Electrical Impedance Tomography (EIT) and Its Medical Applications: A Review

R.Harikumar, R.Prabu, S.Raghavan

Abstract - This paper reviews the principles of Electrical Impedance Tomography (EIT), different types of current patterns and reconstruction algorithms to assess its potential in medical imaging. A current injection pattern in EIT has its own current distribution profile within the subject under test. Hence, different current patterns have different sensitivity, spatial resolution and distinguishability. Image reconstruction studies with subject or practical phantoms are essential to assess the performance of EIT systems for their validation, calibration and comparison purposes. Impedance imaging of real objects or tissue phantoms with different current injection methods is also essential for better assessment of the biomedical EIT systems. More specifically, this work reviews the three different image reconstruction techniques including back-projection method, iterative method and one-step linearized method. In this review, Resistivity images are reconstructed from the boundary data using Electrical Impedance Tomography and Diffuse Optical Tomography Reconstruction Software (EIDORS).

KEYWORDS: Electrical Impedance Tomography (EIT), Stimulation patterns, regularization, Images.

I. INTRODUCTION

Electrical impedance tomography (EIT) [1] is a non-invasive imaging modality that can be used to image conductive subjects. In EIT the internal conductivity distribution of the subject is reconstructed based on electrical measurements from electrodes attached around the boundary. In EIT, electrodes are attached on the surface of a subject and a certain current pattern is injected into the subject through stimulation electrodes. Commonly alternating current is used as stimulation whose amplitude is usually several mA with frequency between 1~100 kHz. The voltages are measured using voltage measurement electrodes. An image reconstruction method is then used to calculate the internal conductivity distribution from the boundary data.

EIT has numerous practical applications, e.g. in quality control and fault detection for various materials [2], geological exploration [3] and medical imaging [4]. In present days, EIT has been extensively researched in medical applications [5-9]. The possible medical applications for EIT [10] are monitoring for lung problems, such as accumulating fluid or a collapsed lung [11], noninvasive monitoring of heart function and blood flow, monitoring for internal bleeding, screening for breast cancer, studying emptying of the stomach, studying pelvic fluid accumulation as a possible cause of pelvic pain, quantifying severity of premenstrual syndrome by determine the amount of intracellular versus extracellular fluid, determining the boundary between dead and living tissue.

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Measuring local internal temperature changes associated with hyperthermia treatments or cryosurgery, and improving electrocardiograms and electroencephalograms.

In medical applications, due to the differences in bioelectrical properties between tissues, the impedance distribution can indicates the structural and functional properties of the object. In EIT, the current flow is determined by the impedance distribution within the object. As well, the problem is ill-posed which meaning that large changes in impedance at the interior of the object can result in only small voltage changes at the surface.

EIT equipment has relatively low cost and good portability and it is easy to be operated and maintained. The current stimulation is not hazardous to humans in contrast to exposure to x-ray or radioisotopes in nuclear medicine. EIT shows potential to be used as a bedside real-time monitoring system which is affordable in hospitals and clinics.

II. METHODS AND MATERIALS

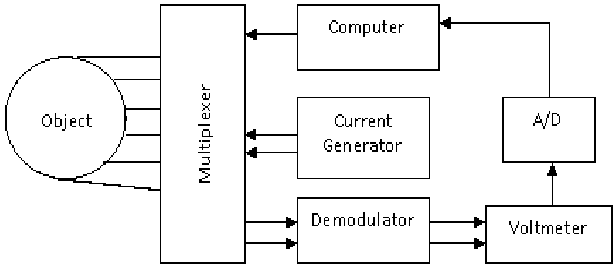

Figure 1. Block diagram of a very simple EIT system which shows main components.

An EIT system mainly consists of two parts, which is data acquisition hardware and image reconstruction software. Figure 1 shows the basic block diagram of a very simple EIT system which comprised of

1. An array of electrodes, attached to the surface of the object
2. A current generator is used for generating a constant sinusoidal alternating current to inject into the surface
3. To perform data acquisition, a multiplexer circuit is necessary for switching the current injector and voltmeter among the different data channels.
4. Demodulator/voltmeter is another important part of the system for voltage measurement from the surface.
5. For cancelling the noise, filters are used and ADC is used for converting to digital signal and interfacing to the Computer.
6. An Image Reconstruction algorithm, which reconstructs images of internal resistivity distribution of the object from the voltage measurements.
7. A computer (display, hard copy, keyboard, storage, etc.) is used to enable an

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easy user access to the image analysis.

