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Effect of rib-cage structure on acoustic chest impedance

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Summary
When a stethoscope is placed on the surface of the chest, the coupler picks up sound from heart and lungs transmitted through the tissues of the ribcage and from the surface of the skin. If the acoustic impedance of the chest surface is known, it is possible to optimize the coupler for picking up even weak sounds originating from e.g. the heart. The acoustic impedance is influenced by the structure of the ribcage; hence the acoustic impedance will change depending on if the coupler has been placed on a top of a rib or between the ribs (the intercostal).
The impedance of the chest is measured in the frequency range from 40 Hz to 5 kHz using an acoustic impedance tube made specifically for the purpose. The measurements are carried out in a grid pattern on the surface of the chest. The grid is aligned according to the ribs; hence the measurements are either on a top of the ribs or between the ribs. The measurements reveal the structure of the ribcage from an acoustic point of view in addition to describing the variation of the impedance depending on the position of the coupler. The measurements are carried out on a small number of subjects. The assessment of the ribcage structure based on impedance measurements is a part of a larger study which aims at optimizing an acoustic coupler for picking up weak murmur sounds from the coronary arteries of the heart.

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1. Introduction

When an auscultation is carried out on the ribcage with a stethoscope or another transducer that is able to pick up sound from e.g. the heart, the internal structure of the ribcage will influence the recorded sound. A major influence is expected from the ribs, hence the frequency response will depend on whether the transducer has been placed on the top of a rib, between the ribs or, if the transducer is sufficiently large, covering two ribs and the gab between. The latter is suggesting an averaging over the area covered by the transducer, while the two first positions of the transducer will produce the largest difference to the recorded sound.

The ideal way to assess this difference would be to measure the transfer function through the tissues and ribs of the ribcage, however the insufficiencies of the heart as a controlled sound source excludes this option. Instead a measurement of the chest impedance using an impedance tube will reveal the impedance the coupler is looks into, when placed on the surface of the chest, and consequently also reveal the influence caused by the ribs.

By measuring the impedance of the chest in a grid pattern, where the measuring points in the grid are aligned according to the ribs, it is possible to show the variation related to the position and additionally also to draw an impedance map of the ribcage, showing the impedance as a function of the position.

The variation caused by the rib of the ribcage is not expected to influence the entire frequency response, hence the variation will be larger for certain frequency ranges. Consequently frequency ranges with large variation have to be determined before the impedance map can be drawn.

2. Method

A dedicated standing wave tube was developed for the purpose, using known principles for standing waves in tubes and pipes [1] to measure the chest impedance from 40 Hz to 5 kHz.

2.1. Measurement tube and equipment

The chest impedances were measured using a measuring tube (standing wave tube) with four fixed microphones positioned along the side of the tube (see

Table I. Dimensions of impedance tube.

Dimensions		
Diameter	20	mm
Δl_{12}	30	mm
Δl_{13}	140	mm
Δl_{14}	600	mm
l_{end}	10	mm
L	660	mm

figure 1). The dimensions of the tube along with position of the microphones can be found in Table I. The tube is made of aluminum with a recess for each microphone (Sennheiser KE-4-211). Fittings of nylon keep the microphones in place. A loudspeaker (Vifa M19MD-39-08) is mounted at the top of the standing wave tube. At the opposite end of the tube a recess makes it possible to attach different terminations for calibration and measuring purposes.

The frequency range from 40 Hz to 5 kHz is defined by the dimensions of the tube, position of the microphones and limitations of the measuring equipment [2]. The upper frequency limit is determined by the wavelength, thus the distance between the two microphones must be shorter than half the wavelength. The lower limit is determined by the precision of the acquisition system since the phase difference of the signals pickup up by a pair of microphones is small at low frequencies and the following calculations are susceptible to noise and other inaccuracies. Another constrain to the frequency range is the diameter of the tube. To ensure plane wave propagation in tube, the diameter must be smaller than the wave length of the upper frequency limit of the excitation signal. The ISO 10534[3] standard provides a recommendation for calculating the diameter:

$$d < \frac{0.58\ c_0}{f_u}$$

where f_u is the upper frequency limit of the measuring range and d is the diameter of the tube. With an upper limit of 5 kHz, the tube diameter must be smaller than 39mm, a requirement that is easily satisfied with the chosen diameter.

The signals from the four microphones are recorded using a Behringer ADA8000 (modified with fixed gain settings) that is capable of sampling the input signal at 48 kHz. The acquisition system is connected to a computer and operated from Matlab.

