

Electrical Impedance Tomography (EIT): A Review

Ruzairi Abdul Rahim^{1,4*}, Anita Ahmad¹, Ahmad Azahari Hamzah³, Abu Ubaidah Shamsudin², Elmy Johana Mohamad², Muhamad Shukri Abdul Manaf¹, Nasarudin Ahmad¹, Khairul Hamimah Abas¹, Yasmin Abdul Wahab⁵

¹Faculty of Electrical Engineering, Universiti Teknologi Malaysia 81310 UTM Skudai, Johor.

²Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia

³Section of Chemical Engineering Technology, Universiti Kuala Lumpur. Malaysian Institute of Chemical and Bioengineering TTEchnology (UniKL MICET), 78000, Alor Gajah, Melaka

⁴Aimflex Systems Sdn. Bhd, Jln Persiaran Teknologi, Taman Teknologi Johor, 81400 Senai, Johor Darul Ta'zim

⁵Faculty of Electrical & Electronics Engineering Technology, Universiti Malaysia Pahang Al- Sultan Abdullah, 26600 Pekan, Pahang, Malaysia

Corresponding author* email: ruzairi@fke.utm.my

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ABSTRACT

Electrical Impedance Tomography (EIT) is a non-invasive imaging technique that estimates the internal electrical conductivity distribution of a subject using surface electrode measurements. This paper provides a comprehensive review of EIT, detailing its fundamental operating principles, system construction, and diverse applications, particularly within the medical field. Unlike conventional imaging modalities such as CT or MRI, EIT offers a portable, low-cost, and radiation-free alternative suitable for continuous, real-time bedside monitoring. The study outlines the essential hardware components, including active and passive electrode arrays, and discusses the complex non-linear inverse algorithms required for image reconstruction. Key medical applications are highlighted, including the monitoring of pulmonary ventilation and lung injury, early detection of breast cancer, analysis of intracranial bleeding and brain function, and fetal monitoring. The paper also explores recent technological advancements, such as the use of nanoparticle sensitizers to enhance tissue contrast and the development of micro-electrode arrays for precise measurements. Despite challenges regarding low spatial resolution and sensitivity to noise, EIT remains a promising tool for physiological monitoring. The review concludes that ongoing improvements in hardware design and reconstruction algorithms are expanding EIT's clinical utility, offering a safer and more accessible solution for long-term patient diagnosis and care.

Keywords: Electrical Impedance Tomography (EIT), Medical Imaging, Non-invasive Monitoring, Image Reconstruction

1. Introduction

Electrical impedance tomography method is one of tomography method that has been used widely in medical field. This tomography method can be classified as electromagnetic tomography modalities. In electromagnetic tomography there are consists of electrical capacitance tomography, electrical impedance tomography and magnetic induction tomography. [46] This method can produced a cross sectional image of conductive region of interest. This system is known as soft field method. [39] The basic structure or concept of impedance tomography methods is same with electrical resistance tomography method, where it used a pair of electrodes to measure the region of interest. But the way it measure a little bit different where electrical resistance method measure the resistivity of object while electrical impedance tomography measure the impedance. Impedance is a complex ratio of the voltage and current in an alternating current circuit. [7] Impedance consist of two part; real and imaginary part. The differentiation between electrical impedance tomography and electrical resistance tomography also come from the calculation and algorithm. [39]

Electrical impedance tomography is use in medical imaging, non-destructive testing, geophysical prospecting and industrial process monitoring. [149] But, this tomography method is widely use in medical field because it is not requiring the exposure of ionizing radiation. [1] This system also portable, low cost, but has low spatial resolution. [7] Besides that, this system is suitable for studying the physiological process which modify the electrical conductivity of body. This system can produce an image of respiratory and gastric activity base on the conductivity distribution by the movements of liquids or gasses. [24] This method widely uses to monitor lung problems, heart function and blood flow,

internal bleeding, screening breast cancer and many more. [1] This system also a validate system for imaging gastric function, pulmonary ventilation, brain function, pelvic congestion, hyperthermia and other gastrointestinal function. [7] Electrical impedance tomography firstly used to monitor respiratory function in 1983. [2] Previously, they use pressure volume curves and respiratory system compliance but these systems not capable to produce data of lung process at regional basis. [2] Electrical impedance tomography system is very good to use in medical fields because it has high sensitivity to the movement of bloods and other fluids in our body and it is suitable to apply for real time imaging process. [9] In medical applications, electrical impedance tomography has two types of different current applied. First, it called as Applied Potential Tomography (APT) where electrical currents are applied to the body using a pair of adjacent electrodes. Second method is known as Applied Current Method (ACT) where the electrical currents are applied to all the electrodes and voltage different between the electrodes are measured. [1]