A. Stimulation And Measurement

Electrical impedance tomography reconstructs the conductivity and permittivity within an object based on the conditions of voltage and current on the surface of the object. To find out the conditions of the current and voltage on the surface, we can inject the current through a set of the electrodes in contact with the surface and measure the developed voltages. There are many ways in the current-injecting electrodes, voltage measuring electrodes and current patterns. This section describes various methods by which the current is injected and the voltages are measured.

B. Adjacent Drive Method

The adjacent drive method [12], also called as the neighbouring method, is the most common current driven pattern. In this method, the current is applied through adjacent electrodes and the voltage is measured sequentially from all other adjacent electrode pairs without the pairs containing one or both the current electrodes. Figure.2 shows the adjacent method for a 16-electrode EIT system with a circular domain surrounded by 16 surface electrodes named as the electrode-1 to electrode-16. In adjacent method, the first current projection is P1, the current is injected through electrode-1 (1) and electrode-2 (2) and the voltages differences (V1,V2,V3, . . ., V13) are measured sequentially with 13 electrode pairs 3–4, 4–5, . . . and 15–16. Voltages are not measured between pairs (16-1), (1-2), or (2-3) (Figure.2.2a). Therefore the first current projection (P1) gives 13 differential voltage data.

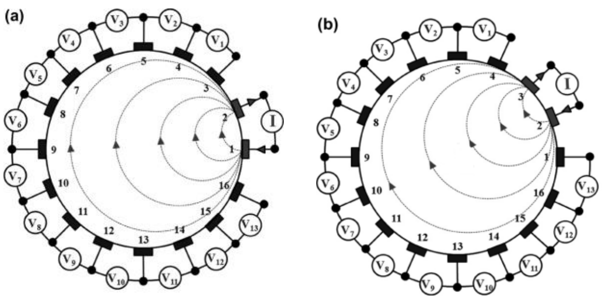

Figure 2. Adjacent Current driven patterns (a) first current projection (P1) (b) second current projection (P2)

In second current projection (P2), the current is injected through electrodes- 2 (2) and electrodes-3 (3) and the voltage differences (V1, V2, V3,... V13) are measured sequentially with 13 electrode pairs 4–5, 5–6, … and 16–1 as shown in Figure.2.b. Voltages are not measured between pairs (1-2), (2-3), or (3-4). Hence, this current projection (P2) gives 13 differential voltage data. This process is repeated until current has been injected between all 16 adjacent pairs of electrodes. This is called a frame of data which will produce 16×13 = 208 measurements.

The adjacent method provides N^2 measurements, where N is the number of electrodes. But to avoid the problem of unknown contact impedance, the voltage is not measured at a current injecting electrode so the number of measurements is reduced to N (N −3). The four-electrode reciprocity theorem states that for any measurement set the mutual impedance is preserved under an interchange of injection and measurement pairs. Hence only N (N − 1)/2 of the measurements are independent. So, it is common to use all N (N − 3) measurements in most reconstruction algorithms. Thus a 16 electrode system will produce 208 measurements of which 104 are independent but all 208 are used in the reconstruction algorithm. The current density is highest between the injecting electrodes, and decreases rapidly as a function of distance. The method is as a result very sensitive to conductivity contrasts near the boundary and insensitive to central contrasts. It is also sensitive to perturbations in the boundary shape of the object, in the positioning of the electrodes and is quite sensitive to measurement error and noise [1].

C. Opposite Method

The opposite or polar drive pattern [13], which is commonly used in brain EIT [20], applies current through electrodes that are 180° apart while voltage differences are measured on the remaining electrodes. Hence this method is known as Opposite Method. Voltage differences are measured on the voltage electrodes with respect to the electrode (called as the voltage reference electrode) adjacent to the current-injecting electrode (Figure.3)

