Global Journal of Pure and Applied Mathematics.
ISSN 0973-1768 Volume 12, Number 5 (2016), pp. 4569-4578
© Research India Publications
http://www.ripublication.com/gjpam.htm

Mathematic Model for Spectral Characteristics of Respiratory Sounds Registered in Trachea Region

Artem Shamilyevich Bureev, Ekaterina Yuryevna Dikman,
Dmitry Sergeevich Zhdanov, Ivan Yuryevich Zemlyakov
Mikhail Sergeevich Kutsov

National Research Tomsk State University,
36 Lenina Prospekt, Tomsk, 634050 Russia.

Abstract

The authors propose a model for the spectral characteristics of respiratory sounds registered in the human trachea region. Signals are synthesized within three frequency intervals with due account for the specifics of respiratory sound parameters in the trachea region. The authors present the results of the modeling and verification of the signals synthesized by means of the model proposed.

Keywords: Cardiopulmonary resuscitation, respiratory sound, spectral characteristic, acoustic signal, trachea, modeling.

INTRODUCTION

When performing resuscitation procedures in the field environment and under emergency conditions, there is a problem with controlling patients' state of health, specifically, the presence of unassisted breathing and palpitation. There are several methods to control patients' state of health, but all of them distract resuscitators' attention from the process of resuscitation. The situation aggravates, when resuscitation procedures are performed outside of medical institutions or by one person only [1]. Consequently, there is the need for automated control over the work of patients' vital and essential systems by means of inexpensive and compact technical devices in the process of cardiopulmonary resuscitation and transportation to medical institutions.

The research team has developed a device to control the CPR procedure based on the analysis of acoustic signals created by the blood and air flow in the trachea. When working on the method to control the function of the respiratory system, the authors faced the need for developing mathematic models able to generate normal and abnormal respiratory sounds. Consequently, a basic model had to describe normal physiological respiratory sounds. The authors decided to use the spectral structure of these sounds as the key parameter for this model, since different findings of the spectral analysis of normal and abnormal respiratory sounds are widely represented in literature [2, 3, 4, 5].

MATERIALS AND METHODS

First attempts to explain the origin of respiratory sounds were undertaken as early as the twenties of the XX century [6, 7]. However, there is still no complete physical description of the generation and transmission of respiratory sounds in the human chest and large airways. Moreover, there is no official, quantitative description that completely meets clinical criteria, which is the reason for further development of various models for respiratory sounds and different classifications based on these models [3, 8, 9].

Many authors reasonably associate not only the intensity but also spectral characteristics of respiratory sounds with the airflow rate, anatomical features of respiratory tracts and even the composition of breathing air [10, 11, 12]. During the act of breathing, the spectral characteristics of respiratory sounds shift in time. At the same time, the amplitude-frequency and time-frequency characteristics of respiratory sounds registered in case of various pathological conditions differ insignificantly, and existing hardware and software equipment cannot use them for the differential diagnostics of diseases [5, 11, 13].

The article [14] shows that sounds registered in healthy adults’ trachea and chest at the airflow of 1.6-2.6 m/s are independent biological signals that have different origins and are characterized by an insignificant overlap of their spectral characteristics. At the same time, many researchers single out three spectral zones of these signals [3]:

- low-frequency (from 120-130 Hz to 280-300 Hz), about 45-55% of the spectral power fall into this zone;
- medium-frequency (from 300 Hz to 500 Hz), 30-35% of the spectral power fall into this zone;
- high-frequency (500+ Hz), 10-20% of the spectral power fall into this zone.

