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Application and Analysis of EIT Image Sequences for Real-time Monitoring of Local Aeration in a Respiratory-like Phantom Device

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ABSTRACT: The present study demonstrates the applicability of the Electrical Impedance Tomography (EIT) technique for real-time monitoring of inspiration and expiration behavior in a respiratory phantom device. The phantom device, which serves as a mechano-electrical simulator of the human respiratory system, is coupled to a real-time monitoring instrument operating based on the EIT technique. This study reveals that the whole system could act as a helpful apparatus for researchers and physicians in improving their ventilation maneuvers for patients. The phantom specifically helps in designing and examining the results of a larger number of experiments, setting up more qualified test environments, and finally more optimal tuning of ventilator devices. The device's physical appearance and structure resemble the human's chest cage, making it suitable to be used as a model of the human respiratory system. Experimental results support the applicability of the phantom and EIT system for real-time monitoring of local aerations in different experimental conditions. Additionally, several recorded and analyzed data leads us to better processing and understanding of the EIT technique and its capabilities in respiration studies. The current work could be considered as a proof of concept and a step towards automatically and intelligently suggesting ventilator settings for optimal adoption of treatment strategies and patient management in hospitals in the future.

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1- Introduction

Optimal respiratory support for patients with severe respiratory problems and those receiving ventilatory treatment in intensive care units (ICUs) is a matter of great importance for physicians and ICU specialists. The optimal selection of parameter settings in a ventilator device is exceptionally crucial in this context. Typically, a specialist or physician adjusts ventilator settings for each patient based on their expertise, which may involve initialization and guided adjustments through trial and error. However, it is widely observed that suboptimal parameter selections may cause some irreparable side effects and damage to the lung tissue and even could lead to a patient's death. Insufficient ventilation to certain lung regions can result in lung tissue collapse, while excessive ventilation can cause overdistension [1]. Therefore, if the physicians simultaneously monitor the quality of lung aeration status in different lung regions during their patient management, they could perform better adjustments in ventilator settings and hence expedite patient improvement [2]. In addition to reducing the mortality rates associated with improved treatment management, there will also be a significant reduction in time costs and financial expenses, due to decreased hospitalization time for patients. This reduction has been identified as a critical issue worldwide during the COVID-19 pandemic.

Electrical Impedance Tomography (EIT) is a technique that can assist physicians in real-time monitoring of lung aeration in patients [3]. There are several different techniques that try to give a real-time view of respiration with different purposes. Some of the techniques include MEMS resonators [4], depth cameras and radars [5], and respiratory effort belts [6]. However, none of the abovementioned techniques can give information about the "local aeration" of the lungs inside the body. We need some "imaging" technique to have that local information EIT is a specific technology that provides that local information for the doctor. The EIT device operates based on the principle that the electrical conductance of the lungs (containing air) is significantly lower than the other adjacent tissues (e.g., muscles, blood, and interstitial fluids). Accordingly, the distribution of electrical current into the tissues and the distribution pattern of the electrical impedance values are used to reconstruct the EIT images. EIT images may not have efficient spatial resolutions compared to other imaging modalities like CT scans (Fig.1). However, they offer advantages such as higher time resolutions, greater accessibility at the bedside, lower cost and no use of ionizing radiations. In general, EIT should provide some functional images from inside the body and just a real-time "global"

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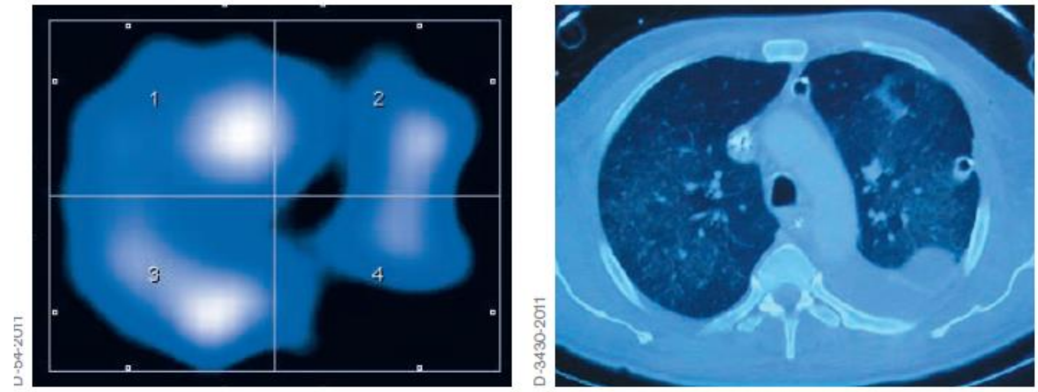


Fig. 1. Left: the EIT image corresponding to a patient with an abnormal left lung, Right: the CT-scan image of the same patient (picture adopted from [8]).

view of the anatomy, not an exact and fine structural one.