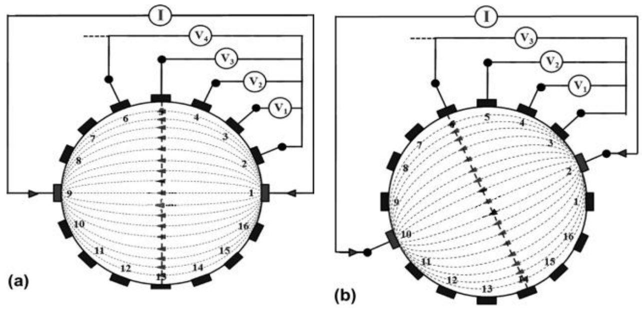

Figure 3. Opposite current Driven pattern (a) first current projection (P1) (b) second current projection (P2)

In the first current projection (P1) of the opposite method, the current is injected through electrodes-1 (1) and electrode-9 (9) and the differential voltages (V1, V2, V3, . . ., V13) are measured sequentially from 13 electrode pairs 2–3, 2–4, . . . and 2–16 (Figure.3a) considering the electrode 2(2) as the reference. Hence the P1 gives 13 differential voltage data.

The second current projection-2 (P2), the current is injected through electrodes-2 (2) and electrode-10 (10) as shown in Figure.2.3b. and the differential voltages (V1,V2, V3,..., V13) are measured sequentially from the 13 electrode pairs 3–4, 3–5,... and 3–1 (Figure.3b) considering electrode-3(3) as the voltage reference electrode. Hence the second current projection gives 13 differential voltage data. This process is repeated until current has been injected between all 16 pairs of electrodes. Therefore in opposite method, a complete scan of a 16- electrode EIT system yields 16 X 13 = 208 voltage measurements. Thus with 16 electrodes the opposite method yields 8×13 =104 measurements of which half are independent. Thus the opposite method suffers from the disadvantage that for the same number of electrodes, the number of available current injections that can be applied is less than for the adjacent method.

The opposite method offers a better distribution of the sensitivity, as the current travels with greater uniformity through the imaged body. Therefore compared to the adjacent method, the opposite strategy is less sensitive to conductivity changes at the boundary [1].

D. Cross Method

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The cross or diagonal drive pattern [14] is rarely used. In the cross method, adjacent electrodes are selected as current and voltage references. In this method, first current is injected between electrodes 16 and 2, while 13 voltage measurements are taken using electrode-1 as the reference against the other 13 electrodes. Hence, the current is injected through electrodes- 16 (16) and electrodes-2 (2) and the differential voltages (V1, V2, V3,.., V13) are measured sequentially with 13 electrode pairs 1–3, 1–4,.. and 1–15 (Fig.4a) considering electrode-1 (1) as the voltage reference (Fig.4a). Therefore the cross method gives 13 differential voltage data. Next current is applied to electrodes 16 and 4 while 13 voltage measurements are taken using electrode 1 as the reference. This is repeated for currents injected between electrodes (16-4), (16-8), (16-10), (16-12), (16-14). The entire procedure yields 7 X 13 = 91 measurements.

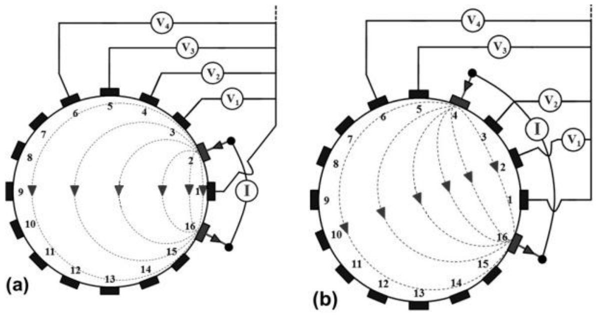

Figure.4.Cross current driven pattern (a) first current projection (P1) (b) second current projection (P2)

The entire procedure is repeated once more, with the reference electrodes changed to electrodes 3 and 2. Therefore current is applied between electrode 3 and electrodes- (5, 7, 9, 11... 1) with voltage measured at the other 13 electrodes with electrode 2 as a reference. This procedure gives a further 91 differential voltage measurements. From these 91 + 91 = 182 measurements, only 104 data are independent. The cross method does not have as good a sensitivity in the periphery as does the adjacent method, but has better sensitivity over the entire region[1].

