Evaluation of the use of frequency response in the diagnosis of pleural effusion on a phantom model of the human lungs

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Abstract— **Pleural effusion is one of the most widespread respiratory diseases in the world. Current diagnostic techniques include a combination of medical history and x-ray or CT scan imaging of the chest. However, these techniques are expensive and impractical in resource limited settings. We propose a new method based on sound transmission into the respiratory system through the chest wall. To evaluate this technique, a sine sweep signal with a frequency range between 100 Hz and 1000 Hz was transmitted into a phantom model of the human lungs capable of simulating healthy and effused conditions. The frequency response of the model under both conditions was computed and compared to evaluate the diagnostic performance of the new method. The results indicate that there is a significant difference between the frequency response of healthy and effused lungs, which suggests that the new technique may be suitable for the clinical diagnosis of pleural effusion.**

I. Introduction

Pleural effusion, is one of the most common respiratory diseases in the world, with approximately 1.5 million people diagnosed each year in the United States alone [1-2]. It is characterized by an abnormal collection of fluid between the two pleural membranes in the lungs. Over the past few decades, respiratory sound analysis has been developed to aid in the diagnosis of respiratory diseases. However, the majority of the previous work has focused more on the measurement and analysis of respiratory systems, rather than on disease diagnosis. Sound transmission into the respiratory system is one of the techniques used to determine the physical properties of the respiratory system [3-5]. Several researchers have injected sounds into the mouth of human subjects in an attempt to accurately measure the transmitted sound on the chest of the subject and to compute the transfer function of healthy subjects [6-10]. In addition, a few researchers have used this method to aid in the detection of respiratory diseases, including pleural effusion [11-12]. The advantages of this technique include its non-invasiveness, low cost and portability, which make it attractive for application in resource constrained settings.

Mulligan et al. developed a technique using a transfer function in the detection of fluid in the lungs [11]. This method involves the transmission of white Gaussian noise into the mouth and recording the sound, using four microphones on the chest, to determine the transfer function of the lung. They calculated the transfer function, using adaptive filtering, for three healthy human chests as well as for a phantom model of the human lungs. They found that fluid in the lung affects the transfer function. However, they did not consider the influence of microphone location on the chest. In the other study, the evaluation of using time delay technique in detection of fluid in the lungs was performed by Minaei Zaeim et al. using a phantom model of the human lungs [12]. They calculated the time delay between transmitted sounds using a loudspeaker from the trachea of the phantom model and received sound using an accelerometer located on the chest of the model. This technique was used to detect fluid in the lungs.

In this study, a novel diagnostic technique based on the transmission of sound into the chest wall and the recording of the transmitted sound at the mouth was evaluated using a phantom model of the human lungs capable of simulating both healthy and effused conditions. From this analysis insights into the use of frequency response in the diagnosis of pleural effusion are presented.

II. Methods

A. Phantom model design

A phantom model of the human lungs based on the average dimensions of a healthy adult human male was fabricated. The model can simulate both healthy and effused lungs (i.e., containing fluid) since it has similar acoustic properties to the lung parenchyma, the rib-cages and soft tissues in the human chest. Felex foam ITX (Smooth-On Inc., Easton, PA) was used to model the lung parenchyma because it has a similar density (160 kg/m^3) and phase speed (27.5 m/s) to human lung tissue [13]. To model the rib cage and the surrounding soft tissue in the chest, polyvinyl chloride (PVC) material with a density of 1450 kg/m^3 and Body Double® Skin-Safe Silicone rubber with a density of 1170 kg/m^3 were

Table I
SUMMARY OF MATERIALS USED TO BUILD THE PHANTOM MODEL OF THE HUMAN LUNGS

Material	Density (kg/m^3)	Speed of sound (m/s)
Felex foam ITX	160	27.5
Polyvinyl chloride (PVC)	1450	2400
Body Double® Skin-Safe Silicone rubber	1170	1530

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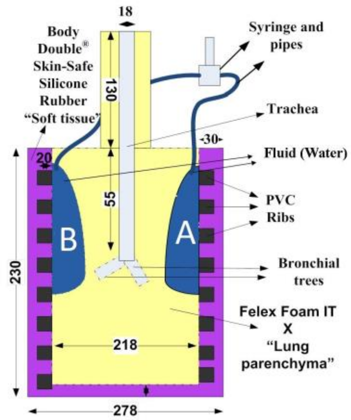

Fig. 1. Cross section through the phantom model of the human lungs (all dimensions in mm).

used. These material properties are summarized in Table I.

