Arti Khana (ak724)
ECE 5030
Professor Land

Electrical Impedance Tomography

Introduction

Electrical impedance tomography (EIT) is an imaging modality that was developed over 70 years ago for nonmedical purposes. EIT, also known as biompedance imaging or tomography, is the study of passive electrical properties of the biological tissues. It was designed by the Sheffield group. EIT is based on two main ideas. First, the fact that there is a large resistivity contrast between a wide range of tissue types which allows for the use of resistivity to form anatomical images. Second, there is clear distinction between normal and pathological tissues.

The system applies current through electrodes that are placed on the body's surface and the resulting voltage difference across adjacent pairs of electrodes is measured. The current applied is usually constant and known as the excitation current. The result is a map of the electric conductivity and permittivity inside the body. EIT then uses this to reconstruct and display the electrical signals measured [1]. The reconstruction algorithm the group used is based on the filter back-projection method used in X-Ray CT imaging. The result is images in a 2D plane [3]. To improve the spatial resolution, different current distributions can be applied to the body and repeating the procedure to measure the voltages. As a result, an image reconstruction method can then be used to create the tomographic image.

The voltages and currents at specific locations in the body are known while the impedance in the body is unknown. At low frequencies, this can be related to the Laplace equation: $\nabla \cdot \sigma \nabla \square = 0$ where σ is the conductivity and $\square$ is the potential. These measures represent the spatial filed whose magnitudes are functions of position. EIT images were initially created by measuring changes in resistivity over time but using the same reconstruction methods, images are now produced using the changes in frequency. The electric potential u in the body is governed by the following equation:

$$\nabla \cdot \gamma(x,\omega) \nabla u = 0,$$

where x is point in the body, u is the electric potential, and the admittivity γ is given by $\gamma(x,\omega) = \sigma(x,\omega) + i\omega\varepsilon(x,\omega)$, σ is the electric conductivity, ε is the electric permittivity, and ω is the angular frequency of the applied current [1]. The electric impedance is the inverse of $\gamma(x)$ and it measures the ratio between the electric field and electric current at location x contained in the body.

Although it was initially designed for industry applications, there are a number of medical problems for which EIT and its capabilities of knowing the time-varying distribution of the electrical conductivity and permittivity inside the body would be useful. Conductivity is the measure of how easily a material conducts electricity and permittivity is a measure of how easily charges separate in a material exposed to an electrical field. This is significant and applicable to the medical field because different tissues exhibit different conductivities and permittivities. High conductivity materials allow both direct and alternating currents while high permittivity materials only allow alternating currents. Knowing this is beneficial to understanding EIT because a time-varying map of the electric properties can show, for example, the regions in the lung that are ventilated but not perfused by blood. Knowing these electrical properties can be useful to monitor numerous medical problems such as a collapsed or fluid filled lung, blood flow and cardiac function, internal bleeding, screening for breast cancer, etc. This modality can also be used to improve the current technologies of ECGs and EEGs [1].

Compared to other imaging modalities such as X-ray and PET, EIT is much cheaper, smaller, and eliminates the need for ionizing radiation. It can also produce thousands of images per second. It requires low cost instrumentation, easily applicable in practice and enables online monitoring. It is different from x-ray technique in that low-frequency electrical current cannot be confined to a plane. Therefore, the change in conductivity anywhere in the area can affect all measurements, not just those in the ray path.

EIT was developed for industry use but is also used in the medical field. It is primarily used to study gastric emptying and lung function. In the industry, it is generally used to image the distribution of oil and water in pipelines and the flow of substances in a mixing vessel. In some ways, the industry applications are more desirable because one of the difficulties of EIT is related to the fixing of electrodes on the human body. In industry, this problem is circumvented because it is possible to use a rigid, fixed array of electrodes.

