source positions. Therefore, a full measurement circle using the adjacent algorithm contains 3904 differential voltage measurements. This method is also called the Brown and Segal data collection method [6] and is the most commonly used in EIT [5].

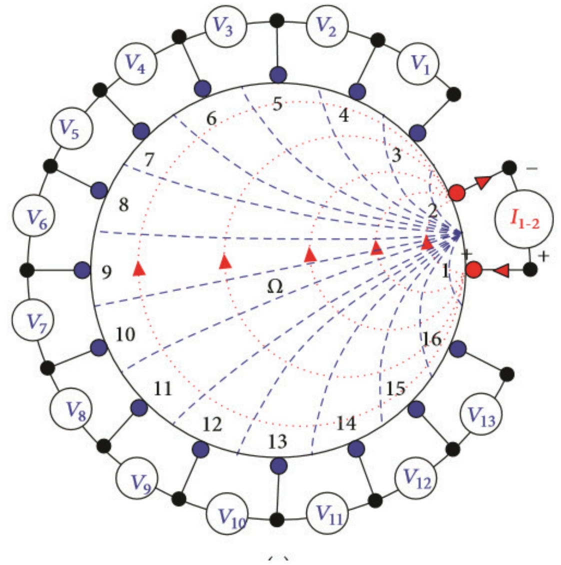

Fig 2: Brown and Segal adjacent measurement protocol (shown here with a 16 electrodes EIT system)

C. A Circuitry Test

It is important to verify that an EIT system works satisfactorily and will provide the corresponding images after the appropriate processing. In general, bio signals are characterized by very low SNR that negatively affects imaging quality. Thus, it is needed to be determined if the imaging errors are caused due to the hardware system, the electrodes or the measured area [7]. In order to test the hardware, along with the basic tests of each sub circuit, a simple circuit for testing all the circuitry and its functionality was developed. This test system was created by disconnecting the electrodes and placing constant 1kΩ resistors between each adjacent multiplexer channel. Acting sinusoidal current input of 600μA peak-to-peak at 10kHz, the differential voltage across each resistor is then measured equally at 25mV peak-to-peak, which verifies the right circuitry system function.

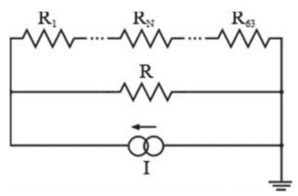

Fig 3: EIT calibration circuit diagram

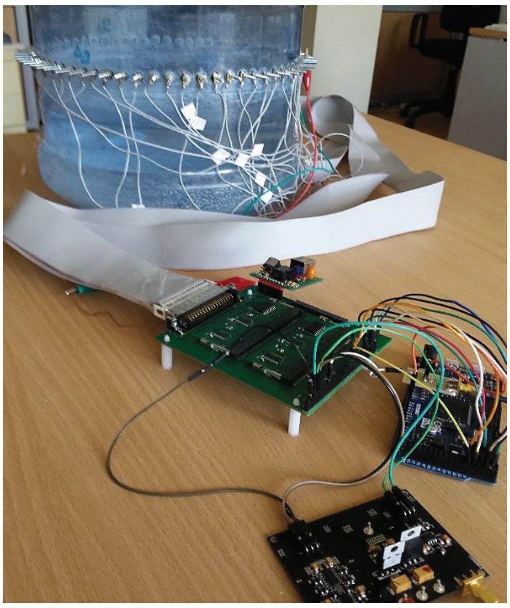

Fig 4: Photograph of the EIT system used for the measurements

III. MULTI-FREQUENCY MEASUREMENTS

This section includes three subsections. In the first one, the mathematical problem that has to be solved for the image reconstruction is introduced. In subsection B, a description of the experimental phantom model is presented. The final subsection includes the measurement results and its comparisons.

