A New Method of Visualizing Lung Ventilation by Means of Breathing Sounds

Oskar Seifert, Volker Gross, Henning Schneider, Martin Kramer, Andreas Weissflog, Keywan Sohrabi

***Abstract*— Standard imaging procedures to determine lung ventilation are CAT-scan and magnetic resonance imaging. These procedures involve high radiation exposure, high expenditure and plenty of time. They are not suitable for preventive and multi-examinations, neither for monitoring. The new ThoraView®-system dynamically displays lung ventilation based on lung sound detection and analysis. The aim of this study was to validate (i) the display of lung ventilation (ii) and if ThoraView® can detect and display nonventilated areas. In a clinical study, 17 healthy piglets were examined. Nonventilated lung areas were created using a bronchial blocker. CAT-Scan and magnetic resonance imaging were used to verify the regional distribution of (non)ventilation. The ThoraView®-system used 30+1 microphones on a dorsally positioned microphone pad to record and analyze breathing sounds. Greyscale pixel values of ThoraView® images from both ventilated and nonventilated lung sides were compared. High values indicate high ventilation, whereas low values stand for less ventilation. The new system was able to successfully detect and display lung ventilation and also nonventilated areas. Mean grey pixel values were 346.47 ± 8.42 and 404.27 ± 4.92 for the blocked and nonblocked lung sides, respectively. Significance was $p \leq 0.01$. We conclude that ThoraView® has the potential to substantially support clinical routine as an innovative and comfortable monitoring device for the increasing numbers of respiratory diseases. Further studies are necessary to validate the operational capability in human medicine.**

***Index Terms*— Dynamic lung ventilation, lung imaging, pulmonary diagnostics**

I. Introduction

Sufficient lung ventilation is a crucial requirement for an effective gas exchange between pulmonary alveoli and capillaries. Therefore, quantification of the lung ventilation is extremely important in diagnostics, therapy planning and therapy monitoring of many pulmonary disorders. Respiratory diseases belong to the most common diseases and causes of death in human medicine [1]. Airway obstructions due to pulmonary diseases can lead to an unequal or insufficient ventilatory distribution, causing severe ventilation-perfusion disorders. Standard imaging procedures for the diagnosis of lung ventilation are computer assisted tomography (CAT-scan) and magnetic resonance imaging (MRI) [2]. These procedures involve high radiation exposure, expenditure and are not suitable for preventive and multi-examinations and neither for monitoring. Furthermore, the given information is nondynamic and therefore limited. There have been several approaches to dynamically display lung ventilation in order to find out more about respiration, rather than anatomic conditions. However, these technologies have numerous limitations. One example is the Vibration Response Imaging (VRI), which works by detecting acoustic lung vibrations from the patient's back [3], [4]. These vibrations are then converted into images. Its major limitations are the low resolution and the limited recording time of three to four breathes. The system needs about 30 s to process the data and to display it on the screen. The VRI never functioned as a real-time (online) system and is faced with many artifacts due to the extremely touch-sensitive sensors type. Another example is Electrical Impedance Tomography (EIT), which also measures and displays lung ventilation. It uses ECG-type electrodes to create images based on the internal impedance of the patient [5]-[7]. The impedance correlates with the ventilation of the patient at a particular moment and a particular area. It works relatively fast and displays images in real time. However, it can only display one transversal plane of the human lung, therefore limiting the overall diagnostic view [8]. The technology also provides a relatively low spatial image resolution. Advances in computer technology in general made it now possible to acquire, process, analyze, and store lung sound signals from multiple sites and visualize regional acoustic changes during real-time respiration. Thus, they provide a more complete and less subjective assessment of pulmonary function and ventilation.

This paper introduces a comfortable and mobile approach to dynamically visualize lung ventilation. The new ThoraView-system uses surface skin sensors (microphones) that are spatially distributed and attached onto the individual's back. Breathing sounds spread out through the lung and get damped – depending on the physiological conditions (i.e. obstructions,
blockages). The microphones record and analyze the incoming sounds and the analyzer creates a dynamic display of lung ventilation. An additional oral sound application may visualize inaudible lung areas.

The aim of the study was the validation of the ThoraView-System. We assume by hypothesis that the new system dynamically displays lung ventilation. Furthermore, it

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is capable of distinguishing between ventilated and nonventilated lung areas. The oral application of defined sound signals affect resolution and specificity on these areas.