For image reconstructions algorithm, electrical impedance tomography method produce a little bit complex compare to other method such as CT image and X-Ray computed tomography because both applications only let a direct beam of radiation go through the region of interest and the scattering of energy can neglect. But, for electrical impedance tomography, scattering energy need to be consider because it work based on the distribution of electrical currents. It is a non linear method of measurement. [2] For this tomography method, the image reconstruction is produce by determining the inverse problems. [25] The speciality of this method is, it is a high speed measurement system and it can capture repeated changes of electrical properties that occurred at the region of interest. [2] This method also can produce real time images and can captured video stream of regional ventilation. [4]

Today's application using electrical impedance tomography can produce two dimensional images and three dimensional images. [6] For two dimensional images, the data gathered is base on the sensors or electrodes that position around the body of entire object measured. [6] This two dimensional image can be produce using non iterative reconstruction algorithm. [26] But, for three dimensional images, the image reconstruction required the entire surface of the object volume data. [6] Three dimensional image procedure also face with some difficulties such as high demand for computational process, and quite sensitive to numerical or data error and to reduce some of these problems, researcher develop a non iterative procedures. [27]

In any types of tomography methods, these systems faced with the same problem which is low quality of image reconstruction. The main reason of this problem usually due to the hardware construction which is not shielded firmly and this can cause noise. Besides that, low quality image also come from the approximation of potential field model in the sensitivity matrix calculation. [6] to give high precision of image reconstruction using electrical impedance tomography method; many new development of this system is introduced. Many different strategies are applied such as additional electrodes, multiple electrodes current injection and multiple frequencies applied. [7] Sometimes, it's hard to measure the accuracy of image because different natures of application have different conductivity and permittivity. So as a conclusion, to produce high quality of image, it depends on the application is used for. From that stage of knowledge, the development of electrical impedance tomography can be made according to the requirement of applications to produce high quality of image reconstruction. [7]

Electrical impedance tomography faces with nonlinearity problems. Researcher in today's are nonstop developing new algorithm to solved this problem. For an example, they introduce sparsity concept for image reconstruction that can produce accurate and sharp image. This reconstruction method gives very close conductivity location with the true value. [19] Some other researcher introduced an application of induced current. [8] This method has been introduced since 1990 as a new invention for conductivity imaging of human tissues. [8] In this method, different shapes of coil are used to generate different primary magnetic fields. As we know, induced current is proportional to the rate of the changes of flux in a loop of wire. From their research, they found that induce current can produce more independent measurements compared to injected currents. But for injecting currents method, number of electrodes should be increased to produce more independent measurement results. [8] Another perspective shows that the large number of electrodes can cause high loading for computational time for image reconstruction. [12] Besides that, the best selecting of conductivity distribution can contribute for the image reconstruction enhancement. [23]

1.1 Basic Construction of Electrical Impedance Methods

The basics concept for electrical impedance tomography is same with electrical resistance tomography. This method required a minimum two numbers of electrodes plates. Both electrodes must be inserted in the object that we want to construct it cross sectional images. One of the electrodes will act as transmitter and another one act as transmitter. While the current flow through the electrodes, the changes of conductivity and permittivity can be measure easily.