The clinical application of the EIT device has been expanding at an increasing rate in recent years [7], and events such as the COVID-19 pandemic have further emphasized the importance of addressing this issue. EIT is anticipated to become a standard monitoring method, assisting in optimal and personalized ventilation of patients and ultimately enhancing patient safety during ventilation [3].

It seems that the automatic analysis of long sequences of EIT images -EIT image sequences indeed- is crucial in advancing its future clinical applications. One of the objectives of the proposed study is to take a step towards providing a platform for the automatic analysis and better understanding of EIT data/images as a valuable monitoring tool. Similar to other analytical and processing approaches, a key requirement for achieving this is access to a large amount of EIT data images recorded under various experimental conditions. However, there are currently limitations to conducting this kind of experiments and analysis on humans. Firstly, EIT device has not yet been fully applied as a clinical tool in healthcare facilities. Although some significant medical equipment manufacturing companies produce and release this technology, it is still not widely available to healthcare professionals. Therefore, it is not feasible to obtain a high number of clinical recordings from actual patients yet (unlike electrocardiographs for example, that are widely used in healthcare). Secondly, even if an adequate number of these devices were available to healthcare professionals, it would not be possible to subject those patients with severe medical complications to various types of trial and error-like experiments and expose them to inherent risks just to gather more and more data. Hence, we must consider some alternative solutions.

One of these alternative solutions is to achieve a suitable "model" of the patient and use it instead of the patient in our experiments and EIT data gathering and processing tasks. By using an appropriate model, we can simulate multiple and diverse experiments and maneuvers, and accurately predict the potential outcomes without subjecting patients to any specific risks.

Generally speaking, a model of the human respiratory system can be realized in different forms, from using another living organism in experiments (such as pigs) to a mechanical simulator of the human respiratory system (commonly known as a phantom) or even a fully computational and numerical model [9] [10] [11]12]]. A robust computational model could be embedded into a ventilator device and assist the physician in their pre-treatment planning by allowing a series of numerical and virtual experiments to be conducted beforehand. Subsequently, the optimal device settings can be determined based on the patient's current condition. Such a model can contribute to the study and design of various experiments and respiratory maneuvers, guiding us towards intelligent ventilation automation, automatic ventilator adjustments, and personalized treatment for each patient in near future [1], [13].

This article presents an intermediate step in this direction, leading to the design and construction of an electro-mechanical respiratory simulator device (phantom). In biomedical engineering, a phantom refers to a physical imitation of the human body or a living organism. Phantoms have various applications in medicine, including medical students' training [13], as well as the improvement or enhancement of medical imaging techniques and devices [14, 15].

The main objective of designing and using the respiratory phantom in this research is twofold. Firstly, it aims to reduce potential risks associated with conducting various experiments on living organisms while increasing the flexibility of experiment designs and respiratory maneuvers. Secondly, this device can further assist in optimizing the design and developing the capabilities of the EIT recording device itself, since it offers a higher level of realism compared to other phantoms used in EIT studies [16] [17] [18].

Section 2 of the article introduces the physical

Fig. 2. This Fig.ure shows the evolution of our concept designs for the respiratory phantom, with the ideas progressing from left to right.

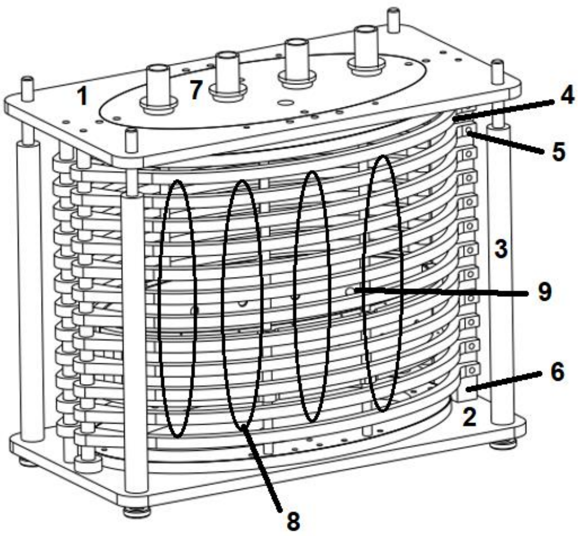


Fig. 3. The schematic diagram of the designed phantom. Numbered parts are introduced in the paper.

specifications of the respiratory phantom device and explains how it functions. In this section, we will not only explain the mechanical specifications of the phantom but also discuss its electrical characteristics. Furthermore, the EIT device and the principles of its function will be described. Subsequently, the results of some experiments and EIT recordings from the phantom will be presented in section 3. Data is collected during different artificial breathing maneuvers conducted by a ventilator in different simulated healthy and unhealthy conditions of the phantom and different ventilator settings. Section 4 presents a summary of the whole work and a discussion about the future horizon of the current study.

