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Simulation Study of Noninvasive Electrical Impedance Technique for Continuous Monitoring of Acute Respiratory Distress Syndrome

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ABSTRACT

Acute Respiratory Distress Syndrome (ARDS) can develop in patients due to COVID-19 or flu like viruses if it enters the lower respiratory tract and damages the lungs. These conditions are more commonly known as Pneumothorax (collapsed lung) and Pulmonary Edema (excess fluid accumulation in the lungs) diseases. Healthy lungs have higher electrical impedance than lungs with Pneumothorax and Pulmonary Edema diseases. Electrical Impedance Technique (EIT) which uses surface electrodes for small amount of current (1 mA, 50 kHz) injection & impedance measurements, can be used for ARDS monitoring. Electrical impedance technique has no known health hazard like harmful radiation as in case of X-ray and CT scan. Therefore, EIT method can be used for continuous monitoring of Pneumothorax and Pulmonary Edema diseases. Alam et. al [4, 5] have developed a new current drive and measurements protocol, the Anterior-Posterior Electrical Impedance (APEI) Technique specifically designed for lungs monitoring and found more sensitive than existing electrical impedance measurement techniques for lung function. The developed APEI technique may be useful for the continuous monitoring of ARDS patients by continuously measuring impedance changes and computing the average Relative Electric Potential Changes (REPC). Using our APEI Technique the average REPC values found were (a) 3.24% for healthy lungs at inspiration and expiration, (b) 5.97% for healthy lungs at inspiration and pneumothorax, (c) 2.82% for healthy lungs at expiration and pneumothorax (d) 8.07% for healthy lungs at inspiration and pulmonary edema and (e) 4.99% for healthy lungs at expiration and pulmonary edema respectively. Whereas using the existing widely used Adjacent Current Drive Electrical Impedance Technique the corresponding average REPC values were 1.41%, 2.97%, 1.59%, 4.50%, 3.15% respectively. It is clear from these results that our developed APEI technique have very good sensitivity and accuracy, and may be used for continuous monitoring of ARDS patients including Covid-19 patients.

Keywords: Acute Respiratory Distress Syndrome, Pneumothorax, Pulmonary Edema, Bio impedance, Electrical Impedance Method, Relative Electric Potential Change, Coivid-19 patients.

1. Introduction

Biological cells and tissues contain both the free and bound charges and due to the free charges it can conduct electrical current when external electric field is applied, and show Electrical impedance commonly known as bio impedance. The different human healthy organs show different values of bio impedance are the basis for Electric Impedance Technique. Under an alternating electrical excitation the organs show different electrical bio-impedance which depends on tissue composition and frequency of the applied ac signal. Therefore at a given frequency and excitation (current) the electrical impedance of the biological tissues are influenced by their physiological and physiochemical conditions like healthy or disease and varies from subject to subject [1, 3]. Lungs are the important organ of the respiratory system and its main function is gas exchange, it deliver oxygen (O_2) to the blood and remove carbon dioxide (CO_2) from it [18]. The lung tissues have higher impedance than the muscle. The lung impedance is higher during inspiration than during expiration due to inhalation of insulating air. Pathological changes modify the electrical tissue properties, e.g., lung edema decreases the pulmonary electrical impedance [16]. Most Researchers around the world uses 1 mA alternating current at 50 kHz for EIT technique for human subjects which is assumed to be safe and non- health hazard for biological tissues, and are used in this simulation study.

In case of Pneumothorax where some parts of lungs get partially collapsed and in case of Pulmonary Edema excess fluid is accumulated in the lungs. Therefore, healthy lungs tissues have higher electrical impedance than that of lungs with Pneumothorax and Pulmonary Edema. The electrical impedance technique can be used for continuous monitoring patients with ARDS like, Pneumothorax and Pulmonary Edema diseases

2. Electrical Impedance Measurement Methods or Protocols

In Electrical Imlpedance Technique (EIT) cuurents are injected into the object under test and resulting electrical voltages are measured from the surface eletrodes. Two widely used EIT measuments methods or Protocols are : Neighbouring Method or Adjacent Drive Method and Opposite Current Drive Method are desbrbed briefly.

