Electrical Impedance Tomography (EIT) – A Review

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ABSTRACT

Electrical Impedance Tomography (EIT) is a non-invasive imaging technique widely applied in medical, industrial, and geophysical fields. This review explores the fundamental principles, construction, and applications of EIT, emphasizing its role in medical diagnostics. EIT operates by measuring impedance variations using electrodes, enabling real-time imaging of physiological processes such as lung ventilation, cardiac function, and blood flow. Its advantages include portability, low cost, and the absence of ionizing radiation, making it suitable for continuous monitoring. However, challenges such as low spatial resolution and complex image reconstruction persist. Advances in algorithms, electrode designs, and nanoparticle-enhanced methods have improved image quality and diagnostic accuracy. EIT's applications extend to detecting early-stage cancer, monitoring pulmonary and intracranial conditions, and fetal health assessment. Despite limitations, EIT's adaptability and safety position it as a promising tool for diverse medical and industrial applications

Keywords: Electrical Impedance Tomography (EIT)

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 prospection 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]

1.2 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.1[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]

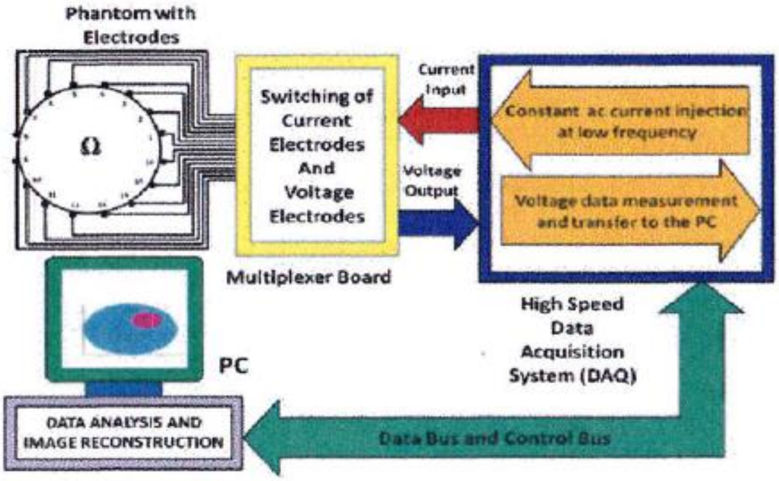

Figure 1. Basic construction for electrical impedance tomography

1.3 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 use to reconstruct an image by solving it differential equation with different image modalities. [41]

1.4 Applications of Electrical Impedance Tomography Methods

Electrical impedance tomography mostly used in medical field. But, this method also contributes for geophysics and environmental science for locating underground mineral deposits and detecting leaks underground pipe. It also can be use for detecting corrosion, and small defect such as cracks. [3]This system also can be applied for the process industries application. For an example, this system is capable to measure the impedance distribution insides 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 use in medical because it has the capability to detect and identify cells based on the sizes, orientation, and thickness of membranes. In our body, the fluids contribute as conductive region while cells contribute as permittivity regions. [3]This conductivity and permittivity value is totally give different value base on different tissues and organs. [28] But, safety standards must be full fill by this system because it deals with human life. [7]

There are another reasons why electrical impedance tomography method is really needed in today's medical field. The 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 present of cancer tissues at early stage. [31]Besides that, this instrument is not suggested to use rapidly because patient can expose to the radiation. Another method to detect cancer is by using ultrasound devices. This ultrasound device also has limitation where this system only can detect lump which is 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 the disadvantage where this system is easily can detect slightly external voltage or current interruption and this will cause huge effect in internal conductivity value. [32] Another advantages of this system is ; it is a long term measurement system where this system can monitor patient for real time monitoring process for a long period without give 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 human body. [10]This method measures the changes in electrical properties that occur in tissues body. This application is important to detect early stage of cancer. [10]To increase the ability of electrical impedance tomography method to detect the changes of cells or tissues conductivity, nano-particle enhanced method is introduced. [10] The basic concept of this tomography method is by measuring the potential on body surface by injecting small amount of current into human body. Sensitizers are introduced in this medical application to enhance the image produce by this tomography method. The types of sanitizers are ultra pure water, normal saline, and gold particle. [110]For ultra pure water, it will help increased the impedance of tissues due to its high conductivity. Normal saline also will increase the conductivity of tissues. This method will help doctor to differentiate the normal and cancerous tissues. [10]By using this sanitizers, tumours can be detected at early stages. [10]Beside that, nano-particles is suitable to use because of it miniature size and can reduce harm from side effect. These sensitizers help to improve the accuracy and high quality of image reconstruction.