2.2. Calculation of Impedance

The sound pressure measured at each of the four microphone positions is used for the calculation of the reflectance. Any combination of pairs of microphones can be used for the calculation of reflectance within certain frequency limits. These frequency limits are shown Table II for the pairs of microphones that are used for the calculation of impedance.

Table II. Frequency ranges for different combinations of microphones used for the calculation of reflectance and impedance.

Microphone pair	Frequency range	
Mic 1-2	1000 - 5000	Hz
Mic 1-3	220 - 500	Hz
Mic 1-4	40 - 225	Hz
Mic 2-3	500 - 1000	Hz
Mic 2-4	40 - 225	Hz

Based on the sound pressure measured at each microphone position, the reflectance is calculated for each pair if microphones in Table II using equation 1 [4]:

$$r = \frac{(p_1/p_2) - e^{-jkl_\Delta}}{e^{+jkl_\Delta} - (p_1/p_2)} e^{+2jkl_{end}} \quad (1)$$

where p_1 and p_2 are the sound pressures measured by microphone 1 and 2 respectively for each pair of microphones. l_Δ is the distance between the two microphones and l_{end} is distance to the open end of the tube. k is the wave number. From equation 1, the impedance Z is determined by:

$$Z = \rho_0 c \frac{r+1}{r-1} \quad (2)$$

2.3. MLS sequence as exitation signal

The excitation signal was a Maximum Length Sequence (MLS) [5]. The sequence was an 18^{th} order with three repetitions for averaging of the signals. The impulse response was calculated for each signal and truncated to 8000 samples, before the signal was transformed into the frequency domain and used for calculation of the reflectance and impedance.

2.4. Position control and subjects

The impedance tube was mounted in a gyroscopic support, in order to angle the tube perpendicular to the chest. This way, it is possible to achieve a contact to the skin without leakage, which otherwise would influence the measurements.

The force effectively applied was adjusted by moving a counterweight on the setup, that allowed adjustment of the force from zero gram to one kilogram. A weight of 500g was chosen, since this weight provides a stable and reliable contact to the skin. The weight adjustment is not precise down to a single gram and further the weight applied to skin is also influenced by the angle of the tube. However these two inaccuracies are ignored.

To provide the most realistic scenario the measurements if the impedance were carried out on the same side as the general practitioner would carry

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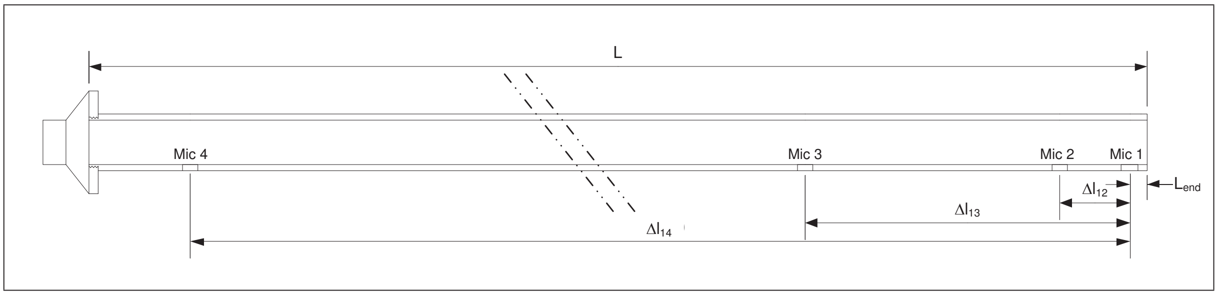

Figure 1. Impedance tube. Dimensions can be found in Table I.

out auscultation in order to listen for heart sounds; namely the left side. The same measurements of the impedance could have been carried out on the right side of the chest, but it is unknown to which degree deeper laying structures of the chest, e.g. lungs, might influence the impedance. The measurements were carried out on two male subjects.

2.5. Sampling frequency and Nyquist theorem

The sampling frequency of ribs and intercostals between the ribs barely satisfies the Nyquist sampling theorem due to the distance between measuring points and the diameter of the tube which is $20mm$. Thus the diameter of the tube results in an upper limit of resolution, unless a significant overlap is accepted which would most likely provide a mean value between the impedance measured on the top of a rib and in the intercostal between the ribs. Further knowledge about the variation of impedance is not achieved by performing overlapping measurements.

3. Measurement procedure

3.1. Alignment of grid

The grid was aligned according to the position of the ribs as shown on figure 3 where the green and black lines indicate the ribs and the intercostals between the ribs respectively. By using the ribs as guidelines for the measurements, it is expected to achieve the largest difference of the impedance.

The grid could also have been aligned with equal distance between the measuring points. However due to the sampling frequency of the ribs and the considerations regarding the variation of the impedance mentioned in section 2.5, the equivalent distance would pose a risk of not getting measurements at extremity of the impedance.