Neighbouring Method or Adjacent Drive Method

Brown and Segar (1987) suggested a method whereby the current is applied through a adjacent pairs of electrodes and the voltages are measured successively from all other adjacent electrode pairs [9]. Figure 1(a) illustrates the method with 16 equally spaced electrodes. The current is first applied through electrodes 1 & 2 shown in Figure 1(a), and voltages are measured through electrode pairs 3-4, 4-5, -----, 15-16. However, in practice voltage measumens are not made for current carriyng electordes (pair 2-3 and 16-1) to avoid contact impedance problem. Then the procedure is repeated for all other electrode pairs to complete all the measurements.

Opposite Current Drive Method

In this method currents are injected through two diametrically opposed electrodes (e.g. electrodes 16 & 8 in Figure 1(b)), and volages are measured from the rest of the pairs of electodes. The current distribution in this method is more uniform and therefore, has a more uniform sensitivity.

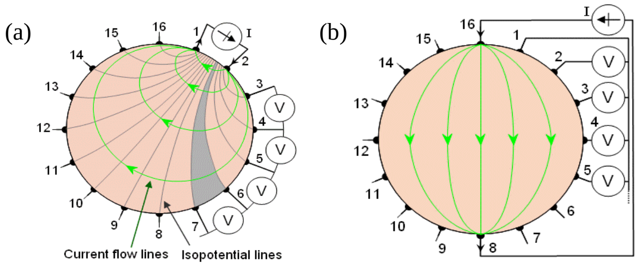

Fig. 1. (a) Neighbouring method of data collection. (b) Opposite method of impedance data collection.

3. Material and Methods

The microscopic anatomical structure of Health Lungs with no fluid in the alveoli and Lungs with Pulmonary Edema where fluids have accumulated in the alveoli are shown in the Figure 2 [14]. In case of Pneumothorax some of the alveolus are get collapsed and cannot contains gases.

In the existing Adjacent Current Drive EIT method two adjacent surface electrodes were used for small and safe current (1mA, 50 kHz) injection and other eight surface electrodes were placed around the horizontal chest plane for voltage calculations as shown in figure 3. But in our developed the Anterior-Posterior Electrical Impedance (APEI) Technique the two surface electrodes were used for small and safe current (1mA, 50 kHz assumed safe) injection at the center of the anterior and posterior side of the chest along the right lung, and the other eight surface electrodes were placed at the posterior side of the chest along the right lung following the ellipsoid shape as lungs for voltage calculations as shown in the figure 5. The COMSOL Multiphysics Version 4.3 simulation software were used in these simulations. The AC/DC Module of COMSOL Multiphysics provides a unique environment for the three dimensional simulation studies, and are used in our 3D simulation for healthy lungs and diseased lungs [10, 11].The dimension and parameters of the chest phantom (eccentric cone shaped) were: a – semiaxis = 10 cm, b- semiaxis =20 cm, height= 42 cm, ratio=1, electrical conductivity = 0.352 S/m, relative permittivity = 10094. For right lung (ellipsoid shaped) a- semi principal axis = 4.5 cm, b- semi principal axis = 6 cm, c – semi principal axis =16 cm but for left lung (ellipsoid shaped) a- semiaxis = 4 cm, b- semiaxis = 4.5 cm, c- semiaxis = 17 cm and lung connector (cylindrical shaped) radius =3 cm, height = 6 cm, electrical conductivity= 0.103 S/m and relative permittivity =4272.50 for healthy lung at inspiration, and 0.262 S/m, 8531.40 respectively for healthy lung at expiration. The surface electrodes (Silver) were sphere shaped of radius = 1cm, electrical conductivity = 6.16×10^{7} (S/m) and relative permittivity =3.4 [11, 12, 13]. The dimension of lungs with Pneumothorax and Pulmonary Edema and their connector were same but their electrical conductivity and relative permittivity were taken 0.60 S/m and 1000, 1.50 S/m and 98.56 respectively [11].

In order to simulate healthy or diseased lung during breathing, electrical conductivity (σ) and relative permittivity ($\in$) of the lung were varied between deflated and inflated lung.Visceral movement (i.e. geometrical changes) during a breath cycle was not considered. In our study diseased lungs like- Pneumothorax and Pulmonary Edema were modeled by changing of electrical conductivity [12]. In this computer simulation studies 1mA alternating current and frequency of 50 kHz was considered.