II. Materials and Methods

In a preclinical trial, we investigated 17 pigs (7 male, 10 female, 10 weeks old, Ø 27kg). They were narcotized, ventilated mechanically (Cicero EM, Dräger, Germany) and dorsally positioned on a stabilizing rest cushion. A bronchial blocker (Rüsch, Germany) was inserted through the endotracheal tube to create a nonventilated lung area (NVA) on one lung side. This area represents a pathological scenario (i.e. obstruction/blockage) that can occur in several lung diseases. The lung sides were blocked randomly, depending on the insertion process. We then examined the entire lung with the help of CAT-Scan (16-slice spiral, Philips), MRI (1-Tesla, Philips) and ThoraView (ThoraTech GmbH, Giessen, Germany). CAT-Scan and MRI served as validation for the blocked lung area. During the examination with ThoraView, lung sounds of each animal were recorded for eight minutes – four minutes of normal breathing and four minutes of breathing with oral sound application (400 Hz tone). A CAT-scan was performed at the beginning and at the end of each examination. This served as a validation for possible physiological changes during anesthesia and mechanical ventilation. The overall process to examine one pig took about five hours. Vital parameters were monitored at all times. One anesthetist and three assistants were necessary to conduct one examination.

The gathered images from CAT-scan and MRI show the transverse plane, whereas ThoraView images show the frontal plane. By using a marker (liquid filled capsule) on the skin surface, it was still possible to align the different planes. The ThoraView system uses 30 microphones to detect lung sounds (Fig. 1). An additional microphone records tracheal sounds to distinguish between ins- and expiration [9]. The microphones are integrated into a microphone pad (Neoprene®), which is connected to the required hardware for data acquisition (National Instruments USB-6259 Mass Term) and to a display monitor. The microphones which rest against the animal's back guarantee an entire and consistent lung sound detection. The animal's body weight creates a sufficient microphone contact pressure. A sound generator is installed on a moving arm and is used for the assessment of oral sound application on image resolution and specificity. It is assumed that an oral transfer of sound signals which are damped depending on the ventilation disorder enables the operator to see peripheral lung ventilation that stays hidden in other procedures. Therefore, inaudible lung areas may be made visible. The sound signals spread inside the lung, get damped at certain areas and will eventually be recorded by the microphones. This assessment is part of the hypothesis described in the introduction.

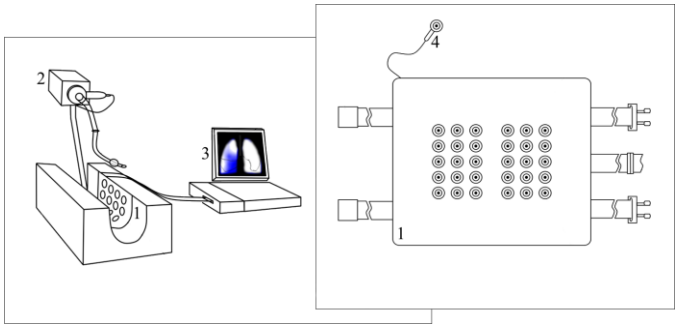

Fig. 1. ThoraView's device components: microphone pad (1), sound generator (2), display monitor (3) and tracheal microphone (4).

The audio and image processing uses multifractal analysis and the signal's attenuation coefficients and runtime. That way, the acoustic output signals are converted into continuous moving images. Both audio and image data can be processed further on. Exterior noises are filtered out up to a certain extent. The created ThoraView image shows the lung ventilation in a frontal view (Fig. 2).

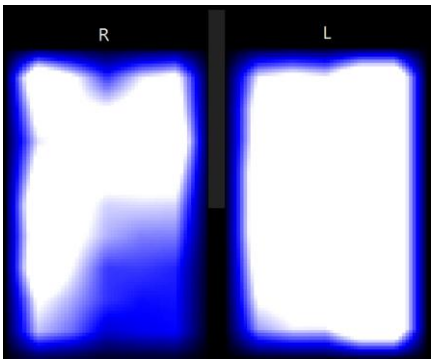

Fig. 2. ThoraView image of both lung sides in frontal view during inspiration. NVA on the lower right lung side.

White regions indicate well ventilated areas (hearable sounds), whereas blue regions represent less- or nonventilated areas (less sound). The system allows an adjustment of the sensitivity in case of audio overmodulation. This guarantees an adequate image quality even for very loud or quiet sounds.