2.2 Electrical impedance tomography for imaging tissues cells

Living tissues cells have a conducting cytoplasm and covered by a thin layer of insulating cells membrane. When these cells exposed with an electric field, this cells will behave as an insulating objects. This result will help 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 method can produce an image reconstruction that map the electrical impedance distribution inside human tissues. Changes in membranes resistance can be enhance by using fluorescent marker (sensitizers), current voltage measurement and patch clamps. [11]This method is applied by surrounding the body or organ with electrodes that have injection of currents. This method is very useful for detection cancer at early stages. It is because this method is safe from any ionizing radiation that can give some bad affect to our body. [12]One of the applications of electrical impedance tomography is use for breast cancer detection. This system becomes one of the alternative methods to diagnosis and imaging the breast cancer tissues. [27]Although it is low spatial resolution, but it is low cost, portable and not produce any hazardous radiation to patients. [27]

2.3 Electrical impedance tomography for monitoring lung air and liquid volumes

Previously, pulmonary mechanics parameter is use to measure the flow and pressure at mouth and oesophagus, while X-Ray is use to measure the fluid movements in lungs. However both method has their limitation 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]

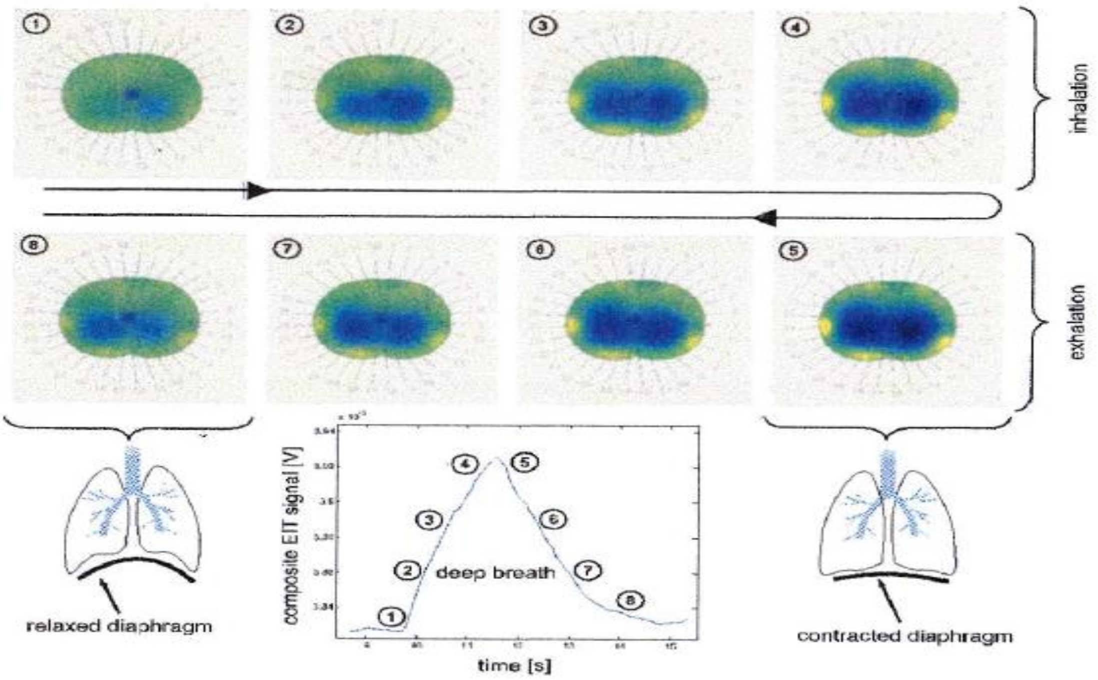

Figure 2. Image reconstruction of thorax region during inhalation and exhalation cycle.

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]

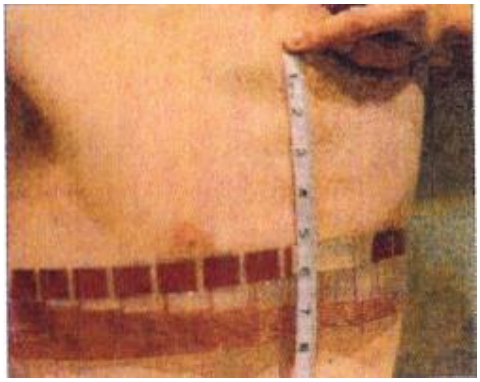

Figure 3. A stripe of electrode plate is place around human chest. [101]

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 base on the image reconstruction captured using electrical impedance tomography system. [36]Another approach that introduce by researchers are using neural-fuzzy modelling to increase the quality of image processing. This approaches help in estimating the relationship between lung absolute resistivity and lung volume. [38]