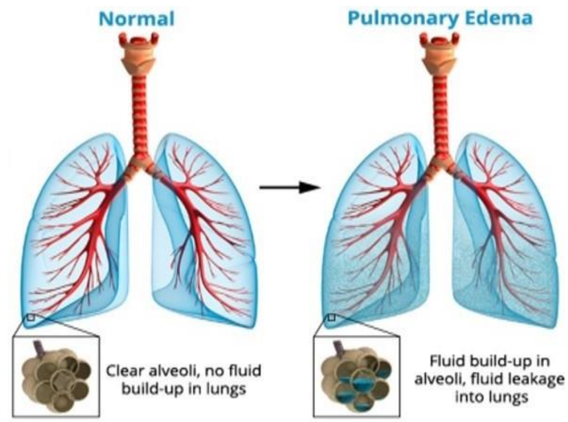

Fig. 2. Healthy (Normal) Lungs and Pulmonary Edema Lungs.

Computer simulated digital chest/thorax phantom and electrodes for the Adjacent Current Drive Electrical Impedance Technique is shown in the Figure 3, where electrodes A and C acts as current drive and electrodes 1 through 8 as voltage measurements electrodes.

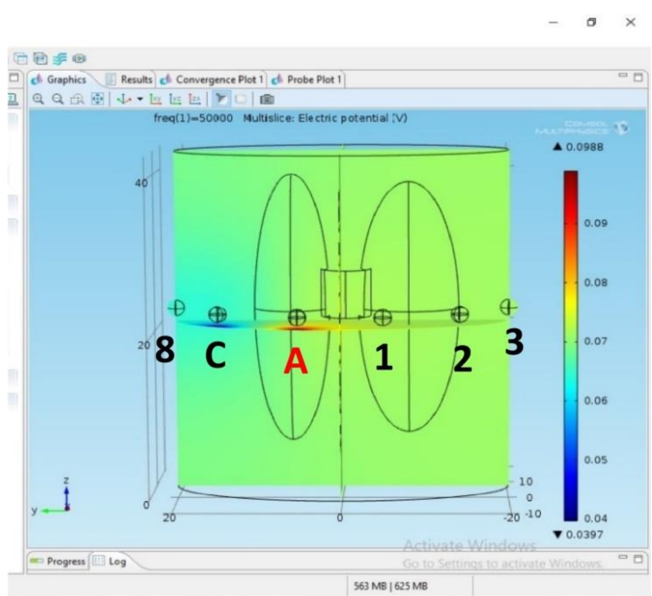

Fig. 3. Computer generated Chest/ Thorax Phantom.

Mesh view of simulated computer generated digital chest/thorax phantom and electrodes of the Adjacent Current Drive Electrical Impedance Technique is shown in Figure 4.

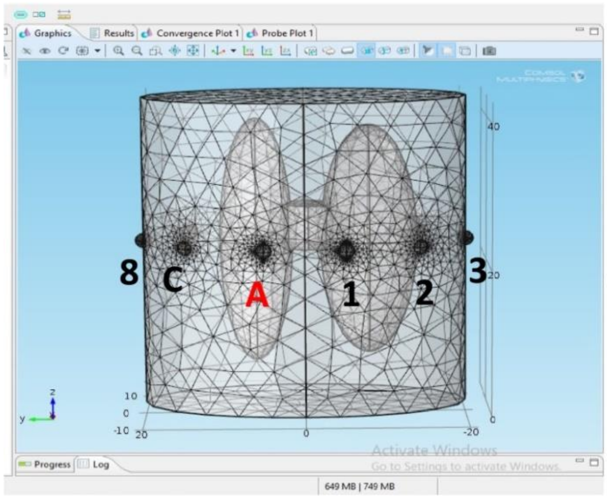

Fig. 4. Mesh view of chest/thorax phantom.

After mesh analysis number of vertex elements 150, number of edge elements 1218, number of boundary elements 8802, number of elements 49650, free meshing time 3.64 sec and minimum element quality 0.0002288.

Simulated computer generated digital chest/thorax phantom and the Anterior - Posterior Electrical Impedance (APEI) Technique as developed by us are shown in the Figure 5(a) and 5(b). The electrode A & electrode C acts as Anode and Cathode for current injection, and electrodes 1 through 8 are as voltage measurements electrodes.