In order to validate the system's ability to detect and display NVAs, regions of interest were defined (Fig. 3). Images were taken during the inspiratory breath cycle of each animal. For evaluation purposes, the images were converted into greyscale images using MATLAB (The MathWorks, Inc.). Their lower normal ventilated lung side was compared with the lower blocked lung side regarding their greyscale pixel values. These values represent the ventilation intensity of the animal. This applies to the scenarios with and without oral sound application. A paired two-tailed student's t-test was performed to check for significant differences between mean values, which are displayed with standard error.

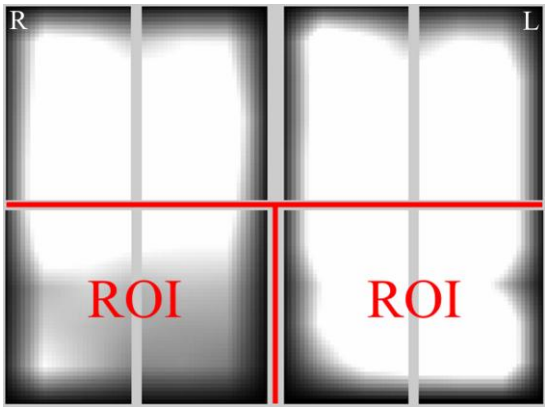

Fig. 3. Defined regions of interest indicated in red. Right lung side blocked.

III. Results

The clinical study was completed successfully. NVAs that were induced by the bronchial blocker could be verified with both CAT-scan an MRI, which served as basis for the evaluation with ThoraView (Fig. 4). The right lung side could be blocked in 14 animals, the left lung side in three animals. The area of nonventilation varied from small areas up to almost one entire lung side in some cases.

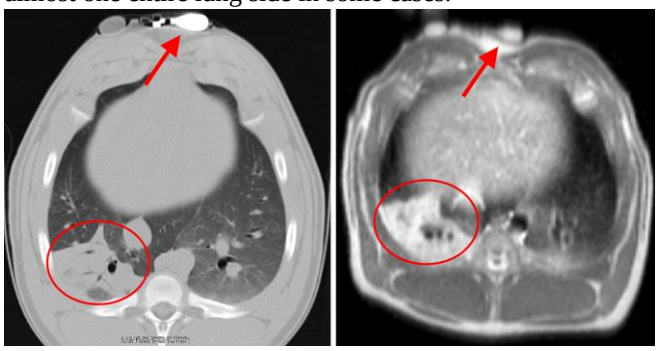
Fig. 4. Validation of created NVAs (circled in red) with CAT-scan (left) and MRI (right). Marker verifies same plane (red arrow).

ThoraView was also able to display the NVAs during different severities of blockage (Fig.5). Blue regions indicate NVAs.

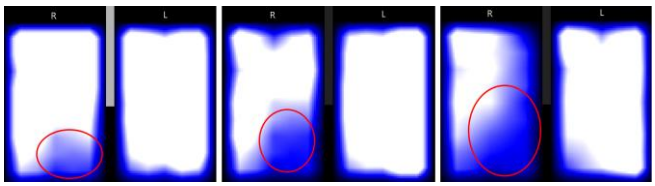
Fig. 5. Slight NVA (left), medium NVA (mid) and large NVA (right).

When looking at the greyscale values of the animal's lung ventilation individually, NVAs could be identified on each blocked lung side (Fig. 6, 7). A higher value indicates a brighter image, which can be found in well ventilated areas. Lower values stand for darker areas that remain less ventilated.

Without oral sound application, mean values were 346.47 ± 8.42 and 404.27 ± 4.92 for the blocked and nonblocked lung side, respectively. The p-value was $p \leq 0.01$. With oral sound application, mean values were 367.2 ± 12.56 and 410.47 ± 5.12 for the blocked and nonblocked lung side, respectively. The p-value was $p \leq 0.01$.

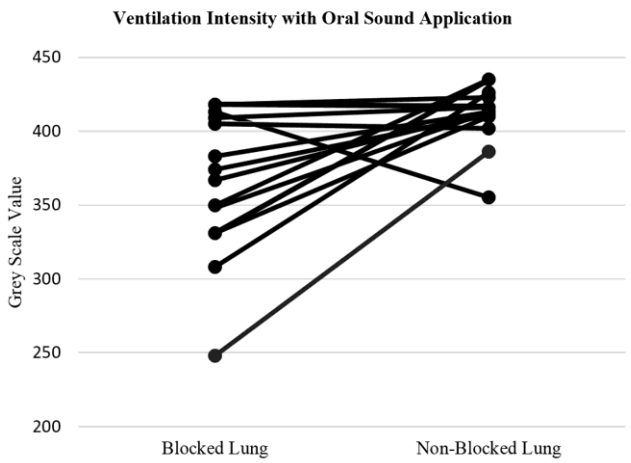

Fig. 6. Comparing greyscale pixel values on blocked vs. nonblocked lung side with oral sound application ($p \leq 0.01$).