A. Introduction to the Image Reconstruction Problem

Assuming slow (or no) conductivity changes, from Maxwell's equations it is known that:

$$J = \sigma E$$

$$E = -\nabla V$$

Where J is the current volume density, σ the conductivity, E the electric field intensity and V the voltage. Thus the volume current is:

$$J = -\sigma \nabla V \, .$$

There are no internal current sources in the interior of the circular tank, so:

$$\nabla J = 0$$

The result is the equation:

$$\sigma \nabla^2 \varphi + \nabla \sigma \nabla \varphi = 0$$

This equation is known as the governing equation of EIT [4]. Both conductivity σ and interior potential φ are unknown, the boundary voltage values and the problem's geometry are known, so it becomes a nonlinear problem that is currently impossible to be analytically solved [6]. Those kind of problems are mainly solved with the finite element method, a numerical technique, through which the forward mathematical model can be derived. Dirichlet and Neumann boundary conditions reduce the solution space of the problem [5] [6] [7].

In this work, MATLAB 16.a software was used for the image reconstruction. In order to perform the operations mentioned above the EIDORS open source code was used [8]. The reconstruction needs at least two measurement cycles to be done. The first one is used as reference (homogeneous) and the second as inhomogeneous, where conductivity changes take place [1] [3].

B. The Phantom Model Experimental Setup

For experimental needs, a 27,5cm diameter circular tank model was used, where the electrodes are placed symmetrically around the tank, with an angle of pi/32 rad between each pair. 2D imaging is used, despite the fact that this geometry is not the most appropriate for 2D processing, due to the 3D route that the current follows. To set the homogeneous measurement model, the tank is filled with salty water which is then stirred well to distribute the mixture uniformly. The purpose of this process is to have a well set reference measurement field without errors, probably caused by spatial changes in chemical composition, to increase the further inhomogeneous measurements' reliability. Another important restriction is to keep the setup immobile during the measurement process, because any even small object movement in the tank could cause loose of the examination area's stability.

C. Measurements and Comparisons

For the purposes of this work, the voltage amplitude of the outputs was measured, although a complete output measurement cycle should contain the phase difference between outputs. In the homogeneous model, as the selected voltage electrode pairs approach the current source, the current density between them increases. Due to equal resistivity between each electrode pair, higher voltage amplitudes are expected. Far from the current sources, current density and thus voltage approaches zero [9]. This is periodically repeated every 61 values, as shown in Fig 5. The expected "U" shape has improved in comparison with the one presented in [5] due to hardware improvements on the system.

To observe the effect of the current frequency to the output voltage amplitudes and consequently to the image quality and the information provided, measurements were carried out at several low frequencies. The homogeneous measurements were performed by filling the circular tank with water and saline, which was mixed to achieve uniformity of the salt content and thus constant conductivity. The inhomogeneous measurements were performed by placing a 1.5 litre and a 0.5 litre empty plastic bottle almost antidiametrically in the tank water. An empty plastic bottle contains air which inserts very high impedance areas in the water tank. The experiment took place at 10 kHz, 15 kHz, 20 kHz, 25 kHz, 35 kHz, 70 kHz and 90 kHz, covering frequencies that provide high EIT performance.

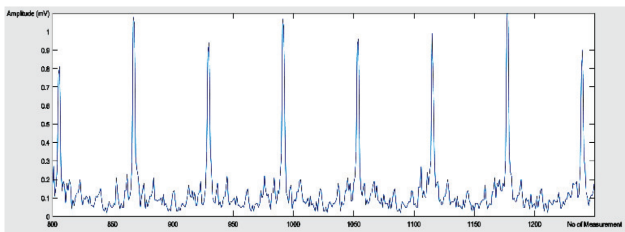

Fig5:Part of EIT homogeneous measurement cycle (10 kHz)

