NEW FEATURES OF SOUND PROPAGATION THROUGH HUMAN LUNGS REVEALED BY MEANS OF CONVOLUTION TECHNIQUE

Vladimir Korenbaum and Anton Shiryaev

Pacific Oceanological Institute, Russian Academy of Sciences, Vladivostok, Russia
email: v-kor@poi.dvo.ru

The objective is study of characteristics of sound propagation through human lungs in the frequency ranges of 80-1000 Hz and 10-19 kHz. The receiving apparatus included accelerometer sensors for both frequency ranges and the 3-component accelerometer sensor for 80-1000 Hz band. The chirp or phase-manipulated signals were emitted into human thorax/mouth. It was found a domination of longitudinal sound wave transmission vs transversal one in the 80-1000 Hz with velocities of 100-15 m/s. Under sounding into mouth a significant difference in the vertical angles of the first 2-3 arrivals was revealed, confirming considerations on different sources of emission. Under sounding into chest supraclavicular area vertical angles of 1-2 arrivals (from 50 m/s) were close indicating the common point source. For 10-19 kHz range an existence of low-speed arrivals with propagation velocities of 150-50 m/s, which amplitude and/or velocity was inversely dependent on the air-filling of lungs (inspiration/exhalation) was revealed. These arrivals may be treated as a result of sound propagation mainly through the lung parenchyma. On the contrary, the amplitudes of high-speed arrivals with velocities of 150-1000 m/s are enhanced with a decrease in air-filling of lungs and may be connected to the sound propagation mainly through high-density tissues of thorax. In water-like medium with bubbles (alveoli diameter 0.2 – 0.3 mm) according to Minnaert, 1933, a resonant frequency is f = 22 – 33 kHz. Consequently in both frequency ranges a sound velocity should be governed by air compliance in alveoli and density of alveoli wall tissue. Thus in both frequency ranges sound velocities through normal (air-filled) parenchyma should be close in value. This really was shown in our current experiments for low-speed arrivals. Keywords: respiratory acoustics, signal processing, human lungs, sound propagation

1. Introduction

In 1816, Rene Laennec invented a method of auscultation of lungs with a stethoscope, mounted on the surface of the chest. This non-invasive technique is widely used in medical practice for about 2 centuries. However, the technology is subjective and does not meet the requirements of modern evidence-based medicine.

Intensive research on the objectification of respiratory acoustics started since 1970s [1, 2]. However, reliable diagnostic techniques have not yet been developed. In particular, no progress has yet been made in the development of low-frequency acoustic imaging/tomography of the lungs [3]. One of the main problems is very poor knowledge of sound propagation in human breathing system [4, 5].

We proposed an original method [6] of sounding human lungs through mouth and from supraclavicular chest areas with complex signal, making convolution of emitted and received signals
(compression technique). This procedure accomplishing for frequency bands of 80-1000 Hz [7, 8] and 10-19 kHz [9] directly revealed multiple sound propagation paths to a chest wall.

The objective of the work is more detailed study of characteristics of sound propagation through human lungs in vivo in the frequency ranges of 80-1000 Hz and 10-19 kHz by means of convolution technique used during transmission sounding.

2. Model assumptions

The studied acoustic system is limited by the surface of the chest (about 30 cm diameter). Its internal part is filled with parenchyma – a mixture of micro bubbles and water-like tissue. The speed of sound for a longitudinal wave, at least below 1 kHz is determined by the compressibility of air in the bubbles and the density of tissues (close to water). As a result, the speed of sound in the lung parenchyma has a low value of about 30 m/s, which at frequencies of 100-300 Hz (most intensive transmission) gives a longitudinal sound wave length of 30-10 cm, thus wave size of studied area is (1-3)λ.

The lung parenchyma is delimited from the external environment by the chest wall formed by soft tissues with a low shear modulus. The velocity of longitudinal sound waves in the chest wall is close to the speed of sound in the water. Since the thickness of the chest wall is 2-3 cm (wave size λ/1000), it can be represented by a thin layer lying on a soft boundary in the wave sense.

Main features of the lung parenchyma are high damping, which allows neglecting reflected and re-reflected sound waves, and a very low shear modulus, which does not allow an existence of transverse and shear waves.

Thus, we consider an approximate acoustic model representing a source (more often a point source) that emits into an unbounded-like medium. However, measurements of the acoustic characteristics of the source are commonly made in its near-wave zone. Moreover, the sensors have, as a rule (at least below 1 kHz), small wave dimensions, which allows us to assume that the sound wave incident on them is locally flat.