EIT is a noninvasive modality, which aims to image conductivity distribution within a test volume by measuring the voltage applied on the electrodes that are attached to the surface when current is passed through them. The electrode voltages induced by the electric currents are a highly nonlinear function of the conductivity distribution. Iterative algorithms are used to invert current-voltage data to produce a conductivity distribution although there are more direct methods proposed. Iterative reconstruction methods compare a set of voltage measurements predicted by a model using an assumed conductivity distribution with physical measurements made on the object to be imaged. The model conductivity distribution is updated at each iteration to reduce the difference between the two sets of measurements [10].

Limitations and Difficulties

Although EIT is advantageous in many respects, it does have some limitations. EIT has low spatial resolution, thus leading to large variability of images between subjects. Until recent years, there was only one EIT system that was commercially available. It uses a single current source and 16 electrodes to make low resolution images of conductivity changes in the body. One of the limitations of this type of design is the resolution. To circumvent this issue here, number of electrodes placed on the body can be increased to improve the resolution. In general many electrodes must be used to produce a good image for clinical purposes. The data must be measured accurately and quickly. The recording is made by applying current to the body via electrodes and then the voltage developed between other electrodes is measured. Thus, to obtain reasonable images, at least one hundred measurements need to be made. Since current does not confine itself to a plane, measurements should be made on as large of a surface as possible, thus the need for so many electrodes.

Some other difficulties of EIT include the development of reconstruction algorithms and hardware for data capture. [3] There is also a lot of instability in the system leading to error. Some of the errors can be removed by improving the hardware design and thus improving the common mode rejection ratio which in turn reduces the effects of stray capacitance. It is crucial that all the systems be calibrated to obtain maximum signal and minimum error.

Based on the Sheffield system, for one type of reconstructed image, dynamic image, the EIT system was developed to make serial-in-phase voltage measurements. The system uses a constant current generator that is connected to the electrodes on the body, usually via a multiplexer, and current is supplied to the object to be imaged. This results in a voltage that varies sinusoidally when the body's surface is sampled via other electrodes and differentially amplified. The signal can then be demodulated by rectification using the reference waveform and filtered to acquire a voltage level, which is a measure of the impedance. The primary sources of error result from common mode effects such as skin-electrode contact impedance and stray capacitance. The electrode combination is the final source of error for each measurement since it is dependent on the effects of the complex interaction. [3]

EIT is also difficult in image reconstruction because a system of simultaneous equations relating every voxel to every measurement must be solved due to the nonlinear nature of the reconstruction. This is not the case in x-ray CT because the beam of radiation is collimated so the path is passed straight through the body and as a result, attenuation of the beam is only affected by the matter along the path. This would not be a stand alone problem if a reasonable number of unknown conductivity parameters were recovered from a reasonable number of measurements.

How it Works: Measurements and Electrodes

EIT recordings are typically made by applying current to the body through a set of electrodes and measuring the voltage developed between other electrodes. As mentioned before, to get decent images, a minimum of one hundred measurements must be made, but should be closer to one thousand measurements.

When modeling the electrodes, the current boundary is unknown for all locations in the body. The current sent along the wires attached to N discrete electrodes is known, which in turn is attached to the object's boundary [2]. This model approximates the current density by a constant at the surface of each electrode and by zero in the gaps between the electrodes. This model is appealing because it is quite simple but it is not very accurate. The complete electrode model has a current density on the boundary which is greatest at the edge of the electrodes (for passive electrodes as well). This effect is reduced so the contact impedance increases [5].

To measure the electrical properties, the geometry of the electrodes, excitation pattern and measurements collected can all be changed as desired [5]. The size of the electrode is also an important parameter in static EIT imaging and there are many situations where this is of great importance. For example, it can be difficult to size electrodes to fit in complicated measurement geometries. [8]

It is advantageous in EIT systems to model the observed voltages with the same precision as they are measured in order to make the highest resolution reconstructions of the internal conductivity that the measurement precision allows. [9] In EIT, current is injected into the object and the voltage is then measured to estimate the object's resistivity distribution. The pattern of electrodes affects measured voltage data because the electrode-skin contact impedance is high and varies with electrode placement [11].