2- Phantom Device Properties and Design

The respiratory phantom developed here simulates certain structural, functional, and electro-mechanical properties of the human thoracic system that play a role in respiration. The phantom can be connected to a ventilator device and simulate a breathing behavior. Simultaneously, real-time EIT signals from the phantom are recorded. Therefore, the phantom not only mimics the respiratory mechanical function but also provides moment-to-moment electrical data, through EIT, about the local aeration inside it.

2- 1- Mechanical Design

Different structural and functional considerations were considered in our design of the phantom, resulting in an acceptable representation of the mechanical movements and electrical properties of the chest cavity. Some of our primary and evolving designs are presented in Fig.2 (The final and accepted concept design is seen on the right side of Fig.2). The phantom is made of various components, including a transparent plastic enclosure as a movable cage which is limited in its upper and lower sides by two solid surfaces (Parts 1 and 2 of Fig.3). This enclosure, which is completely sealed to the solid surfaces, serves as a movable wall imitating the movements of the chest cavity during respiration. It is filled with a saline solution (with a density of 9 grams of salt per 1000 milliliters of water), to approximate the electrical properties of conductive parts of the respiratory system, such as muscles and blood. Its conductivity should be significantly different from air. Eleven pairs of some rib-like curved plastic pieces (Part 4 in Fig.3) are connected on both sides to two other vertical walls, resembling the sternum and the spines (Part 6 in Fig.3). These connections are made by using some screws and springs (Part 5 in Fig.3) to adjust the level of stiffness and movability of the ribs. By properly

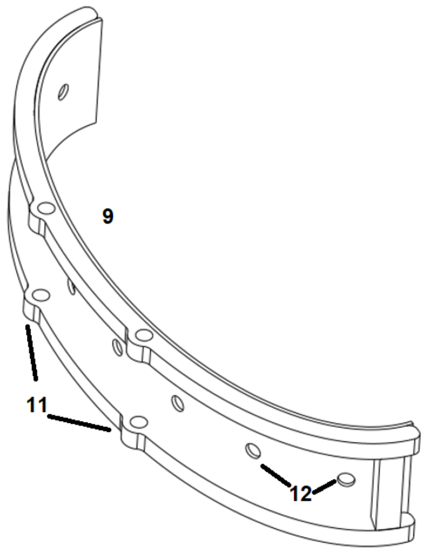


Fig. 4. More detailed form of part 9 in Fig.3: the curved belt housing the EIT electrodes inside the phantom. Indicated holes (number 11) illustrate the location to place adjustable height-regulating screws through them and holes numbered 12 illustrate the positions of metal plate EIT recording electrodes (two sets of 8 electrodes are placed on two belts)

adjusting these screws and springs, we're able to simulate some abnormal respiration patterns (muscle weakness for example) in the phantom.

Inside the plastic cage filled with saline, there are four air-filled balloons located vertically and fixed to the top and down surfaces, resembling lobes of the human lungs (ellipse-shaped elements shown as Part 8 in Fig.3). The upper part of these balloons is connected to air inlet valves, which is supposed to receive the air from the ventilator. The reason for using four balloons (even though humans have two lungs) is because human lungs consist of relatively distinct sections called lobes. To create better spatial differentiation in our studies, we have considered four air-filled sections as an estimation of those lobes (even though it is not exactly similar to the anatomy). The inlet valves are connected to plate number 7 in Fig.3.

Inside the liquid-filled plastic enclosure, there exists a particular setup for locating the EIT recording plate electrodes. There are two curved plastic belts for housing and positioning 16 metallic EIT electrodes (Part 9 in Fig.3). More detailed information about these belts is provided in Fig.4. The belts are located on two adjustable height-regulating screws, and their cross-sectional view could be tuned by the user just by turning the screws and moving the electrodes up and down.

2- 2- Electrical Design for EIT recording

A set of electronic circuits for recording electrical potential signals from the EIT electrodes has been previously designed and calibrated using a specially designed resistance array board [19] and is used in this study (Fig. 5). The signals are recorded and transmitted to the computer via a Bluetooth-receiving USB device. Subsequently, the EIT images are reconstructed using a computer program. As declared before, the whole EIT system takes the electrical impedance as an indicator to visualize the differentiation of lungs with other adjacent tissues (in our case, the differentiation of air-filled balloons with the surrounding conductive liquid). This enables us to observe the changes in local volumes of the lung (balloon) over time.