3. Apparatus

The apparatus hardware (Fig. 1) included receiving accelerometer sensors for both frequency ranges and the 3-component accelerometer sensor for 80-1000 Hz band (Fig. 2). Signals from accelerometer sensors were registered with the 16-channel recorder Powerlab (ADInstruments). The chirp or phase-manipulated signals were emitted by small shaker into human thorax or by the speaker, provided with replaceable tube, into mouth. Places of mounting sensors and emitting shaker are shown in Fig. 3.

4. Results and discussion

There were two pilot experiments in 4 volunteers, signed informed consents.

4.1 Sounding with 3-component sensor in the low-frequency range of 80-1000 Hz

Examples of convolution diagrams – the envelopes of weighted cross-correlation function T_{xy}, for a 3-component sensor are shown in Fig. 4 for sounding through mouth, and from chest surface – Fig. 5. Each peak of the convolution curve in accordance with hydroacoustic, radar considerations and our experience [6-9] is treated as a separate signal arrival (red mark) with its time delay. Sound velocity of each arrival is calculated as direct measured by pelvis-meter distance between shaker position (or the 2-nd tracheal sensor for sounding into mouth) and current sensor position divided by time delay, and it is represented in Fig. 4, 5 and subsequent figures as black numbers.

Due to ratio amplitudes of arrivals by components of 3-component accelerometer sensor the longitudinal, rather than shear, waves with velocities from 100 (mouth) to 15 (shaker Б1, Б2) m/s are preferentially arrive to the surface of the chest through parenchyma (Fig. 4, 5).
Figure 1: Apparatus hardware
1 – portable PC, generating sounding signal, connected to external sound card Transit USB (M-Audio); 2 – power amplifier PHONIC MAX 860; 3 – speaker for emitting low-frequency 80-1000 Hz signal into mouth; 4 – replaceable tube; 5 – sterile sealed container with replaceable tubes; 6 – air exhaust pipe; 7 – shaker 4810 (Bruel & Kjer); 8 – reference accelerometer KD-35 (RFT); 9 – a number of accelerometer sensors based on 333B52 (PCB Piezotronics) placed on technologic support; 10 – power supplies for accelerometers; 11 – 16-channel recorder PowerLab (ADInstruments); 12 – portable PC connected to recorder; 13 – nose clamp.

Figure 2: Accelerometer sensors based on PCB Piezotronics devices, 1-component (right) and 3-component (left).

Figure 3: The scheme of mounting of accelerometers (no. 2-14) and the shaker (B1-B4) at torso.
Figure 4: Envelopes of weighted cross-correlation function $T_{xy}$, for a 3-component accelerometer sensor under sounding through mouth – sensor component having normal orientation to chest surface (green), sensor component having transverse vertical orientation (red), sensor component having transverse horizontal orientation (blue).

Figure 5: Envelopes of weighted cross-correlation function $T_{xy}$, for a 3-component accelerometer sensor under sounding from chest surface (B1) – sensor component having normal orientation to chest surface (green), sensor component having transverse vertical orientation (red), sensor component having transverse horizontal orientation (blue).

When sounding through mouth (Fig. 4), a significant difference in the effective incident angles of the front of the longitudinal wave of the probing signal to the surface of the chest is seen for the
first 2-3 arrivals. This observation confirms previously formulated ideas about the different ways of sound transmission to the chest wall or various sources [6-8]. When sounding by the shaker from the supraclavicular area (B1), 1-2 low-velocity arrivals (below 50 m/s) are observed, and the difference between incidence angles for arrivals is usually smaller (Fig. 5). This observation may be interpreted as a presence of one point source of emission in contrast with sounding though the mouth. Sometimes less intensive and very low-velocity arrivals (below 5 m/s) are present, which may be treated as footprints of shear waves propagating through chest surface.

4.2 Sounding with 1-component sensors in the high-frequency range of 10-19 kHz

The unexpected phenomenon of 10-40 kHz sound transmission through human lungs with speed of about 1000 m/s was revealed not far ago [10]. While later our team in pilot experiment, using signal compression technique, found low- and high-speed sound propagation components in the frequency range of 10-19 kHz [9]. A more detailed study of the characteristics of sound transmission in human lungs in the frequency range of 10-19 kHz is presented here.

Sounding of thorax was performed in two respiratory manoeuvres – breathe hold in maximum inspiration (HF2) and breathe hold in maximum exhalation (HF3).

Convolution curves (envelopes) of weighted correlation function Txy with peaks-arrivals (sound velocities) are presented in diagrams with log scale to include both inspiration (HF2) and exhalation (HF3) data (Fig. 6 – Fig. 9).