Prior to the impedance measurement, the position of the ribs was marked on the chest using ultrasound. The ultrasound probe was placed on the chest close to sternum, where the ribs are easily located due to shallow location beneath the skin.

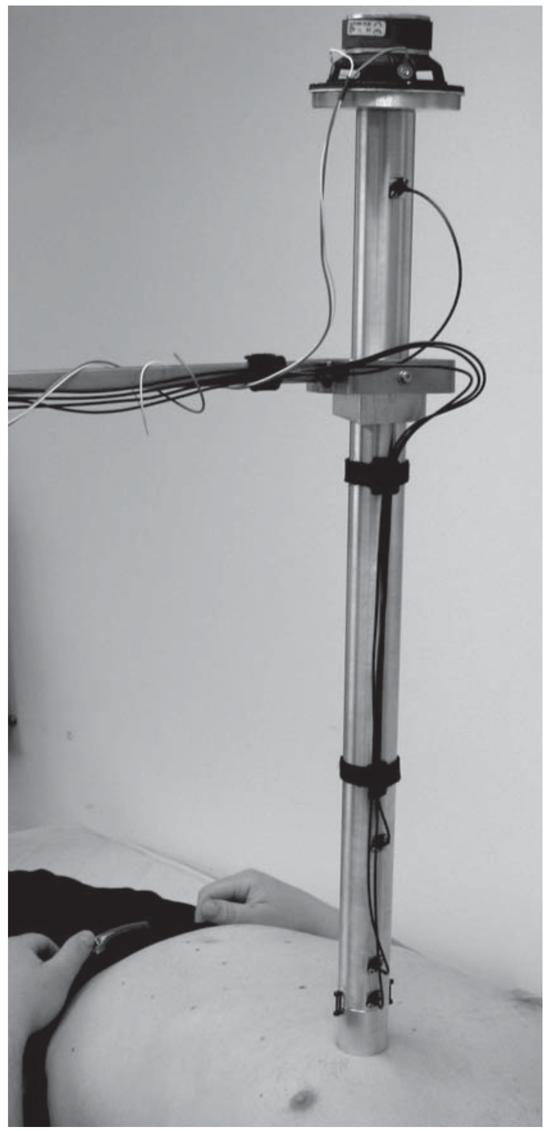

Figure 2. Impedance tube positioned on chest. The gyroscopic support insures a perpendicular angle to the chest.

When a rib was located and shown in the middle of the screen on the ultrasound equipment, a mark was