To create an EIT image, a specific number of electrodes (typically 16 or 32) are initially placed around the patient's chest cavity (Fig.6). Then an electrical current - of relatively low intensity (5-10 mA) and high frequency (50-80 kHz)- is established between a selected pair among the electrodes (for example, electrodes 1 and 16, as shown in Fig.6). After this current injection, the potential difference created due to the distribution of this electrical current into the body is measured across the other electrodes (V1-V13 in Fig.6). The process of injecting electrical current is repeated iteratively 16 times; e.g. between electrode pairs 1-2, 2-3, 3-4 and so on. Finally, we will measure a matrix of 16*13 recorded voltage values from all electrode pairs. These values are then passed into some computational tomographic reconstruction algorithms and numerical analysis methods, like the Finite Element Methods (FEM), to estimate the pattern of electrical impedance values in the cross-section surrounded by the electrodes (Fig.7.a). The final generated pattern of electrical impedance distribution is called an EIT image (Fig.7.b). The computer program for EIT image reconstruction used here exploits some functions from the open-source EIDORS library toolbox [20].

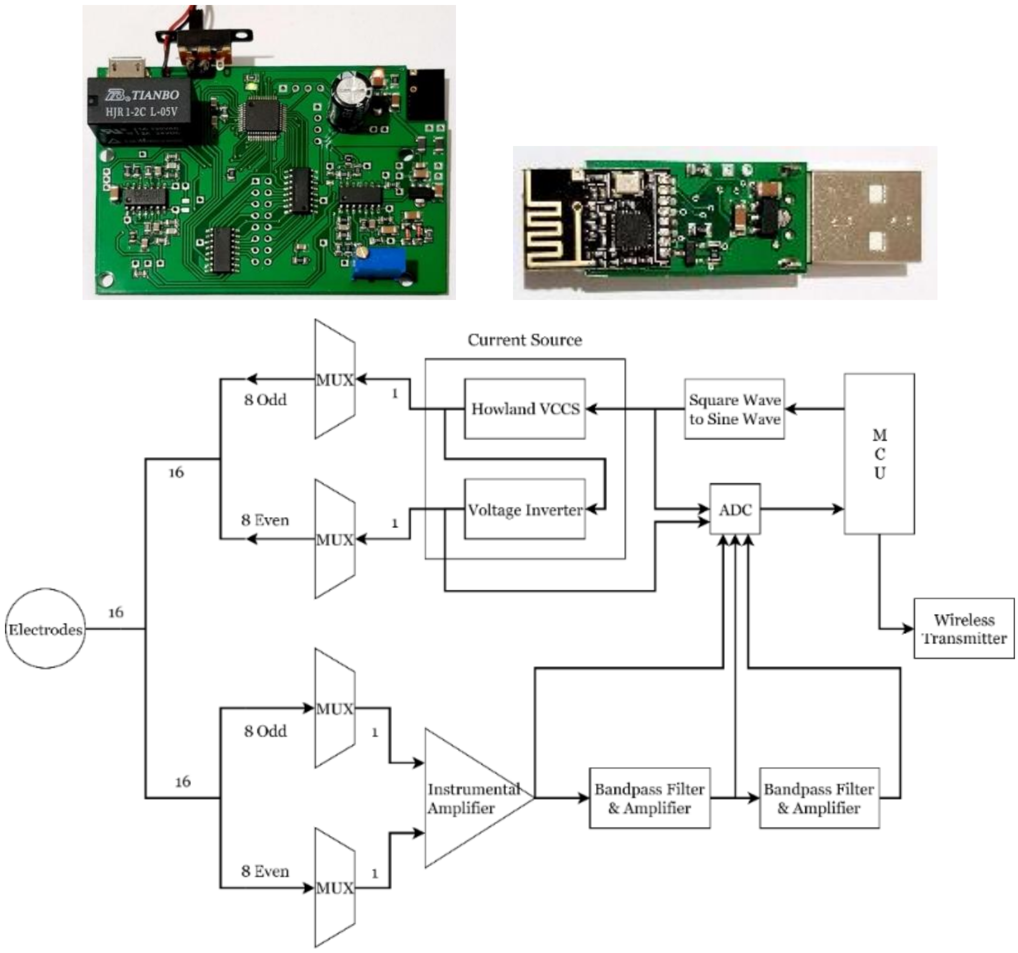


Fig. 5. The circuit designs and the fabricated printed circuit boards used for EIT recordings (picture adopted from [19]).