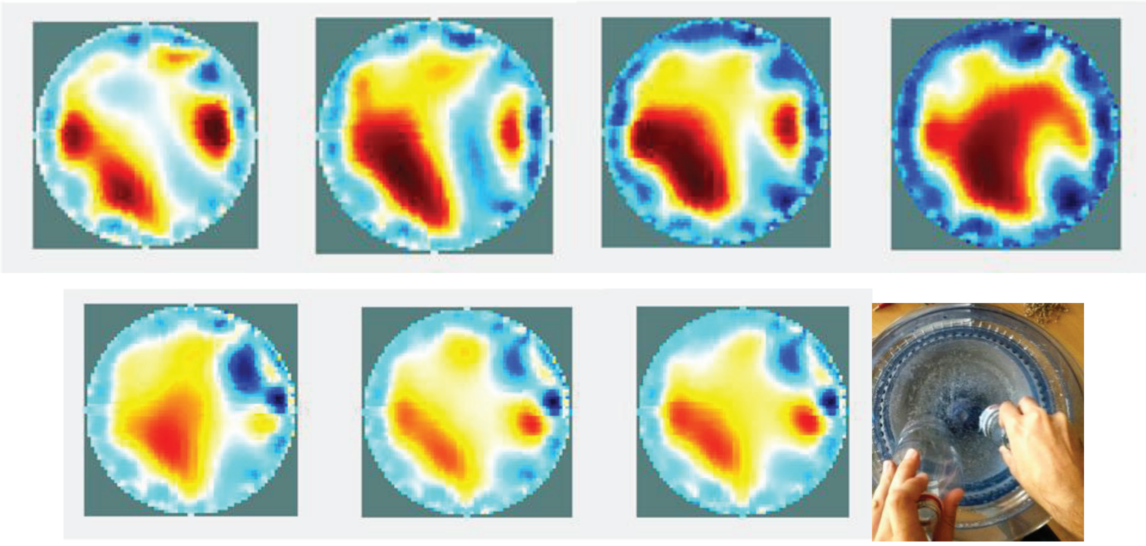

Fig 6: Images of 1.5-liter and 0.5-liter plastic bottles at 10 kHz, 15 kHz, 20 kHz, 25 kHz, 35 kHz, 70 kHz and 90 kHz (from left to right)

By observing the images above, Fig 6, it is obvious that each different frequency measurement cycle gives us unique information about the impedance measured. That is was expected, as water with saline and plastic objects, whose impedance behaviour is close to human lungs, thorax and heart, is characterized by very volatile resistivity, capacity and inductance as frequency changes [4]. In this example, where red colours indicate higher impedance, the overall impedance increases between 15-25 kHz and then decreases. Furthermore, it is notified that conductivity sensitivity in frequency changes is more intense at lower frequencies. Thus, the behaviour of the system should not be simplified as a single pole one, where frequency increase decreases the impedance, because conductivity range and behaviour is non-linear and is determined by many random factors, e.g. waves on the saline water, object movement, etc. [10].

There are many noise factors that negatively affect the image quality and resolution. As aforementioned, biomedical signals have very high sensitivity to many other, internal or external noise sources. The circular phantom model has low stability and is not perfect for 2D imaging. The screws round the tank that act as electrodes do not have an ideal ECG electrode behaviour (ECG electrodes are commonly used for EIT) and have small errors at the equality of the distance between them. The presence of this error is visible even in Fig 5; ideally, in a homogeneous mixture, the peaks should have equal heights and the “U” shapes should have no distinguishable noise between the peaks. Those noise samples are caused by the lack of full homogeneity of the setup content. Despite those facts, a satisfactory approach of the ideal homogeneous model has been exceeded and thus the image quality is improved.

IV. CONCLUSION

In this research, a 64-electrode EIT system was used to take multi-frequency measurements of the conductivity of a liquid circular tank which represents the behaviour of a tissue. Every frequency gave a unique conductivity image, thus, there is no ideal frequency for EIT imaging and such a working system has to be a multi-frequency measuring one. This is very important when EIT is used for medical purposes, because a significant examination finding might be detectable only at a very narrow frequency range. Moreover, the need for faster data acquisition and reconstruction algorithms, along with noise reduction are the main challenges for further advancing the function of an EIT system.

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