Figure 5 (a): Anterior view of simulated computer generated chest phantom (b): Posterior view of simulated computer generated chest phantom. Surface electrode-**C** (-ve electrode) placed anterior side of the right lung (RL) and surface electrode-**A** (+ve electrode) placed posterior side of the right lung for current driving electrodes. Remaining 1 to 8 surface electrodes are placed posterior side of right lung like ellipsoid shape and anticlockwise direction for voltage calculations.

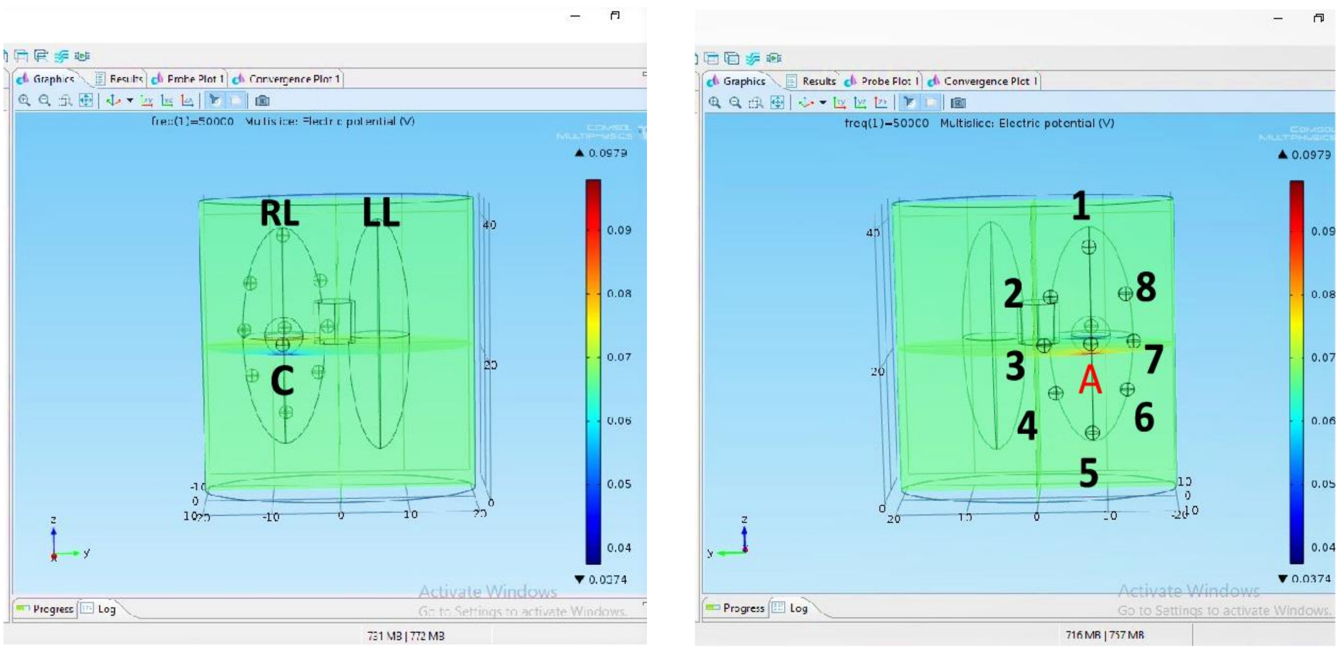

Fig. 5. (a) Anterior view of chest phantom, (b) Posterior view of chest phantom.

Mesh view (Anterior and Posterior respectively) of simulated computer generated Chest Phantoms are shown in Figure 6.

After mesh analysis number of vertex elements 156, number of edge elements 1275, number of boundary elements 9074, number of elements 53311, free meshing time 3.98 sec and minimum element quality 0.036.

4. Results and Discussion

Computer simulations in case of Anterior-Posterior Electrical Impedance (APEI) protocol computed electrical potential at each electrodes for **(a)** healthy lungs at Inspiration (**In**), **(b)** healthy lungs at Expiration (**Ex**), **(c)** lungs with Pneumothorax (**Pn**), and **(d)** lungs with Pulmonary Edema (**PE**) are shown in figure 7. It shows that the calculated electrical potentials for Pneumothorax and Pulmonary Edema are lower than that of healthy lungs at both inspiration and expiration. Therefore, Pneumothorax and Pulmonary Edema can be differentiated from the healthy (Normal) lungs.