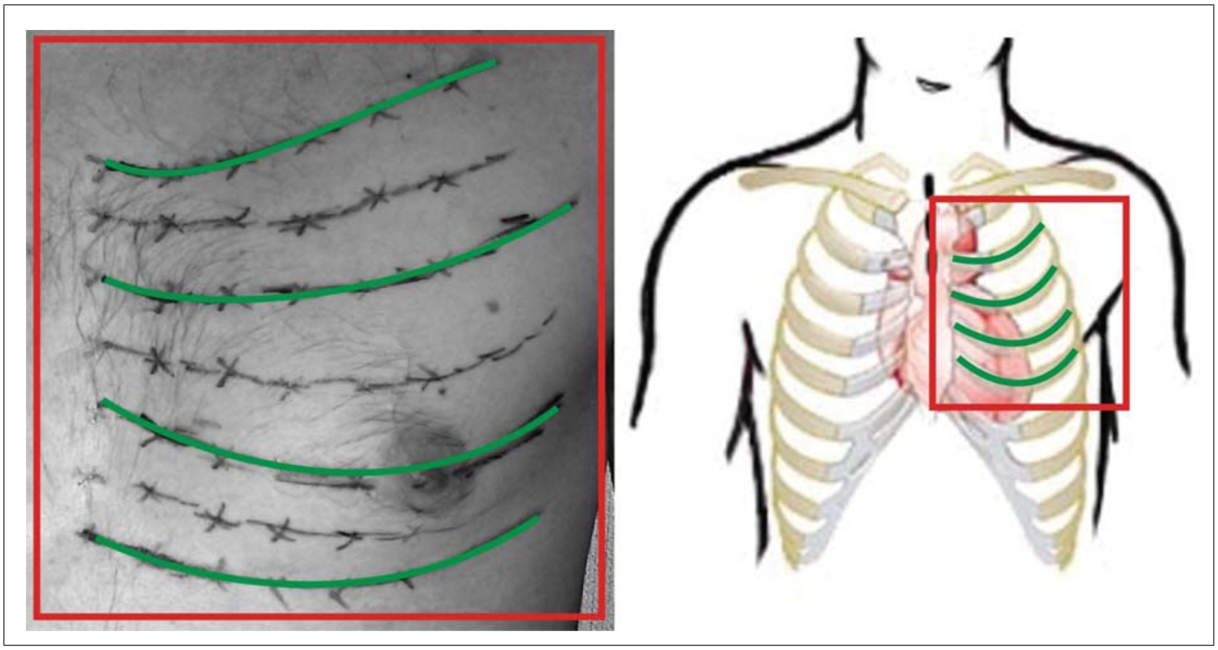

Figure 3. Markings on chest prior to the measurement. The location of the ribs were determined using ultrasound (see section 3.1 for further explanation of the alignment using ultrasound).

drawn on the chest next to the probe, to indicate the position of the rib. This procedure was repeated while following one rib at the time and marks were drawn with sufficient small distances to get a clear picture of the positions of the ribs.

A palpation could have been used instead of ultrasound to reveal the structures of the ribcage. However the method did not seem reliable at positions, where the ribs are covered by muscle tissue and difficult to feel through the skin.

The procedure provided a number of curved "horizontal" lines indicating the ribs, with the upper line corresponding to the first rib below the collarbone. Vertical lines were drawn as straight lines with a distance of approximately two centimeter starting from the center of the sternum. This provided a grid matrix of seven rows and six columns resulting in a total of 42 measurements, where four rows were on the top of a rib and three rows were in the intercourse as shown on figure 3.

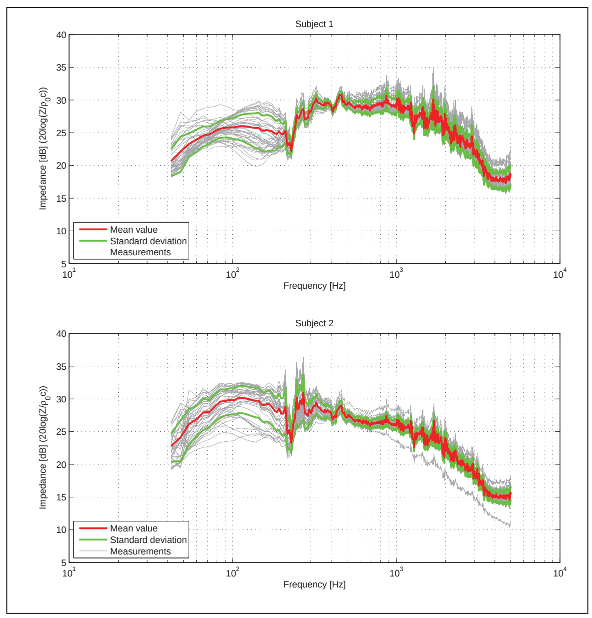

Figure 4. Frequency response of all 42 measurements. The figure shows a higher variance at low frequencies, indicating that the impedance is influenced more from the underlaying structure in this range.

4. Results

Figure 4 shows the frequency response of the 42 measurements carried out on each subject. Additionally also the mean and standard deviation are displayed.

The figure shows, that the variation gets smaller at frequencies above 200 Hz, which indicates a higher degree of homogeneity of the underlaying structures of the ribcage. Consequently the positioning of a transducer for picking up sound will be at less significance at higher frequencies in relation to the impedance. At frequencies below 200 Hz however, the standard deviation is larger, around 5 dB, thus the ribs influence the impedance.