The reason why this method widely uses in medical fields is because; it has capability to differentiate various types of tissues in our body. As we know, different tissues contribute different reading of conductivity and permittivity. Besides that, the information of the high value or low value of conductivity can be seen by image reconstruction. By analyse this image, researchers will get many information of region lung. [3] This method is very important in medical field to monitor collapsed or fluid filled lung, blood flow, and cardiac function. [3] For the lung monitoring process, the distribution of electrical conductivity is based on the alveolar volume stretches. [35]

Electrical impedance tomography system has two main part; hardware and software. For hardware, it consists of many numbers of electrodes that act as transmitter and receivers. This transmitter and receiver can be known as active electrode and passive electrode where active electrode is injected by the current and passive electrode for voltage measurement. [27] For electrode, the low value of contact impedance should be select to gain an accurate data measurement. Normally, 16 numbers of electrode being use because the right numbers of electrodes also can reduce the measurement error due to the contact impedance. [30] All the outputs voltage that given by electrodes will be combined using multiplexer and usually this multiplexer can acquired more than hundreds measurements at one seconds. [40] the receiver will connect with other circuit that can amplify the output reading. After that, this amplified output signal will be send to the data acquisition system. This data acquisition system has two main parts which is timing generator and microcontroller. [1] This timing generator is controlled by microcontroller to produce all the timing and clock signal required for synchronizing the data with computer software. [9] Finally, computer software will generate the output as a sensitivity matrix that describes the relationship between conductivity changes and the boundary voltages. [41] Figure 1 show the basic construction of electrical impedance tomography method measuring the head phantom [45].

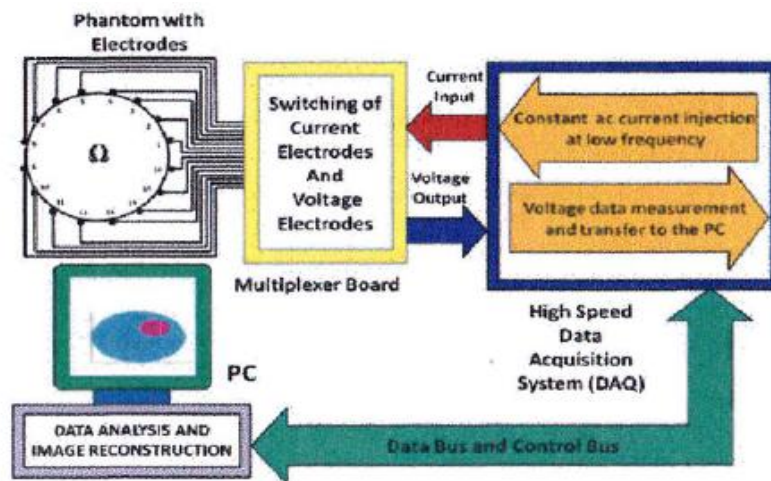


Figure 1. Basic construction for electrical impedance tomography

1.2 Image reconstruction

Electrical impedance tomography system is important in medical field and because of that, the quality of image reconstruction that produce by this system should good enough for analysis. This tomography method has its weaknesses due to low spatial resolution and unclear boundary imaging. Researchers have developed many different algorithms to solve this problem. There are two reconstruction algorithms methods that need to apply; forward problem and inverse problem. For forward problem, it help electrical impedance tomography problem to calculate boundary voltages with given electrical conductivity distribution. While for inverse problem, it takes voltage measurement at the boundary to estimates the conductivity distribution. [48] It has two parts, dynamic and static inverse problem. For dynamic inverse problem, it classified as linear non-iterative while for static inverse problem is iterative algorithms. Most of the iterative numerical algorithm has high performance in imaging high quality and accurate image. [40]

This image reconstruction of the conductivity is a nonlinear inverse boundary value problem. Nonlinear boundary value problem is unstable and has modelling errors. Modelling errors usually cause by truncation of the computational domain and unknown boundary data. [147] Many ideas have been used to increase the quality of image reconstruction by using electrical impedance tomography system. For an example, the number of electrodes must be increased to give high spatial resolution. Multiple current sources also must be match to give a good performance of system. Amplifier that been use in this system must be isolated from receiver by a transformer because this arrangement can act as high pass filter to reduce electrophysiological signals affect the accuracy of the measurements. [109] Sometimes, the low accuracy of image reconstruction is because of the noise that due to spatial variations in applied currents or voltages. To reduce this noise, it is suggested to apply currents and measured voltages rather than applies voltages and measured currents. [5]