E. Trigonometric Method

In the abovementioned methods, current has been injected with a pair of electrodes and the differential voltages have been measured between different pairs of electrodes without the current electrodes. Gisser et al. [15] proposed a current injection method called the adaptive method or trigonometric method. In this method current is injected on all electrodes and voltages are measured on all electrodes. Because current flows through all electrodes at the same time, as many independent current injectors are needed. In the case of the 16-electrode EIT system needs 16 current injectors. The electrodes can be fed a current from -I to +I, allowing different current distributions. In trigonometric method, the boundary potentials are measured with respect to a single grounded electrode. So, for a 16-electrode EIT system, this method produces 15 voltage measurements. The current projection is then rotated one electrode increment and other projections are obtained. As a result, this current injection method produces eight different current projections yielding 8 X 15 = 120 independent voltage data. The noticeable disadvantage of this method is that current drivers are needed for each electrode and the unknown contact impedance will have an effect on the reconstruction.

II. RECONSTRUCTION OF EIT IMAGES

The problem of recovering an unknown conductivity from boundary data is severely ill-posed and the solution depends continuously on the data. In impedance tomography, the fundamental problem in the image reconstruction is that, the electric current cannot be forced to flow linearly in an inhomogeneous volume conductor. Since there are no sources within the volume conductor (the sources all lie on the applied currents) then the potential field. The mathematical model describing the electrical properties of the field is a generalized Lap lace's equation:

$$\nabla \cdot \rho^{-1}(\nabla \phi) = 0 \quad (x, y) \in D \qquad (1)$$

where ρ is the resistivity distribution; ϕ is voltage and D is the tested field. Equation (1) indicates that there are no current sources in the body.

$$\Phi|_{\partial D} = V_0(x,y) \qquad (2)$$

$$\rho^{-1}\frac{\partial y}{\partial x}|_{\partial D} = J_0 \qquad (3)$$

Equation (2) and equation (3) are Neumann boundary condition for equation (1), where V_0 is measuring voltage on boundary; J_0 is current density on boundary; ∂D is the boundary of D; and n is the unit outward normal vector to the boundary surface. Reconstruction algorithm is solved in two steps: a forward problem and an inverse problem. In the forward problem, the voltage is predicted for any given current density on the field, assuming that the field has a constant resistivity ρ. The inverse problem resolves the actual resistivity distribution ρ(x, y) from all possible surface measurements of $\Phi|_{\partial D}$. The forward problem is simply described as "model parameter" ==> "data", and an inverse problem can be described as "data" ==>"model parameter". The forward problem is well-posed but the inverse problem is highly ill-posed and non-linear. There are different numerical methods such as the finite difference method (FDM), the boundary element method (BEM), and the finite element method (FEM) used for solving the forward problem.

The regularization technique is widely used in EIT image reconstruction to deal with ill-conditionness of EIT. To solve ill-conditioned problems numerically, a priori (i.e. in advance) information about the solution, such as an assumption on the smoothness or a bound on the norm, is needed. This technique is the regularization. Regularization can avoid the unexpected situation of data over-fitting. Regularization applies a priori constraint to calculate "reasonable" solutions. The regularization method is generally classified into three types: back-projection method, iterative method and one-step linearized method.

A. Back Projection Method

The principle is similar to the back-projection reconstruction used in CT. For EIT, each measured voltage is assumed to be proportional to the impedance between the driven and the measuring electrode pairs. Equipotential back projection method [16] is back-projects the impedance change recorded between two electrodes onto the reconstruction model (normally a 2D circular image), along the region defined by the

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equipotential lines ending on those electrodes shows in figure 5. The back-projection method intrinsically introduces blur effect so that normally a filtering process is applied to compensate high frequency information afterward.

B. Iterative Method

This method requests a full reconstruction of the conductivity distribution using iterative approach which considers intrinsic nonlinearity. The linearization of EIT forward model is valid only under the condition that the conductivity changes are of low amplitudes. This condition holds for small changes below 20% of the reference value. However, for some physiological activities such as pulmonary ventilation during deep breathing, this condition is not valid any more. The nonlinear method is applicable for these cases (with certain conditions apply).

It works as follows (as shown in Figure 5):

- First an estimation of the conductivity distribution;
- Calculate the estimated voltage values through forward solution;
- Compare the estimated values with the original recorded voltage data and the error is used to calculate the deviation between the real and the estimated conductivities;
- The conductivity vector estimated is then be adjusted.
- This procedure is repeated until the error between the estimated and recorded voltages is minimized to an acceptable level.