We also computed Electrical Impedance Changes $|\Delta Z|_{12}$ between electrodes 1 and 2, similarly for all other electrodes pairs, the above impedance changes $|\Delta Z|$ are computed for four different lung conditions namely at **(a)** Inspiration **(In),** **(b)** Expiration **(Ex),** **(c)** Pneumothorax **(Pn),** and **(d)** Pulmonary Edema **(PE)** and it shown in figure 8. It also shows that Pneumothorax **(Pn),** and **(d)** Pulmonary Edema **(PE)** can be differentiate from normal lungs.

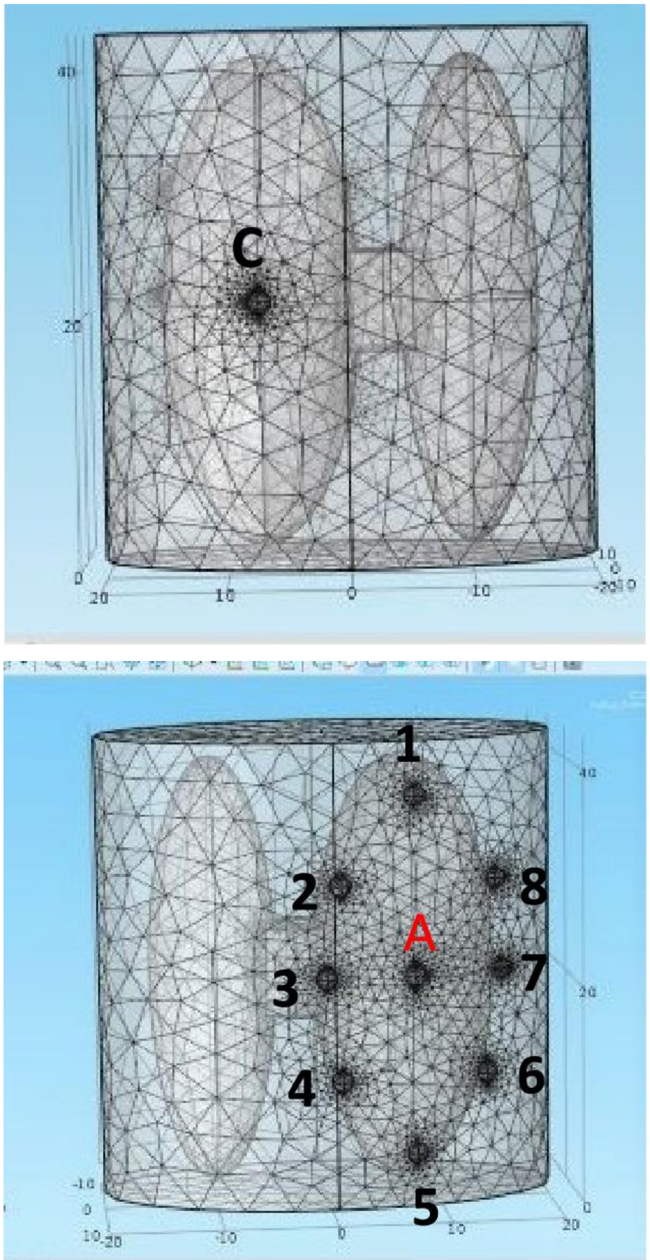

Fig. 6. (a) Anterior Mesh view of chest phantom, (b) Posterior Mesh view of chest phantom

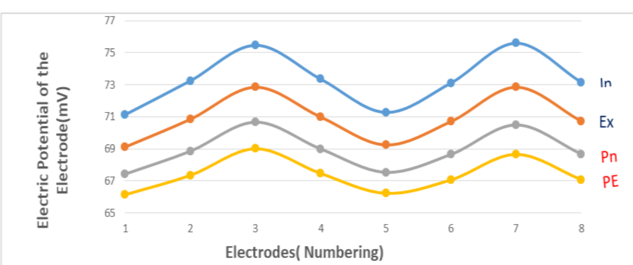

Fig. 7. Electric potentials at different electrodes for different lung conditions.

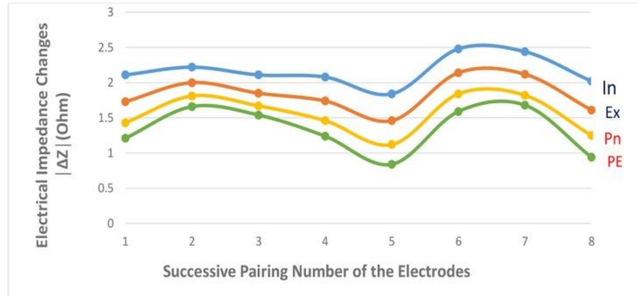

Fig. 8. Electrical Impedance Changes │ΔZ│ for Successive Pair of electrodes for different lungs conditions.