The geometry of the phantom model is cylindrical with a diameter of 278 mm and a height of 230 mm. The trachea was modeled as a molded cylindrical cavity, 28 mm in diameter and 185 mm long [14]. Two main bronchial trees, each with a diameter of 18 mm and a length of 55 mm were added to the end of the trachea as shown in Fig. 1. A rib cage which has a cylindrical band shape with internal diameter of 218 mm, external diameter 258 mm and the thickness of 15 mm, was made from PVC. The distance between adjacent ribs is 12 mm.

To model pleural effusion, two latex plastic bags were used, one of which was filled with 600 ml of water using a syringe, while the other contained 250 ml water as indicated by the labels A and B in Fig. 1.

B. Data acquisition system

The data acquisition system (DAQ) includes: a SigLab 4246 DAQ system, a HBM® Spider DAQ system, a load cell, a Visaton 4692 FX 10 loudspeaker, two PCB piezotronics 387 B02 microphones, a custom designed funnel and a custom-made clamp. A full range Visaton 4692 FX 10 loudspeaker with an approximately flat frequency response over a frequency range of 70 Hz – 22000 Hz and maximum power of 70 W was connected to a 50 mm long PVC funnel in such a way that it covered the entire surface of the loudspeaker. The other side of the funnel has a 7 cm diameter, which was cut so that it can fit completely into the chest of the model as shown in Fig. 2.

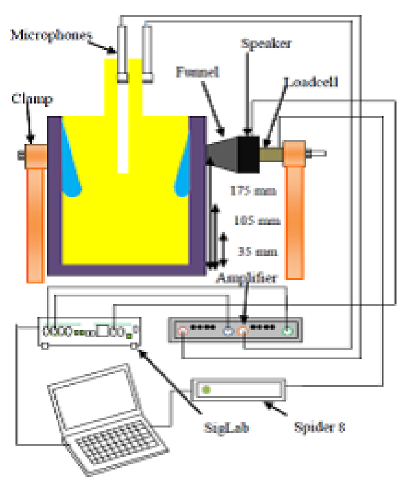

Fig. 2. Schematic illustration of the experimental setup.

C. Testing Procedure

A pre-recorded sound was generated by a loudspeaker and transmitted through the chest of the phantom model. A PCB piezotronics 387 B02 microphone, which has a flat frequency response over a frequency range of 3Hz to 20 KHz, was mounted in the trachea of the model 3 cm below the top of the trachea. Another microphone was placed outside of the model, close to the first microphone, to record the ambient noise. The recorded signal was amplified 100 times using a Kemo® BM 8 amplification system. The amplified signal was digitalized at 2560 Hz using a SigLab 4246 and recorded by a computer for the post processing. Measurements were made at 24 points that form a grid around the cylindrical surface of the model. The measurement points included eight angular positions: 40°, 80°, 120°, 160°, 200°, 240°, 280°and 320° degrees as well as three axial positions of 35 mm, 105 mm and 175 mm. To ensure repeatability, measurements were taken 30 times at each point.

It was found experimentally that the amplitude of the recorded sound from the chest of the phantom model depends on the force applied to the loudspeaker. The applied force was therefore monitored before each measurement using a S2-HBM load cell, placed behind the microphone, and fixed at approximately at 200 N The load cell was connected to the Spider for digitization and monitoring by the computer during the measurement.

However, due to the non-linear behavior of the Body Double® Skin-Safe Silicone rubber the force was found to change less than 1% over the time of measurement The pre-recorded sine sweep signal with a frequency range between 100 Hz and 1000 Hz, with step size of 100 Hz and with flat frequency response, was programmed using the mathematical software MATLAB® and was generated using the SigLab. The pre-recorded sound contains 10240 sample points with a total duration of 4 seconds. The frequency content of the input signal. The pre-recorded sound was played by the loudspeaker continuously. The recorded signal contains 81920 sample points with a total duration of 32 seconds which was 8 complete cycles of recorded sound.