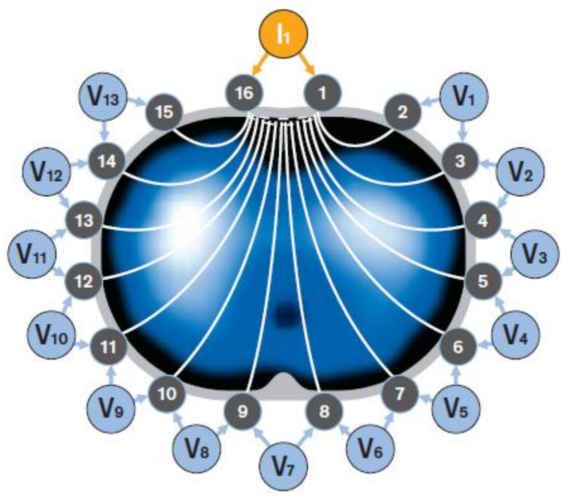
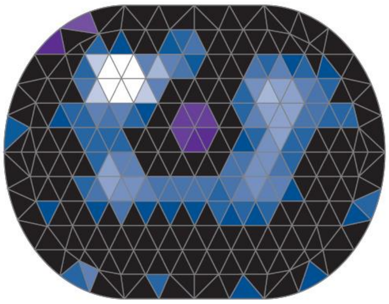


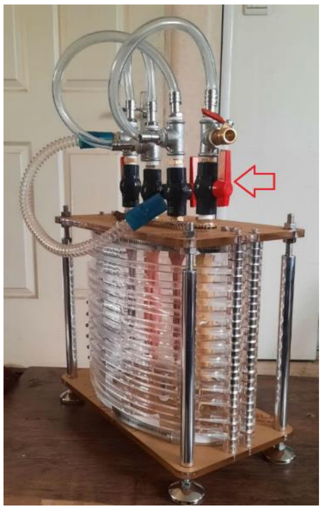
Fig. 6. Placement of 16 EIT electrodes around the chest cavity of an individual. Electrical current is established between pairs of electrodes in an iterative way (here, for example, electrodes 1 and 16). Meanwhile, the electrical potential difference between other electrode pairs is measured (V1, ... V13) (picture adopted from [8]).



(a)

(b)

Fig. 7. (a) Meshing of the cross-sectional surface for numerical image reconstruction based on the FEM method. This image can be further processed and smoothed to provide a more descriptive representation (b) (picture adopted from [8]).



(a)

(b)

Fig. 8. Actual image of the respiratory phantom device. (a) The air valves in the upper part of the device, with one of the four valves indicated by the red arrow, serve as the entry point of air into each balloon. (b) For ease of data analysis, the valves and their connected balloons were numbered from 1 to 4.

3- Experiment designs and Results

As mentioned before, the phantom is designed as a "model" of the human respiratory system. It is supposed to be used for generating and analysis of EIT image sequences in different experimental setups, representing healthy/non-healthy respirations. The actual phantom built and used in our experiments is shown in Fig.8. The device can be connected to a ventilator through the air pathways linked to its related valves (one of them is referred by the red arrow in Fig.8.a). For convenience, the valves and their connected balloons were numbered from 1 to 4 (Fig.8.b). In this study, different experiments were designed based on the openness or closure of these valves (Fig.9). additionally, various EIT-related signals were recorded and analyzed, and they are illustrated in this section.

The phantom is connected to a standard anesthesia machine with a ventilator inside[1] (Fig.10.a). The adjusted ventilatory parameters in the machine, including input pressure, volume, and others, indicate that the entire mechanical structure of the phantom (with four open valves and balloons in the loop) closely mimics the normal respiratory behavior of humans (Fig.10.b).

Experiments were performed in two scenarios and EITs were recorded each time:

1. The Cyrus-3000 model anesthesia machine is manufactured by Saramad-Teb-Paraye Co.

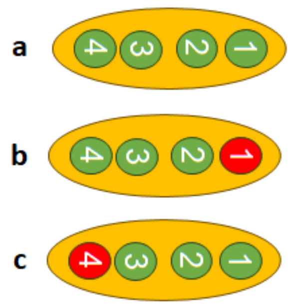


Fig. 9. The experiment setups: (a) normal respiratory mimicry (all valves are open), (b) lack of ventilation in balloon 1 (valve 1 closed), (c) lack of ventilation in balloon 4 (valve 4 closed).

(a) (b)

Fig. 10. (a): Connecting the respiratory phantom equipped with EIT electrodes to a standard anesthesia machine (Cyrus-3000) with a ventilator. (b): the ventilator parameters during recording from normal setup indicate that the phantom is a reasonable model for human respiration, as it exhibits global settings such as a respiration rate of 12 and a tidal volume of approximately 700 ml.