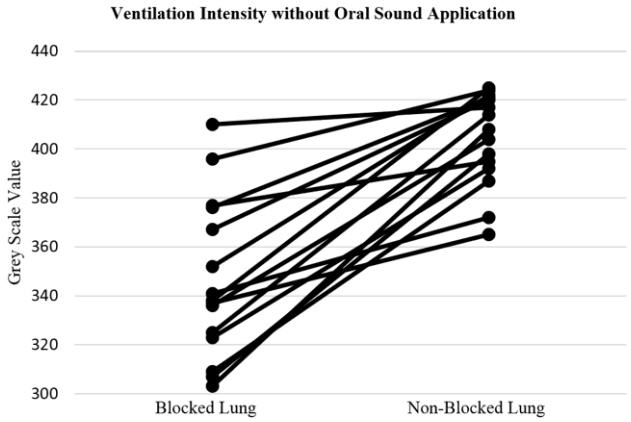

Fig. 7. Comparing greyscale pixel values on blocked vs. nonblocked lung side without oral sound application ($p \leq 0.01$).

When comparing CAT and MRI images to ThoraView images, a correlation is instantly visible (Fig. 8). The ThoraView image is not entirely identical compared to the MRI and CAT-scan images because it represents the frontal plane, whereas MRI and CAT-scan produce transversal plane images in this case. Furthermore, it shows the overlap of the recorded sounds from ventral to dorsal in the frontal plane.

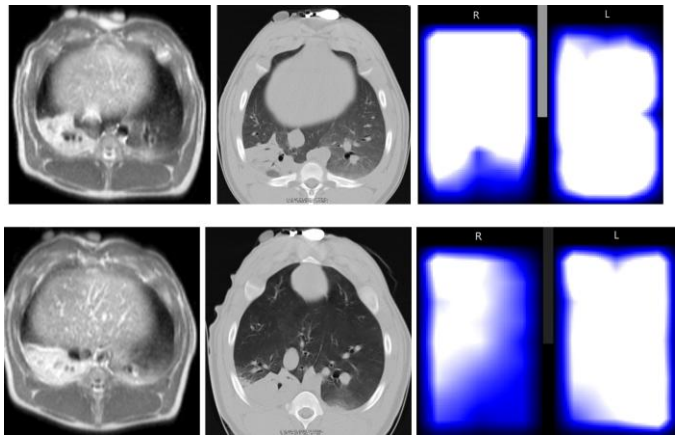
Fig. 8. MRI, CAT and ThoraView images from left to right showing NVAs in animal Nr.15 (1st row) and in animal Nr.6 (2nd row).

IV. Conclusion

ThoraView is able to distinguish between ventilated and nonventilated lung areas in pigs. Both methods (with and without oral sound) work well to fulfill the aims of this study. The oral application of defined sound signals however does not significantly improve resolution in peripheral lung areas and display of ventilation overall. The 400 Hz tone affects the microphone matrix and distorts the display of ventilation in some cases. Hardware adjustments will be necessary to improve the process of sound application to find out about its potential. This includes a better acoustic shielding of each microphone to filter out exterior noises and the 400 Hz tone of adjacent areas. Further developments also include an enhanced artifact recognition, data compression and miniaturization. Apart from hardware and software aspects, the long examination time to conduct all procedures should be kept shorter in further studies to reduce the chance of atelectasis during anesthesia. Especially the MRI examination was time-consuming. Overall, it could be proven that ThoraView is able to dynamically display pulmonary ventilation in animals, even over longer periods of time. It works radiation free, noninvasive and can be worn on the back without any anesthesia necessary. This new diagnostic tool enables long term recordings, thus potentially allowing the detection of mild impairments of lung ventilation over a defined period of time. The aspect of long term recording should be verified in a further study, along with wearing comfort and the influence of body movement on sound quality during the recording. Since pigs are genetically very close to humans, the gathered results from the veterinary application may allow a transfer to human medicine. The system has the potential to identify NVAs and therefore severities of respiratory diseases. We conclude that ThoraView has the potential to substantially support clinical routine as an innovative and comfortable monitoring device for the increasing numbers of respiratory diseases. Further studies are necessary to validate the operational capability in human medicine.

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