Another problem due to the image reconstruction is the boundary problems. Besides that, this boundary problem also occurred clearly when it use for monitoring chest changes breathing. [43]Some researchers have come out with new idea which is called as model shape match. Many experiments are carrying out to get the average shape of certain organs. From the image result it can be use for comparison for medical analysis. This procedure actually complicated and can cause mismatch problems. It is because different patient have different shape of organ. But, by using different reconstruction algorithm, this mismatch problem can give a small error. [33] Finite element methods also use in

electrical impedance tomography methods for image reconstruction. This finite element method is a method that has been used to reconstruct an image by solving its differential equation with different image modalities. [41]

1.3 Applications of Electrical Impedance Tomography Methods

Electrical impedance tomography is mostly used in the medical field. But, this method also contributes to geophysics and environmental science for locating underground mineral deposits and detecting leaks in underground pipes. It can also be used for detecting corrosion, and small defects such as cracks. [3] This system can also be applied for process industries application. For example, this system is capable of measuring the impedance distribution inside a small vessel by placing the electrodes around the vessels. [22] This method is very useful to apply in industries for real-time process monitoring.

This method is used in medicine because it has the capability to detect and identify cells based on their sizes, orientation, and thickness of membranes. In our body, fluids contribute as conductive regions while cells contribute as permittivity regions. [3] This conductivity and permittivity value is totally different based on different tissues and organs. [28] But, safety standards must be fully met by this system because it deals with human life. [7]

There are other reasons why electrical impedance tomography is really needed in today's medical field. Existing instrumentation such as magnetic resonance imaging (MRI) and computerized tomography (CT) have their limitations. For magnetic resonance imaging, it gives high spatial resolution of image but this instrument cannot detect the presence of cancer tissues at an early stage. [31] Besides that, this instrument is not suggested to use rapidly because patients can be exposed to radiation. Another method to detect cancer is by using ultrasound devices. This ultrasound device also has limitations where this system can only detect lumps which are solid or filled with fluid. [31] Electrical impedance tomography has many advantages such as non-invasive, low cost, and no ionizing radiation but this system also has disadvantages where this system can easily detect slightly external voltage or current interruption and this will cause a huge effect on internal conductivity values. [32] Another advantage of this system is that it is a long-term measurement system where this system can monitor patients for real-time monitoring processes for a long period without giving any side effect to the patients. [33]

2. Electrical Impedance Tomography for Medical Field.

2.1 New improvement for electrical impedance tomography by using Nano-particle Sensitizers

Bioelectric impedance measurement is a safe way to determine the electrical properties of tissues inside the human body. [10] This method measures the changes in electrical properties that occur in the tissues of the body. This application is important to detect the early stage of cancer. [10] To increase the ability of electrical impedance tomography to detect changes in cell or tissue conductivity, a nano-particle enhanced method is introduced. [10] The basic concept of this tomography method is by measuring the potential on the body surface by injecting a small amount of current into the human body. Sensitizers are introduced in this medical application to enhance the image produced by this tomography method. The types of sensitizers are ultra-pure water, normal saline, and gold particles. [110] For ultra-pure water, it will help increase the impedance of tissues due to its high conductivity. Normal saline will also increase the conductivity of tissues. This method will help doctors to differentiate normal and cancerous tissues. [10] By using these sensitizers, tumors can be detected at early stages. [10] Besides that, nano-particles are suitable for use because of their miniature size and can reduce harm from side effects. These sensitizers help to improve the accuracy and high quality of image reconstruction.

2.2 Electrical impedance tomography for imaging tissues cells

Living tissue cells have a conducting cytoplasm and are covered by a thin layer of insulating cell membrane. When these cells are exposed to an electric field, these cells will behave as insulating objects. This result will help the electrical impedance tomography system to measure electrical properties in the cells. The growth, differentiation, and the effect of drugs can be monitored using this tomography method. [45]

Electrical impedance tomography can produce an image reconstruction that maps the electrical impedance distribution inside human tissues. Changes in membrane resistance can be enhanced by using fluorescent markers (sensitizers), current voltage measurement, and patch clamps. [11] This method is applied by surrounding the body or organ with electrodes that have injection currents. This method is very useful for detecting cancer at early stages. It is because this method is safe from any ionizing radiation that can give some bad effects to our body. [12] One of the applications of electrical impedance tomography is used for breast cancer detection. This system becomes one of the alternative methods for diagnosis and imaging of breast cancer tissues. [27] Although it has low spatial resolution, it is low cost, portable, and does not produce any hazardous radiation to patients. [27]