All the connected valves were open, allowing airflow to pass into all four balloons. We consider this situation as normal breathing.

One or more valves were kept closed, which mimics some kind of abnormality or occlusion in the ventilation of the phantom.

EIT recordings were conducted for 1 minute, and the respiration rate adjusted in the ventilator was ten inspiration-expiration cycles per minute. The total recording and computation time in the electrical circuit board and the data reading software in the computer (written in MATLAB) was approximately 0.2 seconds. Therefore, 300 measurements of electrical voltage samples were taken in 1 minute. The achieved time resolution of 0.2 s in our system could be considered good enough for a real-time ventilation monitoring task, as each inspiration-expiration cycle takes approximately 6 seconds (10 cycles in our tests).

When all four valves were open (representing a healthy condition), at the end of each breath, all balloons expanded to an equal extent. In the reconstructed image for this condition,

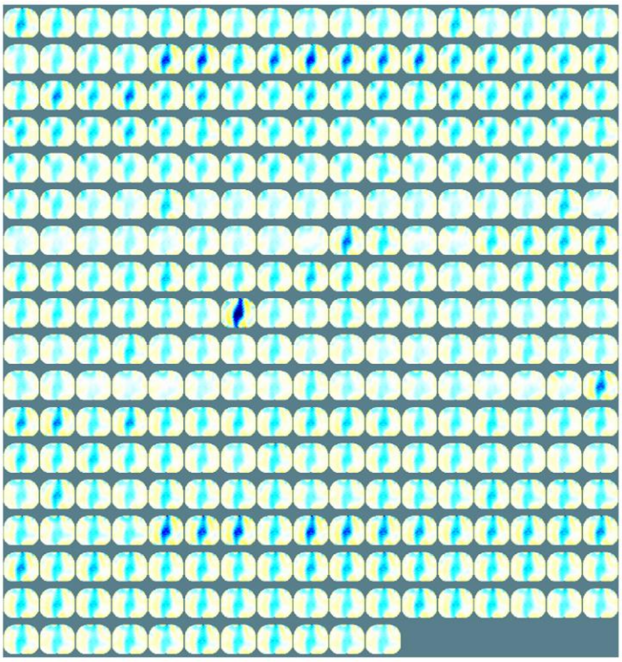


Fig. 11. The EIT recording for a normal respiratory state (with all four valves open), displaying 300 frames recorded over a duration of 1 minute. In the reconstructed images, the middle region undergoes a nearly uniform color change (spatial), indicating the observable normal respiratory cycle.

a consistent color change is observed in the middle region of the image (Fig.11), which means that the aeration is almost uniform in the whole volume of the phantom cage.

To validate the capability of the phantom and EIT device in showing local aeration data, two separate arrangements are proposed here as mimicking unhealthy conditions (Fig. 9-b, c): (1) valve #1 was closed (while the other three were open), (2) valve #4 was closed (while the other three were open). The corresponding reconstructed images of these inadequate simulated respiratory cases are shown in Fig. 12 and Fig. 13, respectively. These results indicate that the EIT-enabled phantom can be used as a test lung and a laboratory apparatus for conducting various arbitrary experiments and recordings. A reliable setup for EIT data collection is provided and further processing and analyzing steps of EIT image sequences could be achieved. An example of EIT analyzing applications is provided in the following.

If the ventilator setup is not properly selected, the aeration may be insufficient. We examined this by setting up a normal situation inside the phantom (All four valves were open) and by giving a low-pressure ventilation as an input to the phantom. EIT signals were recorded simultaneously, but they couldn't show anything meaningful at first (Fig.14.a).

We could see that only two balloons received the air, and the others didn't change their volumes during this low-pressure ventilation. This is not the case for human ventilation, as the physician/operator cannot visually observe the inside of the patient's lungs to see what is happening locally. However, the recorded EIT signals can help the operator identify imperfect aeration, which may be attributed to low-pressure in the input. In our case, by calculating a simple feature, it is possible to recognize when something is wrong. This feature is the mean-value of each EIT reconstructed image frame, which is represented as a time-series (Fig.14.c). As can be seen in Fig.14.c, there is a baseline drift in this signal that should be removed through post-processing steps, such as drift canceling and normalization. The enhanced signal is shown in Fig.14.d which is now a periodic signal representing the expected inspiration-expiration cycles. The corresponding enhanced EIT image sequence is shown in Fig.14. b. Now it is evident that a respiration cycle is detected (unlike the non-periodic pattern of Fig.14.a), However, the new enhanced image sequence highlights the inadequate and non-symmetric pattern of aeration inside the phantom.