D. Data analysis

The data analysis and processing was performed offline using the mathematical software MATLAB® (Natick, MA, USA). After the ambient noise was removed from the recorded signal using a recursive least square (RLS) adaptive filter, the signal was transformed into the frequency domain using a Fast Fourier Transform (FFT). Since the applied signal is composed of sine waves at frequencies between 100 and 1000 Hz with a step size of 100 Hz, the amplitudes of the signal at those frequencies were obtained. These processes were performed for 30 measurements at each grid

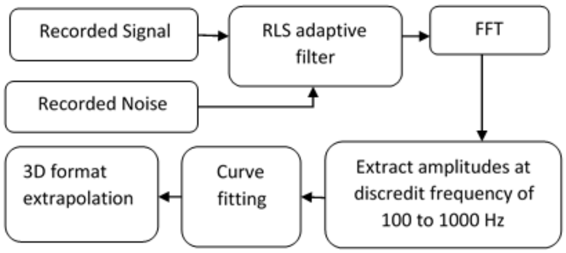

Fig. 3. Data analysis flow chart.

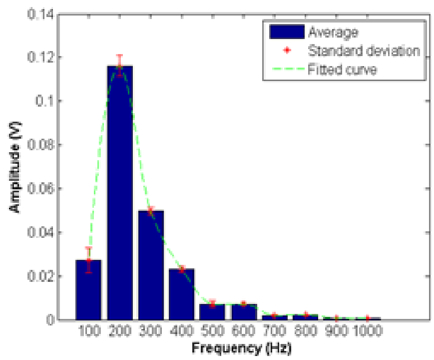

Fig. 4. Calculated data for healthy lung conditions at an axial position of 135 mm and an angular position of 80°.

position around the model. The average amplitude of the signal for each position was computed, as shown by the blue bar at Fig. 4 for the signal recorded for the healthy lung condition at an axial position of 135 mm and angular position of 80°. The standard deviation for each frequency was computed as plotted by the red error bars in Fig. 4. To obtain the frequency response of the system at the other frequencies, a curve was fitted to the average amplitude using a 1-D cubic interpolation method, which is indicated by the green line in Fig. 4. After the computation of the frequency response of the model for all frequencies between 100 Hz and 1 kHz, the data was plotted as a function of frequency for angular measurement positions around the model with the same axial position and amplitude.

III. RESULTS

In Fig. 5 and Fig. 6, the frequency (Hz) is plotted on the main y-axis, as a function of the angular position around the chest of the phantom model (^{0}), while the amplitude of the signal is indicated by the color bar on the secondary y-axis. It is important to recall here that under effused conditions two plastic bags were placed in the phantom model at angular positions of between 80° and 120° and between 220° and 260°, as shown in Fig. 1.

Fig. 5 shows the frequency response of the phantom model simulating healthy lungs for sounds recorded at three axial locations: (a) 175 mm, (b) 105 mm and (c) 35 mm. The highest amplitude frequency response varies with the axial measurement location. At 175 mm it occurs between 80^0 and 120^0, at 105 mm it occurs between 320^0 and 360^0, while at 35 mm it takes place between 80^0 and 120^0. In all cases the attenuation at frequencies above 500 Hz is very high.

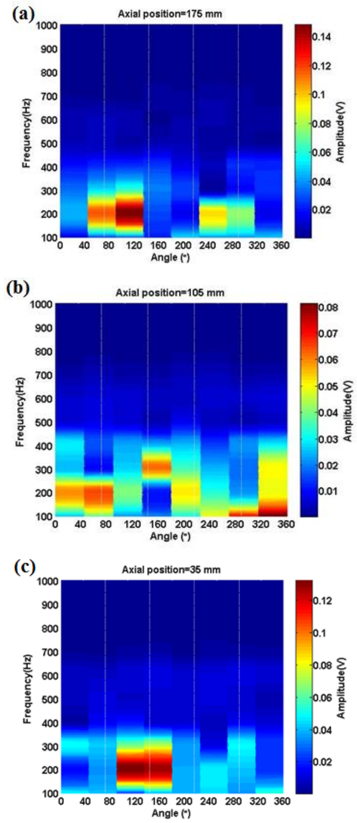

Fig. 5. Frequency response of the phantom model of healthy lungs.