2.3 Electrical impedance tomography for monitoring lung air and liquid volumes

Previously, pulmonary mechanics parameters are used to measure the flow and pressure at the mouth and esophagus, while X-Ray is used to measure the fluid movements in the lungs. However, both methods have their limitations and

disadvantages. [13] Lung air monitoring usually need to be monitor for continuously, but X-Ray tomography use ionizing radiation that is not good for continuous exposure of patients. [13] By using electrical impedance tomography system, it can provide valuable information regarding to the state of aeration and ventilation within the lung. [14] Low constant value of alternating current is applied to the electrode as low as 5 ma. Besides that, low pass filter need to be used to eliminate the cardiac oscillation. [20] This tomography system work based on the changes of the conductivity sense. For an example, when air is filling in the lung, the impedance will change due to breathing process. Fortunately, the large changes of impedance occurred at thorax where functioning lung tissues present. There are two types of ventilation modes. First it is known as spontaneous breathing and mechanical ventilation. The data obtain is base on the changes of lung impedance during spontaneous or ventilator generated breathing. Lung injury also can detect because this part usually consist of low impedance. [15] This tomography method is highly recommended for the use of lung monitoring process because it is non invasive method, free from radiation, easy to implement and portable. It also can monitor real time process system. Figure 2 show the image reconstruction related to the inhalation and exhalation cycle that produce by online monitoring of electrical impedance tomography system. [50]

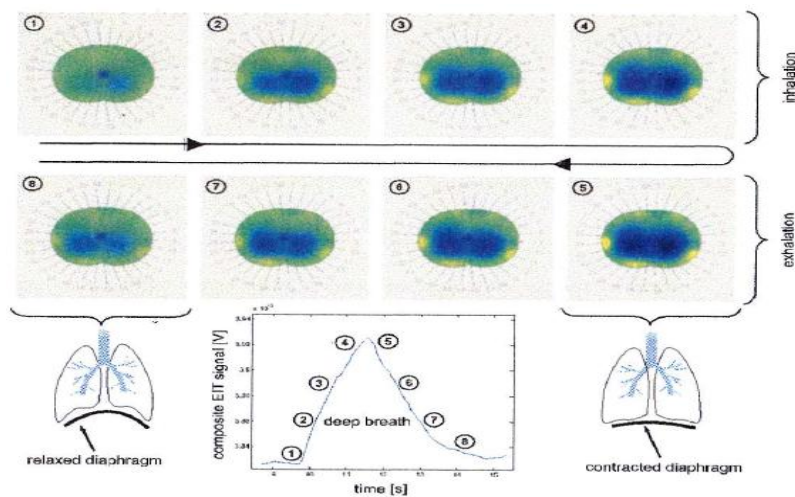


Figure 2. Image reconstruction of thorax region during inhalation and exhalation cycle.

Electrical impedance tomography method also can be used to monitor and diagnosis for pulmonary embolism. Pulmonary embolism happen when there are a blockage occurred at pulmonary artery or its branches by emboli travels through the bloodstream. The image of this problem can be capture base on the impedance changes due to the flow of blood stream. Computed tomography scan is not suggested to use for critical condition patient because it expose with radiation that can cause harm to the patients. [16] Figure 3 shows how the electrode is place around human chest for monitoring lung air and liquid volume. [1]



Figure 3. A stripe of electrode plate is place around human chest. [101]

Other types of sickness that related with our breathing process are known as cystic fibrosis. This is the chronic disease that affects the lungs and the digestive system. This can cause small airways and reduce the flow of air. By using electrical impedance tomography system, this problem can be diagnosis at early stage. Previously, doctors are use spirometry and body plethysmography. But all these instruments have limitation where they cannot measure ventilation distribution. [34]

In the development of this tomography method for lung monitoring, a group of researchers from China has developed a new algorithm known as Global Inhomogeneity (GI) index. The main objective of this new algorithm is to

quantify the tidal volume distribution within the lung for electrical impedance tomography analysis. The development of this new algorithm is based on the image reconstruction captured using electrical impedance tomography system. [36] Another approach that introduced by researchers is using neural-fuzzy modelling to increase the quality of image processing. This approach helps in estimating the relationship between lung absolute resistivity and lung volume. [38]