![Convolution curve](image)

**Figure 6:** The log-scale convolution curve of the type 1 with detected peaks (red marks) in dependence on time delay (ms) and sound velocities (black numbers above peaks) in breathe-holds during inspiration (blue) and expiration (green).

A possibility of decomposition of received signals into high-speed and low-speed arrivals [9] is verified in this independent sample of subjects.

An existence of low-speed arrivals with propagation velocities of 50-150 m/s is revealed, which velocities are inversely dependent on air filling of lungs (inspiration/exhalation). Therefore these arrivals may be treated mainly as the result of sound wave propagation through the lung parenchyma.
On the contrary, the amplitudes of high-speed arrivals found had velocities of 150-1000 m/s. Their amplitudes and/or velocities are enhanced with a decrease in air filling of the lungs in breath hold during exhalation. Thus, the high-speed arrivals may be connected to the dominant sound wave propagation through high-density tissues of thorax.

Figure 7: The log-scale convolution curve of the type 2 (other indication as in Fig. 6).

Figure 8: The log-scale convolution curve of the type 3 (other indication as in Fig. 6).
Four characteristic types of convolution curves for opposite transmission traces were found. Type 1 (Fig. 6) – an appearance of high-speed arrivals in exhalation (HF3) re inspiration (HF2) without significant changing basic low-speed arrivals. Type 2 (Fig. 7) – an essential increase of high-speed arrivals amplitudes in exhalation (HF3) re inspiration (HF2). Type 3 (Fig. 8) – a dramatic increase of high-speed as well as low-speed arrivals amplitudes in exhalation (HF3) re inspiration (HF2). Type 4 (Fig. 9) – an absence of any amplitude or velocity dynamics in ratio of high-speed and low-speed arrivals between exhalation (HF3) and inspiration (HF2).

Figure 9: The log-scale convolution curve of the type 4 (other indication as in Fig. 6).

The convolution curves of type 1 (Fig. 6) and type 2 (Fig. 7) of are the most characteristic for opposite transmission in all 4 volunteers. The type 3 (Fig. 8) is observed more rarely but it is seen for transmission in all 4 volunteers too. The convolution curves of 1-3 types demonstrate a substantial dependence on air-filling of lungs. Only one of these types (the type 4 – Fig. 9) is characterized by the predominance of amplitudes of high-speed arrivals, both during inspiration and exhalation. It may be acoustically interpreted as a local reduction in air-filling and ventilation of lung parenchyma. It is seen only in 2 locations (opposite traces) of one elderly patient with a long-term course of hormone-dependent asthma, but not in 3 other young healthy individuals. Thus the method may be promising to reveal reduced air-filling and ventilation in pulmonary parenchyma.

Since found low-speed arrivals have sound velocity about 150 - 50 m/s for medium frequency 15 kHz of the range these velocities result in wavelengths between 1 cm and 0.33 cm. Such small wavelengths may provide the spatial resolution in lung parenchyma of about the first centimeters! Thus transmission sounding of lungs in the range of 10-19 kHz seems very promising to provide high-resolution acoustic imaging or may be even tomography of pulmonary parenchyma.

4.3 Theory generalization

What mechanism may be considered for the theoretical model of longitudinal wave sound transmission in both 80-1000 Hz and 10-19 kHz frequency ranges? For air bubbles in water the well-known Minnaert (1933) formula \( f = \frac{3.26}{r} \) with alveoli radius \( r = 0.1 - 0.15 \) mm, presents resonance frequency \( f = 22 - 33 \) kHz. Therefore in low-frequency 80-1000 Hz [4] as well as in high-frequency 10-19 kHz ranges the transmission is below fundamental alveoli resonance. Consequently in both
frequency ranges a sound velocity should be governed by air compliance in alveoli and density of alveoli wall tissue. Thus in both frequency ranges sound velocities through normal (air-filled) parenchyma must be close enough. The latter really is seen in our current experiments for low-speed arrivals with found velocities of 50-150 m/s in frequency range of 10-19 kHz as well as for low-speed arrivals with found velocities of 20-50 m/s in frequency range of 80-1000 Hz.

However in the case the question is why there is no sound transmission in lungs for the frequency band of 1-10 kHz [1] lying between 80-1000 Hz and 10-19 kHz ranges, where sound propagation is evident?

5. Conclusions

The obtained results substantially refine the phenomenological basis of sound propagation in lungs and seems promising to provide high-resolution acoustic imaging of pulmonary parenchyma.

The study was supported by the Russian Foundation for Basic Research grant 16-08-00075-a.

REFERENCES