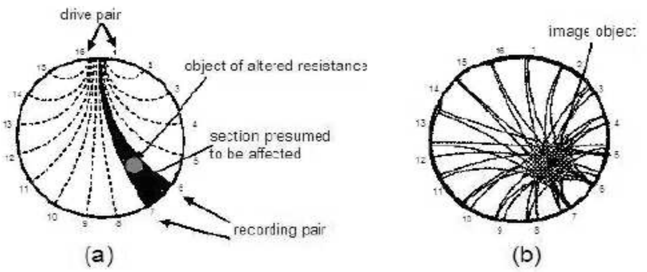

Figure.5. EIT image reconstruction principle by back-projection based on equipotential region (from Holder 2005). (a) Forward projection of EIT. (b) Back projection of EIT.

This method provides more accurate but slower solution compared with the one step linear reconstruction, so that it is suitable for anatomical imaging. But, iterative method is argued to be sensitive to errors. These errors accumulate through iterations and this may introduce instabilities. Hence, iterative methods are good for cases where subjects have well such as tank measurement, and one-step reconstruction is better for in vivo dynamic system measurements.

C. One-Step Linearized Method

This approach simplifies the solution as

$$\hat{x}=By \qquad (4)$$

It addresses the inverse solution as a linear reconstruction matrix B and allows use of advanced regularization methods to solve the inverse problem. The Gauss-Newton (GN) method in EIT [17-19] estimates a solution $\hat{x}$ by minimizing

$$\|y-Jx\|^2_{\Sigma_n^{-1}}+\|x-x_0\|^2_{\Sigma_n^{-1}} \qquad (5)$$

Where $\Sigma_n \in \mathbb{R}^{n_M \times n_M}$ is the covariance matrix of the measurement noise n. Since noise channels are independent, Σ_n is a diagonal matrix with $[\Sigma_n]_{ij} = \sigma_i^2$, where σ_i^2 is the noise variance at channel. Here $\Sigma_n \in \mathbb{R}^{n_N \times n_N}$ is the covariance matrix of the desired image and x_0 represents the expected value of image. Σ_n and Σ_x are modelled a priori.

Let $W = \sigma_n^2\Sigma_n^{-1}$ and $R = \sigma_x^2\Sigma_x^{-1}$. Here σ_n is the mean of noise amplitude and σ_x is the a priori amplitude of image element values. The measurement accuracy is modelled by W. For uncorrelated noise, each diagonal element of W is proportional to the corresponding channel signal-to-noise-ratio (SNR). This one-step linearized reconstruction gives results in a fast solution which is applicable for real time functional imaging. But, the disadvantage is less accurate compare with iterative method.

III. DISCUSSION.

The images are reconstructed for this review from the boundary data collected from the phantom or object with different current patterns using Electrical Impedance and Diffuse Optical reconstruction Software (EIDORS) [20-21]. EIDORS is open source software which is MatLab based image reconstruction algorithm. EIDORS is used to reconstruct the images from electrical or diffuse optical data which is developed with Gauss Newton method. Forward problem and inverse problems are solved with a Finite element method (FEM). For this review, the EIT data's are taken from EIDORS for creating the reconstruction image.

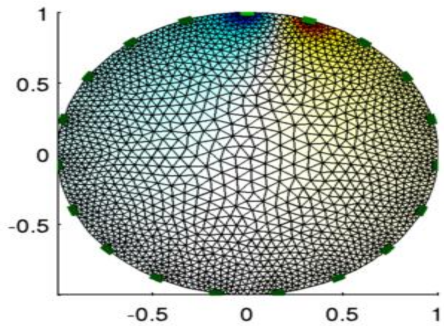

Figure. 6. Voltage pattern for adjacent stimulation

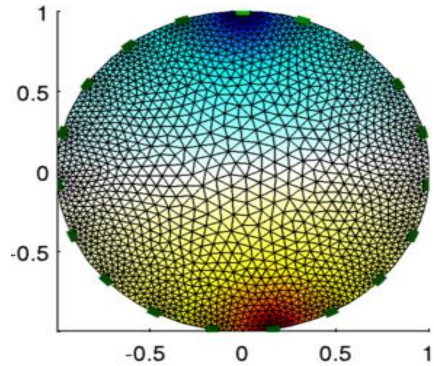

Figure.7. Voltage pattern for opposite stimulation

The voltage pattern for adjacent stimulation which shows (Figure.6.) that the current is injected in the adjacent electrodes and potentials are measured in remaining adjacent electrodes. In this pattern the forward problem is solved using FEM models. Figure.7. shows that the voltage pattern for opposite stimulation, in which the current is injected in the opposite electrodes and potential differences are measured on the voltage electrodes with respect to the reference electrode adjacent to the current-injecting electrode.