2.4 Electrical impedance tomography for intracranial application

Haemorrhage or intracranial bleeding happens when the blood vessel within the skull leaks or ruptures and it is very dangerous. This situation can cause critical issues such as increasing the intracranial pressure. This intracranial pressure may cause limitations in blood supply. Electrical resistance tomography is very useful to produce a real-time image for intracranial bleeding problems. From the image visualisation, it can show the different resistivity of blood and other brain tissues. [29] One of the reasons why this method is widely used in medical applications is because it can be used for real-time monitoring purposes without spreading any chemical or hazardous radiation that can worsen the patient. Because of the speciality above, this tomography method also has been used for diagnosis of brain activity, bleeding, and pressure. [17] From the data obtained, sensitivity maps can be reconstructed based on the details of impedance changes in the brain. [17] The development of this system is very important nowadays for brain analysis. This tomography method allows medical specialists to study deeper inside the brain function in real-time monitoring. [17] Figure 4 shows the system architecture for electrical impedance tomography system for brain analysis. [17]

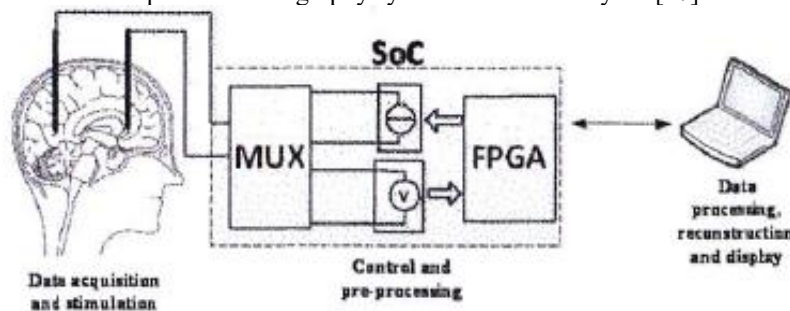


Figure 4. System Architecture for brain analysis using electrical impedance tomography method. [117]

In this case, researchers develop a micro-array of electrodes as can be seen in Figure 5. This micro-electrode is developed using a fibreglass core and partial skull still needs to be open to insert this miniature electrode core. [17]

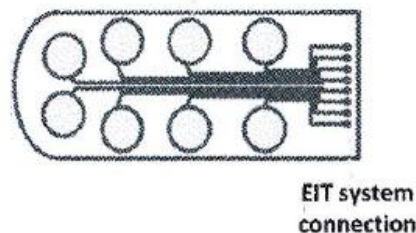


Figure 5. Micro electrode construction [117]

This tomography method also can detect brain tissue ischemia and cerebral infarction. This is due to the capability of electrical impedance tomography to detect changes in impedance values. Another researcher found another method to apply this system without having to access the brain. The electrodes only need to be placed around the head and tied tightly. From their experiment, they can construct the image of swelling tissues in the brain. For this case, they assume that the skull cavity is a hermetic case with constant volume; where resistivity will change proportionally to the volume and tissue location changes. [17]

In the medical industry, head phantoms are built by scientists for experimental purposes. These phantoms are built by scientists to make experiments related to human tissues before they apply their system to their patients. Usually, these head phantoms represent head tissues, skin, skull, cerebrospinal fluid, and brain. By using this head phantom, scientists and researchers can make their studies very detailed in analyzing the requirements of electrical impedances for tomography to be very useful for brain analysis. [42]

2.5 Electrical impedance tomography for fetus monitoring

Usually, ultrasound and cardiotocogram is used for fetus monitoring. These instruments are very important for checking fetus movement, the growth of fetus, and position of placenta. [21] This monitoring procedure is required by

pregnant mother for monthly or daily monitoring of the baby and the mother itself. Electrical impedance tomography method is a new development for the use of fetus monitoring. This new development is design by researchers because they want to solve the problem that face with the previous instruments where they are bulky, expensive, time consuming and need skilled personnel to monitor. [21] For fetus monitoring, the principle of electrical impedance tomography is still the same where electrode plat have to be place around the mothers belly and low current need to be inject into the electrode. This electrode plate will measured the changes of impedance value that occurred inside the mother's belly. Image reconstruction can be produce base on the data obtain. As we know, human tissues have different conductivity and it varies from cerebrospinal fluid to bone over a large scale. [21] Figure 6 shows the system orientation on the mother's belly.