4- Discussion and Conclusion

This work introduces the capabilities of the EIT technique as a real-time monitoring method that can help in better regulations and adjustments of ventilator devices. It also introduces and discusses the role of a unique respiratory phantom device in the development of the abovementioned technique. The phantom device coupled to the EIT technique, presents a specialized laboratory apparatus for different experiment designs and data collection basis. Those valuable, easily, and non-costly in-hand data are targeted to be used in the perspective of developing a model-based real-time ventilatory intelligent control system.

Hence, the current study could be considered as a first step

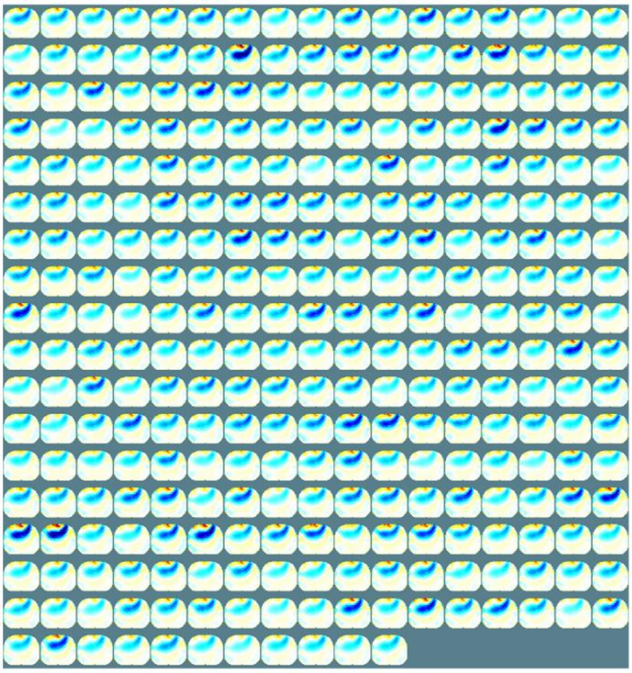


Fig. 12. The EIT recording for the altered respiratory mimicry condition with an anomaly is as Condition 1: Valve number 1 was closed while the other three valves remained open.

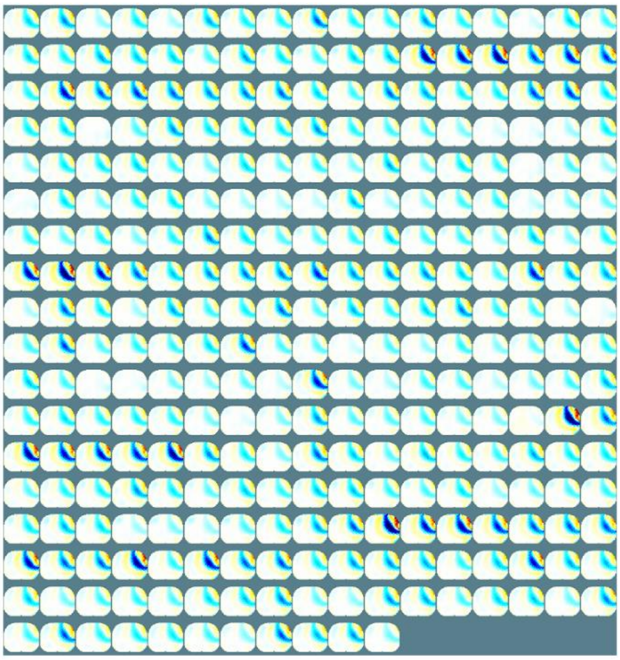


Fig. 13. The EIT recording for the altered respiratory mimicry condition with an anomaly is as Condition 2: Valve number 4 was closed while the other three valves remained open.