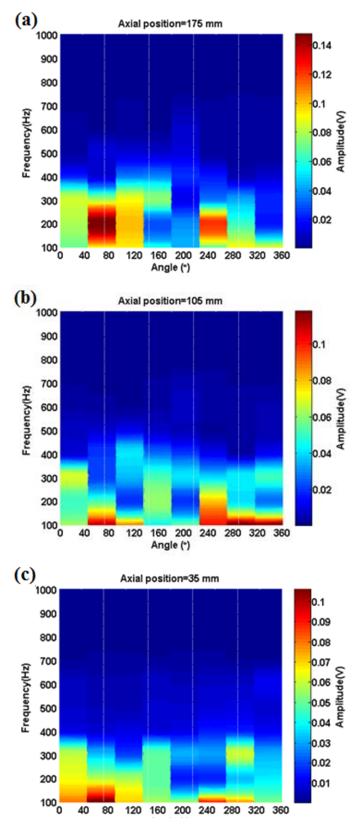

Fig. 6. Frequency response of the phantom model of effused lungs.

Fig. 6 shows the frequency response of the phantom model, under conditions simulating effused lungs, for sounds recorded at three axial locations: (a) 175 mm, (b) 105 mm and (c) 35 mm. The highest amplitude frequency response is similar for each axial measurement location, in contrast to the behavior observed for the healthy lung model. At each axial measurement location high amplitude frequency response occurs at angular locations between 40^0 and 100^0 and between 240^0 and 280^0. In all cases the attenuation at frequencies above 500 Hz is also very high.

IV. DISCUSSION

The results in Fig. 5 (a) show that the frequency responses at the angular positions between 80° and 120° have an amplitude of approximately 220 Hz. Moreover, semi-symmetric behavior can be observed. In this case, the phantom model acted like a low pass filter, which means that the signal attenuated at high frequency. This finding is consistent with the results reported by Reichert et al. on the human lungs [15] and the results reported by Ozer et al. on a phantom model [13]. In Fig. 5 (b) the highest amplitudes of the signals occur at the angular positions between 320° and 360°. This can likely be attributed to the presence of the bronchial tree, which allowed the applied sound to be transmitted through the foam via a shorter distance, thereby leading to a larger amplitude frequency response. It may also be due to a resonance effect, which may have amplified the frequency response. In Fig. 5 (c) the highest amplitudes occur at the locations on the model with angular positions of 80° and 160°, and at frequencies between 180 and 220 Hz. This occurs because of the geometry of the phantom model and the locations of the bronchial tress in the model which affect the resonance frequency at angular position of 80° and 160°. Furthermore, no symmetric behavior can be observed.

The results in Fig. 6 (a) shows that the highest amplitude frequency response occur at the locations with angular positions between 80° and 120° and between 220° and 260°, at a frequency of 200 Hz. These positions correspond to the angular locations in the phantom model where the water bags were placed. By comparing the results of the healthy model and the pleural effusion model with same axial position (Fig. 5 (a) and Fig. 6 (a) respectively), the locations of the fluid filled plastic bags are clearly detectable. In Fig. 6 (b) the results show that the highest amplitudes occur at the locations with angular positions in the range of 280°-360°. Comparison of Fig. 5 (b) and Fig. 6 (b) once again reveals that the presence of fluid in the phantom lung model is easily detectable. Fig. 6 (c) shows that the maximum frequency amplitudes occur at the locations with angular positions between 80° and 120° and between 220° and 260°, which correspond to the angular locations in the phantom model where the fluid filled bags were placed. It is important to note here that although there is no bulk of fluid at the axial position of 35 mm, the location of the fluid is still detectable because the sound was propagated in all directions as it passed through the fluid bulk to reach the microphone located at the trachea of the model. Overall, the results clearly show that there is significant difference between healthy and effused lungs. This suggests that it may be possible to clinically diagnose pleural effusion using sound transmission through the chest wall. However, additional clinical testing is needed in order to confirm these findings in humans.

V. CONCLUSION

An evaluation of the use of frequency response in the diagnosis of pleural effusion has been performed by transmitting a sine sweep signal with a frequency range between 100 Hz and 1000 Hz into a phantom model under conditions simulating both healthy and effused lungs. The FFT of the received signals was computed. The results show that there are significant differences in the frequency responses between healthy and pleurally effused lungs using the phantom model. In addition, the locations of the fluid in the pleural effusion model were accurately detected. These results suggest that this technique may be suitable for the clinical diagnosis of pleural effusion. Future work will focus on evaluation of this technique in human volunteers pending ethical approval.

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