A compound electrode was developed by Ping Hua's group which is composed of two electrodes. It consists of a large outer electrode to inject current and a small inner electrode to measure voltage. The measured voltages from the compound electrodes have smaller amplitudes than conventional electrodes. This shows that this electrode design can minimize contact impedance voltage drop from measured data[see for picture]. The current through the voltage electrodes is limited when the inner voltage electrodes are connected to high-impedance buffers which then lead to a reduction of the voltage drop and the error due to the contact impedance [11]. The following figure shows the electrode and setup.

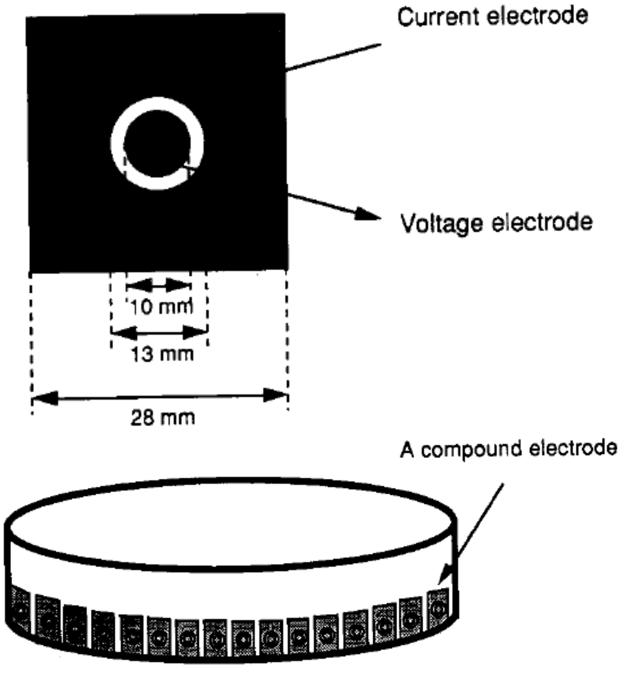

Figure 1: Compound Electrode and Setup [11]

In the electrode setup above, there are 32 electrodes evenly spaced on the phantom object. As stated, the outer electrode is used to inject current and the inner electrode measures voltage.

The voltage electrode area should be minimized so it can recognize the voltage at specific location. On the other hand, a very small electrode has a high contact impedance which consequently requires an unsuitable high input impedance for the voltmeter. Thus, the compound electrode can be used to minimize the effects of electrode impedance in both voltage measurements and reconstruction algorithms to obtain an image superior to images created using conventional electrodes [11].

EIT is sometimes a problem with detecting breast cancer and may give a high rate of false-positives. One of the reasons this happens is because of the non-uniform electrode-skin interface which results in a contrast artifact in the final image. To reduce this effect, a novel disposable electrode-skin interface (cotton fine grid thin layer CFGTL-interface) has been created by Zhenyu Ji's group. The electrode is 0.2 mm thick and has a conductivity similar to that of normal breast tissue [12, see for picture]. The CFGTL-interface has been shown to effectively decrease the variation and the range of data fluctuation which suggest that this novel electrode can also decrease the contrast artifacts that result and may also increase the accuracy of the detection. This is especially designed and suitable for the application of breast cancer detection. This novel design also eliminates the need to use an electrode gel over the skin, as in ultrasound techniques. It is cheap, disposable and also eliminates any worries of cross contamination between patients [12].

Applications

EIT has many applications in the medical field as well as industry. EIT is useful in geophysics and environmental sciences for locating underground mineral deposits, detecting leaks in underground storage tanks, and monitoring flows of injected fluid into the earth for extracting oil or for environmental cleaning [2]. Another area that EIT is used is nondestructive testing. It can be used for detecting corrosion, and small defects such as crack or voids in metals [2]. From its initial use, the system has evolved greatly with its technology as well as its expansion for many uses. In the medical field, EIT is used for detecting pulmonary emboli and breast cancer and monitoring cardiac function and blood flow.