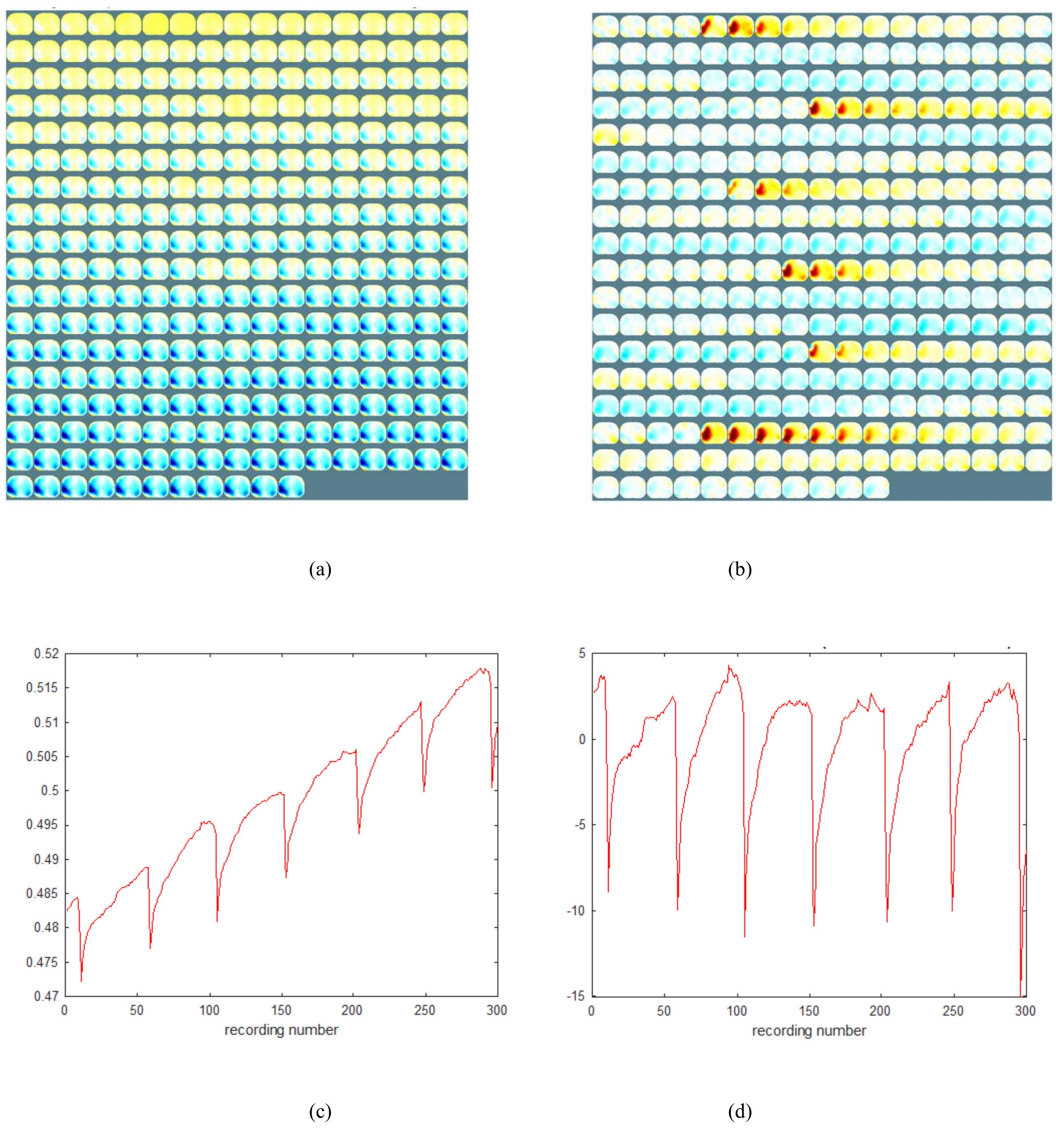


Fig. 14. Unusual EIT values could be a signature of inadequate ventilation. (a) EIT reconstructed the sequence for 1 minute recording under low-pressure settings of the ventilator. This data should be post-processed to be used as reliable data. (b) post-processed and enhanced versions of those EIT images, whose drift has been removed, and the contrast is enhanced. The new sequence reveals the respiration cycle and highlights a problem with local aeration, which is attributed to low-pressure ventilator settings. (c) mean absolute value of the original reconstructed EIT frames, (d) mean absolute value of the post-processed reconstructed the EIT frames (drift-canceling, normalization, and contrast improvements).

and a proof of concept to achieve the final "computational" model for real-time simulation of human lungs during respiration. Such a real-time human respiration- model would serve as a built-in laboratory in the physician's hand, while they are using the ventilator for each patient. This virtual but valid laboratory reduces the vital costs and inherent risks associated with suboptimal ventilation routines. It can also lower the workload of healthcare professionals and even the financial costs related to the long hospitalization of patients.

Another beneficial application of the designed phantom is providing a framework for optimizing the design and application of the EIT device itself for better and more efficient applications. For example, one of the challenges with EIT is that it provides a 2D image of a 3D volume, and has a limited spatial resolution (since it mainly serves as a functional indicator of lung conditions, not a structural imaging tool). Enhancement of the EIT device (in design and application) could help to extract and represent three-dimensional information and higher spatial resolution. The closest and most similar phantom designed to the present work may be a device designed to evaluate the possibility of applying tetrapolar measurements using the EIT device [18]. However, the phantom device presented in our work is a more flexible and realistic simulator of the respiratory system. Details have been reported in our previously published paper [21].

5- Acknowledgements

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