In case of thoracic imaging, EIT is used to measuring the ventilation, perfusion and gas exchange. EIT images reflect the lung function which means EIT displays ventilated lung regions rather than morphological or anatomical structures of the lung. EIT images are contained regional information, when pathological conditions like pleural effusion or atelectasis lead to non-aerated and non-ventilated lung regions. Meanwhile EIT images display lungs regions with trapped air (e.g. pneumothorax) in black because they are not ventilated and also partially or not ventilated regions are displayed in dark blue or black color. Figure 8. shows the some of the examples of EIT status images [23].

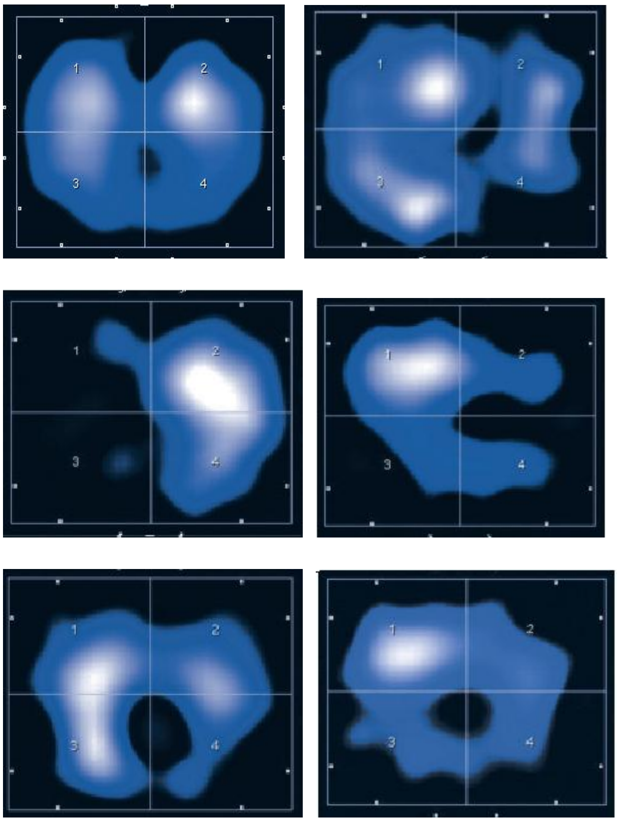

Figure 8. EIT images with various status of lung conditions. From the left to right and top to bottom, the tidal image of a) healthy individual b) patient with pleural effusion in the left lung c) patient with pneumectomy d) patient with a pneumothorax in the left lung e) patient with dorsal atelectasis f) ARDS patient

IV. CONCLUSION

EIT system is having a great potential to provide a new medical imaging modality which is radiation free, non-nephrotoxic, portable and inexpensive. Existing EIT was useful to assessment of regional lung aeration and tidal volume and monitoring rapid lung volume changes. Currently EIT systems are capable of making measurement at much higher rates and recent image reconstruction algorithms provide much improved resolution and robustness to electrode errors with reduced image artifacts and also have greatly reduced noise and interference systems. Some of the commercial systems are currently available in market. . But In the application of control ventilation, an automatic system could be useful in order to better manage of Acute and Weaning phases of mechanical ventilation. To enabling the clinically useful automatic system,

- The systems should be readily available at a affordable cost
- EIT data and images should be accessible in standard formats
- EIT should be robust against electrode contact problems and electrical interference problems.
- Reconstruction Software should have a spontaneous interface focused on the real-time clinical user.
- To enhance clinical decision making, automated approaches for data analysis and interpretation must be included.

In the future, EIT is almost undoubtedly useful in the diagnosis of pulmonary problems, especially for heavily instrumented patients in the ICU to whom the compactness and bedside suitability of EIT are most helpful.

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