The impedance measured is dependent on the amount of water in the body. The impedance can also be used to characterize and identify cells since the impedance between different cells changes based on the size, orientation, and thickness of the membrane among other factors. Additionally, based on the frequency range different physiological mechanisms can be identified such as changes in blood volume [3].

The cells and membranes of tissues in the body are thin but they have a high resistivity and electricity that behaves like small capacitors. The impedance of tissues encompasses two components, the resistance and reactance. Body fluids have conductive characteristics which provide the resistive component while the cell membranes act as imperfect capacitors and contribute to a frequency-dependence. The results are only dependent on liquids outside the cells. The impedance measurements can be made over a frequency range of 20Hz to 1MHz. With high frequencies, the current passes right through the cell membranes (‘capacitors’) and thus is dependent on tissue and liquid both inside and outside the cell. Conversely, at low frequencies, current is hindered by the cell membrane. As a result EIT can be used to measure volumes, shapes, as well as the electrical properties of tissues [3].

The following is further detail of the specific applications and how EIT is used:

EIT is used for pulmonary function through imaging ventilation and detecting blood clots in the lungs or pulmonary emboli, monitoring the drainage of pneumothorax caused by pulmonary lesions. This is made possible because the impedance of air is very high which provides high contrast with the surrounding tissue. Again, other imaging modalities can provide similar information but EIT is advantageous in most applications because it eliminates the need for repeated exposure to radiation. A drawback during the imaging of this is the large source of artifacts caused by the ribs and tissue movement because EIT is a very sensitive system [3].

EIT can be used to measure thoracic blood volume and cardiac output. With EIT, cardiosynchronous averaging can be done and then dynamic images can be produced describing the different times in the cardiac cycle [3].

A common application of EIT is breast cancer detection. Currently, the examinations are done using x-ray mammography and are sometimes uncomfortable and even painful. Using this modality also leads to a 40% false-positive rate and may lead to further unnecessary testing (i.e. biopsy). Further more, it also gives a false-negative 26% of the time. Also with the current method, the test is difficult with younger women because their breast tissue is denser. Even though testing is recommended for women generally over 40, EIT is a better use for this application and studies from the Bayford group show that the false-negative rate may be reduced to less than 10% with a sensitivity of 84% and specificity of 52% [3].

Given that there is a linear relationship between temperature and tissue resistivity, EIT may be useful for noninvasive thermometry. The drawback to this application is the resultant artifacts due to resistance images caused by other physiological factors, which are significant compared with the temperature-dependent changes. For hypothermic treatment, it is unclear if EIT is a feasible for thermometry because of the changes in tissue fluid content and the different impedance spectra of skeletal muscle and tumor tissue. This was observed in rats and thus is still inconclusive as a viable application for EIT [3].

EIT is also used for brain imaging for epilepsy. Focal epilepsy is a functional abnormality usually associated with structural abnormality such as a lesion. A patient’s seizure always generates from the same cerebral focus. EEG is usually the standard for this study but since the electrodes are implanted deep in the brain sometimes, irreversible damage may be caused. EIT can serve as a less invasive and more powerful alternative [3].

In geophysics, electrical properties of materials can have high contrast. For example, a dry rock matrix is insulating compared with liquid filled pores such as hydrocarbon. Hydrocarbon is a pore liquid which is a poor conductor compared to other pore liquids like brine. Subsurface electrical conductivity can vary over several orders of magnitude in the object [2].

EIT Compared to other Modalities

EIT does not have the spatial resolution of other methods like MRI or CT. There have been recent efforts to combine some of these imaging modalities which will be discussed later. The key advantage of EIT is its temporal resolution which is on the order of milliseconds.