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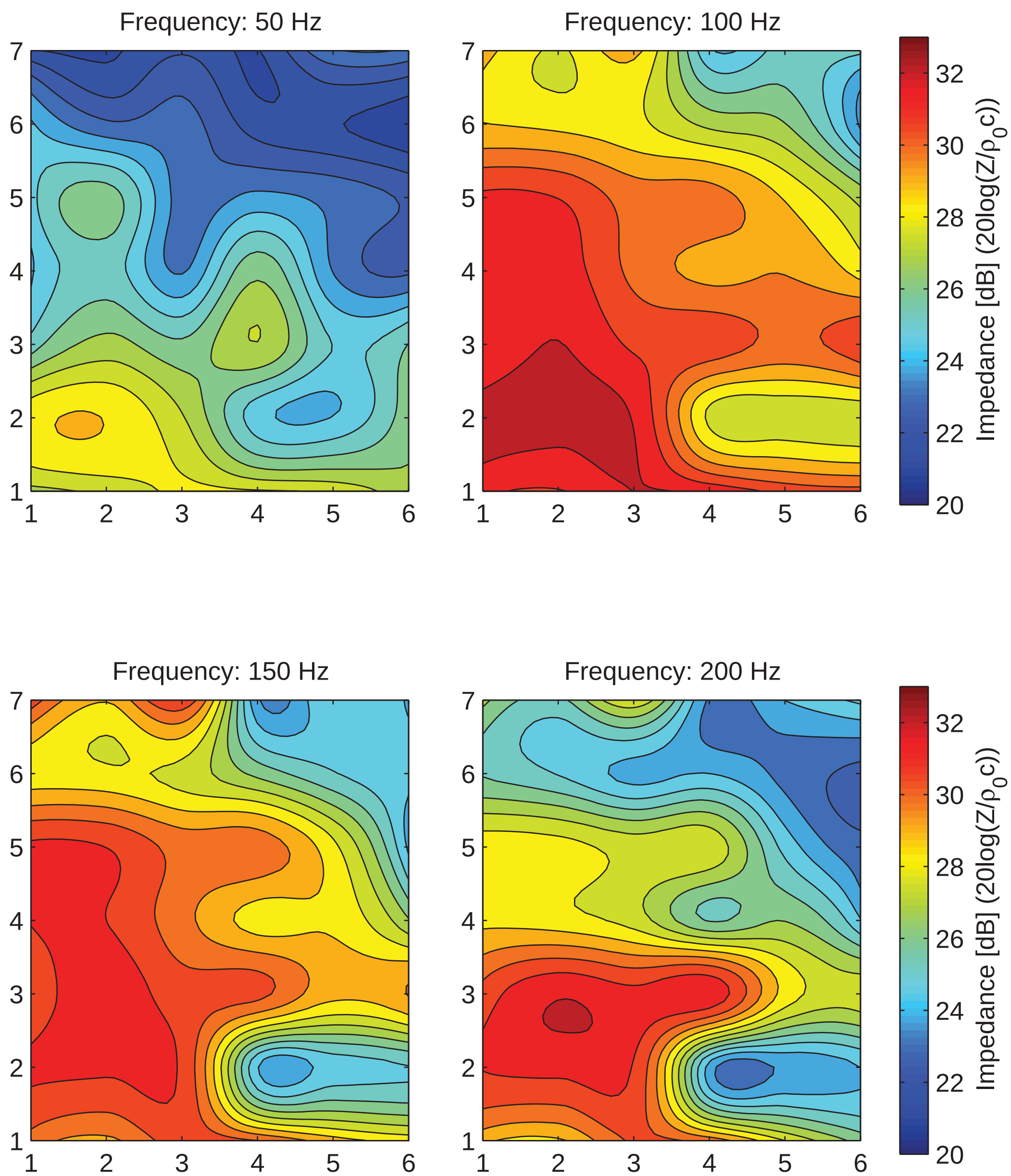

Figure 5. Gridsmeasurements showing the impedance of the ribcage at different frequencies. Interpolation of the measurements has been applied to ease the interpretation of the features on the figure.
Sternum is found next to column one on the figures. The two "red fingers" pointing out from sternum in the middle of the figures corresponds to the ribs, while the gabs between the "fingers" are the intercostals as indicated on Figure 3.

The larger standard deviation at low frequencies yields further investigation, where an impedance map of the chest is drawn to determine, if there is a relation between the increased variation and the ribs of the ribcage. Four frequencies: 50 Hz, 100 Hz, 150 Hz and 200 Hz are chosen for further investigation. For each of the four frequencies the values of the 42 measurements are plotted with equal distance between the measuring points and aligned with the number of the rows and columns as the measurement. The low number of measurements will create a very rough impedance map, where the structures of the rib cage are difficult to identify, hence cubic interpolation is applied to the measurement as shown on Figure 5. The plots are aligned in the same was as Figure 3 with sternum at the left next to column one.

On the figure that shows the impedance at 50 Hz, it is not possible to distinguish features related to the rib cage. On the other three figures, two "fingers" are pointing out from left towards right indicating the two ribs, while the gabs between the fingers are the intercolstals between the ribs. The features are most easy recognizable at 100 Hz and 150 Hz, though still visible at 200 Hz. The three figures also show that the largest impedance is measured next to sternum in the lower region, this could be related to less tissue covers the ribs.

5. Conclusion

The measurements indicated that at frequencies above 200 Hz, the impedance variation related to the ribs were small while at low frequencies a variation of more than 12 dB was measured from a minimum at 40 Hz and a maximum slightly above 100 Hz at different positions. The higher variation led to further investigation, where a map was drawn in order to show the landscape of the ribcage based on the impedance measurements.

The large variation of the impedance due to the position at low frequencies is likely to influence the ability to pick up weak sounds from the heart with a stethoscope or another transducer.

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