2.4 Electrical impedance tomography for intracranial application

Haemorrhage or intracranial bleeding happened when the blood vessel within the skull leaks or ruptured and it is very dangerous. This situation can cause critical issues such as increasing the intracranial pressure. This intracranial pressure may cause limitation in blood supply. Electrical resistance tomography is very useful to produce a real time image for intracranial bleeding problem. 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 use in medical application is because it can use for real time monitoring purpose without spread any chemical or hazardous radiation that can worsen the patient. Because of the speciality above, this tomography method also has been use for diagnosis brain activity, bleeding and pressure. [17]From the data obtain, sensitivity map can be reconstruct based on the detail of impedance changes in brain. [17]The development of this system is very important nowadays for brain analysis. This tomography method allow medical specialist 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]

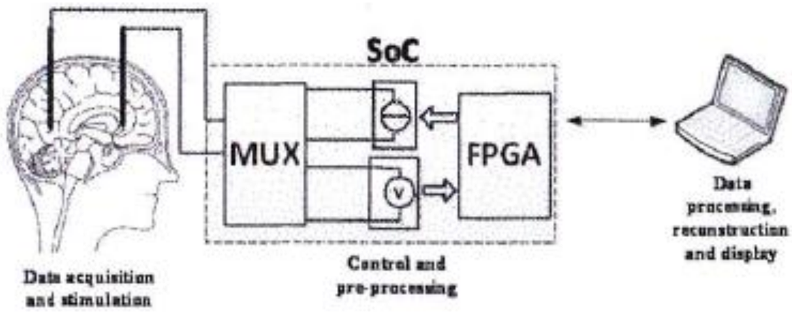

Figure 4. System Architecture for brain analysis using electrical impedance tomography method. [117]

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

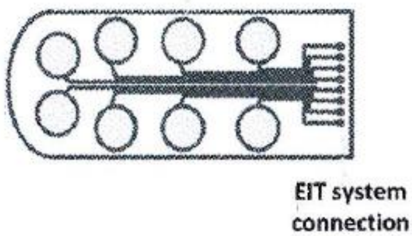

Figure 5: Micro electrode construction 117]

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

In medical industry, head phantoms are building by scientist for experiment purposes. These phantoms are build by scientist to make an experiments related with human tissues before they apply their system to their patients. Usually this head phantoms represent head tissues, skin, skull, cerebrospinal fluid and brain. By using this head phantom, scientist and researchers can make their studies very detail in analyzing the requirement of electrical impedances 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.

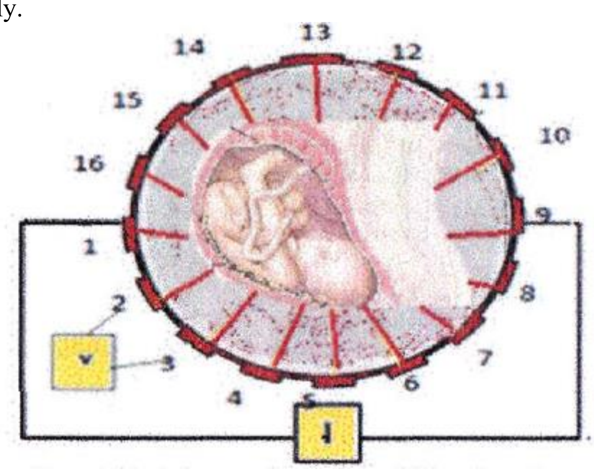

Figure 6: The orientation of electrode for fetus monitoring. [21]

2.6 Electrical impedance tomography system for monitoring retroperitoneal bleeding

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 monitor patients continuously and can give early results about the stage of active retroperitoneal bleeding whether patient need to operate or not. [37] Figure 4 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]

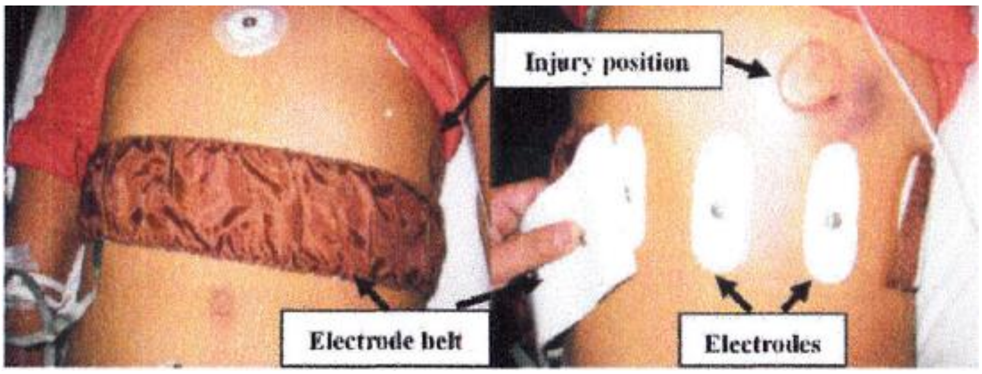

Figure 4: Electrical impedance tomography is apply for monitoring retroperitoneal bleeding

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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