Positron emission tomography has been the standard to quantify regional lung ventilation. JC Richard's research group compared PET to EIT for the application of imaging both injured and noninjured lungs using female piglets. The lungs were mechanically ventilated and injured in a controlled manner and measured under different volume conditions. The results from the study concluded that regional lung ventilation and volume were accurately measured using the EIT system in noninjured and injured lungs and the results validated using the standard PET imaging system. PET, like EIT, is noninvasive and a powerful method to quantify alveolar ventilation and volume. The two systems are comparable but EIT is an important tool for future work because it has the potential to allow the monitoring of the regional lung ventilation and volume at the bedside of patients and also allows for the management of the ventilatory setting on this basis [15].

Electronics

There are three different protocols for injecting current into the object to be imaged. They are adjacent, opposite and optimum injection. The protocol to be used is dependent on the application. For example, to image the brain the current density must be maximized. The optimum injection pattern is ideal for this application however, the complexity of the hardware increases in order to minimize the error on each individual channel [3].

Measurements are less sensitive to changes in conductivity of the object's interior. Thus, induced current EIT is slightly inferior to the technique of injected current EIT (from the Sheffield group) and its sensitivity matrix is better conditioned. On the other hand there is an advantage to the induced current EIT method in that the number of individual measurements can be increased by adding coils while in the injected current EIT method, this can only be achieved by adding more electrodes to the patient or object.

Alexander Ross's group designed a current source using an enhanced Howland topology in parallel with a generalized impedance converter (GIC). The Howland topology is the most common current source for EIT systems. It uses a single opamp with both negative and positive feedback. Having both feedbacks allows for simple adjustment of the output resistance and may cause the circuit to oscillate when driving large capacitive loads at high frequencies. In order to stabilize the circuit, a 10pF capacitor may be added in parallel with the negative feedback component [14]. The following figure shows the enhanced Howland circuit uses by the Ross group.

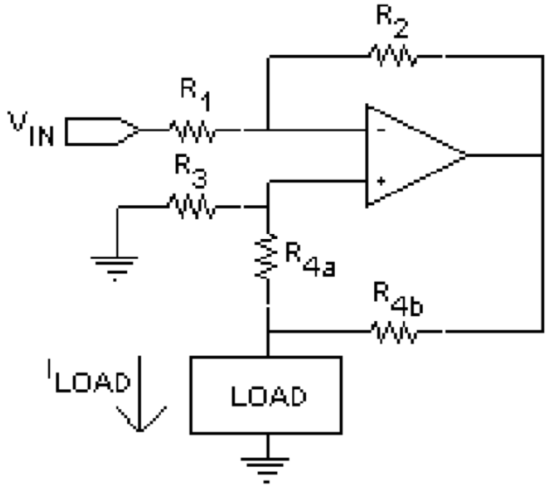

Figure 2: Enhanced Howland Circuit [14]

By replacing R_3 with a potentiometer, the output resistance can be adjusted without affecting the load current.

This combination by Ross et. al. allows for the output resistance to be adjusted independently (just about) and results in an output capacitance from simulated output impedances in excess of 2 GΩ between 100Hz and 1Mhz. The current source was shown to be feasible for high precision, multiple frequency, capacitance compensated for EIT application [14]. Although this has been shown, in application it is not possible to compensate the output capacitance completely in a wide range of frequencies because the system will need to be continually calibrated over time.
This topology is still advantageous over other designs because it uses a small number of elements, is a single device, and has the ability to adjust the output resistance[see source for ckts and formula]. The transconductance of the source is a function of 3 resisors [formula]. In the implementation of this circuit, the output capacitance acts in parallel with the finite output resistance to limit the total output impedance. The stray capacitance is still present even though the output resistance is adjustable which degrades the output impedance and thus, the performance of the circuit.