We have defined a parameter, the Relative Electric Potential Change (REPC) for the same electrode(s) using the formula, $\frac{V_n - V_m}{V_n} \times \mathbf{100\%}$; where n, m are the two different conditions of the lungs. We have also calculated the average REPC values from the eight electrodes. In case of APEI Technique **(a)** the maximum, minimum and the average values of REPC were 3.64%, 2.84% and **3.24%,** respectively between inspiration and expiration of healthy lungs, **(b)** the maximum, minimum and the average values of REPC were 6.75 %, 5.22 % and **5.97 %**, respectively between healthy lungs at inspiration and pneumothorax, **(c)** the maximum, minimum and average values of REPC were 3.23 %, 2.45 % and **2.82 %** respectively between healthy lungs at expiration and pneumothorax, **(d)** the maximum, minimum and the average values of REPC were 9.18 %, 7.03 % and **8.07 %,** respectively between healthy lungs at inspiration and pulmonary edema, **(e)** the maximum, minimum and the average values of REPC were 5.75 %, 4.31 % and **4.99 %** respectively between healthy lungs at expiration and pulmonary edema. Figure 9 shows of the average REPC values (%) for five different lung conditions- **(a)** between Inspiration **(In)** and Expiration **(Ex)** of healthy lungs, **(b)** between Inspiration**(In)** of healthy lungs and Pneumothorax **(Pn), (c)** between Expiration **(Ex)** of healthy lungs and Pneumothorax **(Pn), (d)** between Inspiration**(In)** of healthy lungs and Pulmonary Edema **(PE), (e)** between Expiration **(Ex)** of healthy lungs and Pulmonary Edema **(PE)**.

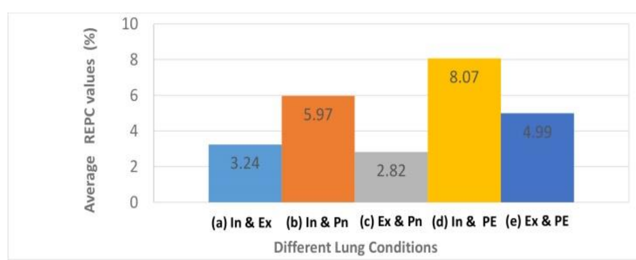

Fig. 9. Average REPC values for different lung conditions for the Anterior-Posterior Electrical Impedance (APEI) Technique.

Similarly we have calculated the REPC values for the existing Adjacent Current Drive Electrical Impedance Technique for the same lung conditions and it shown in the figure 10.

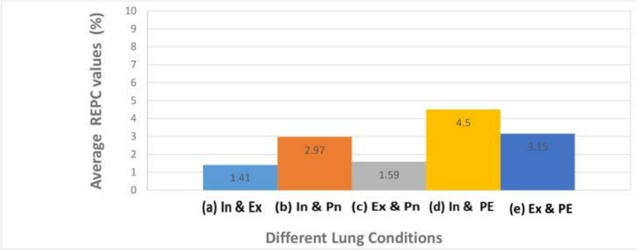

Fig. 10. Average REPC values for different lung conditions for the existing Adjacent Current Drive Electrical Impedance Technique.

Figures 9 and 10 clearly shows that our developed APEI technique is more sensitive than existing Adjacent Current Drive Electrical Impedance Technique in detecting the diseases of lungs from the healthy lungs.

5. Conclusion

The computer simulation results show both the existing Adjacent Current Drive Electrical Impedance Technique and the Anterior-Posterior Electrical Impedance (APEI) Technique can differentiate Acute Respiratory Distress Syndrome (ARDS) from the healthy lungs. Our developed APEI Technique found more sensitive than existing technique. The average REPC values for healthy (normal) lungs at inspiration & diseased lungs are higher than healthy lungs at expiration & diseased lungs. Therefore, the diagnosis of lung diseases will be more accurate during inspirational phases for continuous monitoring of ARDS. However, our developed APEI Technique needs clinical trial before routine use as a diagnostic method for continuous monitoring of ARDS for lung diseases.

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