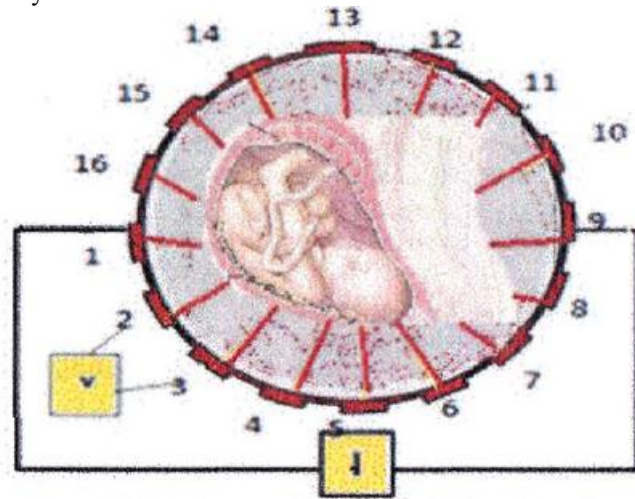


Figure 6. The orientation of electrode for fetus monitoring. [21]

2.6 Electrical impedance tomography system for monitoring retroperitoneal bleeding in a renal trauma patient.

Electrical impedance tomography method very useful to monitor patient that face with active retroperitoneal bleeding. If this problem is not detected at early stage, serious consequences may occurred. In medical instruments , this tomography system is the only instrument that can monitor patients continuously and can give early results about the stage of active retroperitoneal bleeding whether patient need to operate or not. [37] Figure 7 shows the way how electrical impedance tomography system is used. For this case, this system used elastic belt to ensure that electrodes plates have the good contact with the skin. [37]

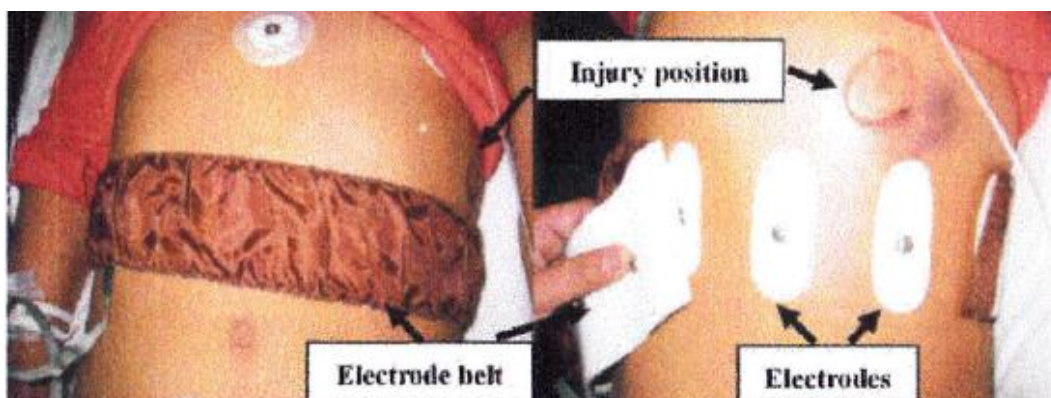


Figure 7. Electrical impedance tomography is apply for monitoring retroperitoneal bleeding

3. Conclusion

Electrical impedance tomography is one of the tomography methods that are suggested to use in medical fields because it is low cost, portable, bedside monitoring, and no hazardous radiation. Although this system has low spatial resolution, researchers nowadays keep on going to produce many ideas to reduce these problems. This tomography

system also can enhanced it 's image reconstruction by improving the electrode model for an example by increasing the number of electrodes or by using different frequency of currents value, increase the capability of the system circuit, and studying the reconstruction method [10]. This system also should be introduce to the process industries because this system also suitable for online monitoring process.

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