In order to create a high precision current source, the output impedance must be high compared to the load driven by the source. Other things to consider are stability, voltage compliance, the sensitivity and capability of the drive current with respect to the circuitry [14]. The results of the study demonstrate the feasibility of creating a high precision, multiple frequency, capacitance compensated current source. The current source should be able to maintain performance at a number of discrete frequencies or a frequency band while remaining stable over a wide range of load impedances. This is important in detecting breast cancer because the complex load value can be used as an approximation to the maximum impedance of healthy or malignant tissue [14].

The Sheffield EIT data-collecting system is the most well known hardware system to collect data from EIT systems. It consists of 16 electrodes with a single current source and a multiplexer, which is used to inject currents with different pairs of electrodes and measure the voltage on adjacent pairs of electrodes. There has since been a newer version of this which uses 8 electrodes and is capable of measuring data at 30 frequencies between 2kHz and 1.6MHz frames per second [3].

Image Reconstruction

The key goal of EIT is to produce images that are physiologically useful. EIT is capable of producing different types of images. The commonly used one is difference imaging where a change in ratio or percentages represents a physiological parameter such as cell size or blood volume. The images are acquired by collecting two separate voltage patterns at different times or frequencies. The reconstructed image shows the difference in the resistivity distribution inside the object. This reconstruction method only solves the problem of the linearized image. The observed data is the subtracted and divided by a reference data set. The reconstruction that results produces an image of the absolute conductivity or permittivity. This absolute method of reconstruction is more difficult that the difference method because the contact impedance of the electrodes is not as well characterized for clinical measurements [3]. The figure below is the electrode setup and difference image created by subtracting images taken at two different times. The first image was made when the heart's ventricles were contracted and the second image was made when the heart's ventricles were filled with blood. In the difference image, there is an increase in the magnitude of the admittivity in the lung region while the ventricles show a decrease in admittivity. This occurs because the blood, which has a higher admittivity, has traveled from the heart to the lungs [1].

Figure 3: Electrode Configuration and Resulting Difference Image [1]

The subject has 32 electrodes attached around his chest. The purpose of the image was to show changes in air and blood volume that result from the subject breathing and blood circulating.

A new method to enhance the images reconstructed with EIT was developed by David Dobson's group. They came up with an idea for reconstructing "blocky" conductivity profiles in EIT. "Blocky" profiles are functions that are piecewise constant and consequently, have sharp defined edges. This method is based on selecting a conductivity distribution that has at least total variation from all conductivities that are consistent with the measured data [7].

One of the difficulties with EIT is the reconstruction of images. Numerous algorithms have been proposed and are used today. In order to reconstruct the data, an approximation of admittivity, γ, must be obtained in the interior from the boundary measurements. This is challenging because it is nonlinear and large changes in the interior correspond to very small changes in the measured data [1,2]. Some of the algorithms are based on linear approximations. There are iterative and noniterative methods, multigrid algorithms, adaptive methods, layer stripping algorithm, NOSER (Newton's One Step Error Reconstructor) algorithm, and many more. This area of EIT is continually growing because it is a large problem in the system.

One of the commonly used methods is the layer stripping algorithm. This is based on the idea of first finding the electrical parameters of the boundary and then mathematically stripping away the outermost known layer. This process is then repeated while each layer is stripped with electrical parameters being found in the process. This method is useful because it is fast and addresses the full nonlinear problem and works well on synthetic data [1,2].

Unresolved Issues

There is still much work needed to be done in developing reconstruction algorithms for clinical data. Many of the current algorithms have many weaknesses that are not easily circumvented. This is especially a problem when a 2D solution is applied to a 3D problem. Another issue is that all prior information must be incorporated in the reconstruction which includes the boundary shape and position of electrodes. Since EIT is a relatively new modality, it is not well defined for all the applications it has the potential to be useful for. Currently, the greatest use for EIT is for breast imaging although many of the areas have great potential.

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