The authors of one of the articles [15] proposed linear, piecewise approximated regression empiric models for respiratory sounds. During the experiment with a large sample (n = 353) consisting of healthy volunteers of both genders with close anthropometric data and aged 25-40 y.o., the authors received three options of the spectral density of normal respiratory sounds. At the same time, in all the cases, spectrogram peaks were localized within the range of 140-184 Hz (mean value: 172.6±12.4 Hz) during the inspiration and within the range of 200–280 Hz (mean value: 232.3±17.1 Hz) during the expiration. The authors connected an increase in the frequency of spectrogram peaks with an increase in the airflow rate in the bronchial tree at this phase of the respiratory cycle. The maximum values of frequencies at the level of -40 dB amounted to 803 Hz and 496 Hz, respectively. The decay rate of high-frequency asymptote amounted to -13…-15 dB/octave. The mean frequencies of inspiratory and expiratory spectral peaks differed in males and females by 8–12% (higher values in females).

There is another model [10], where the authors tried to connect the intensity of the high-frequency (most variable) spectral peaks of respiratory sounds with the volumetric expiratory flow rate in three groups of patients aged 4-7 y.o., 10-13 y.o. and 26-43 y.o. The spectral power density was calculated with the help of fast Fourier transform. The authors showed that there was no statistically significant dependence between the difference in the spectrums of respiratory sounds in the two last groups and the air flow rate in the trachea, which can testify to the fact that the anatomical development of the bronchial tree is completed by the age of 10-12, and the mechanism of respiratory sounds generated by vesicular respiration is established at this age.

Therefore, the analysis of literature data allows making the following conclusions:

- Nowadays the key parameter for the assessment of respiratory sounds is their non-stationary spectral characteristics that change with time and depend on the functional state of our body.
- The spectral density of signals is different for the expiratory phase, one inspiration-expiration cycle or segment with several cycles of this type.
- During quiet respiration (the air flow rate is up to 0.6 m/s), respiratory sounds registered (vesicular respiration) represent the manifestation of side-wall turbulence in the trachea and primary bronchi. Tracheal sounds are registered within the range of 100-450 Hz, bronchial sounds – 250-600 Hz (primary power) and more.
- When registering vesicular respiration, low-frequency asymptote (horizontal or increasing, with the slope of up to 5 dB/octave) and high-frequency asymptote (falling, with the slope of -12…15 dB/octave) are detected.

RESULTS AND DISCUSSION

The models of respiratory sounds examined did not allow synthesizing tracheal sounds that would completely meet the requirements of bronchophonography [16]. Therefore, there is the need for developing a respiratory sound model that will allow synthesizing both physiological and pathological respiratory sounds. From the viewpoint of the imitation of normal respiratory sounds generated by quiet respiration (vesicular sounds), it seems appropriate to develop such a model signal the spectral characteristics of which will be maximally close to the spectrums of signals obtained from experiments.

In order to develop a model for tracheal respiratory sounds, the authors decided to represent signals by means of Fourier trigonometric series

$$y(t) = \frac{a_0}{2} + \sum_{i-1}^{+\infty} (a_i \cos(\omega_i t) + \ b_i \sin \omega_i t)) \tag{1}$$

where a_i, b_i are the amplitudes of the harmonic components of this series, ω_i – signal frequency of the components.

Signals within the observable range of frequencies are characterized by different intensity of their power spectrums, and the nature of these sounds is different [17]. Therefore, the authors decided to use three frequency ranges. During preliminary experiments for the registration of tracheal respiratory sounds, low-frequency (75 Hz – 180 Hz), medium-frequency (180 Hz – 250 Hz) and high-frequency (250 Hz – 1,150 Hz) sound ranges were detected. The specified limits of these frequency ranges were used as model parameters.

Significant Pearson correlation coefficient was chosen as a signal modeling quality criterion. It was calculated during the mutual assessment of the spectral power of the model and reference signals obtained from experiments. The spectral power density $S(\omega)$ can be represented as the averaged square of the spectral density of a theoretically infinite random sequence of numbers

$$S(\omega) = \lim_{N\to\infty} \frac{1}{N+1} \frac{\left|X(e^{j\omega T})\right|^2}{f_d}, \tag{2}$$

where f_d is the sampling frequency of signals, $X\left(e^{j\omega T}\right)$ – spectral density of sequence $x(n)$,

$$X\left(e^{j\omega T}\right) = \sum_{n=-N}^{N} x(n)e^{j\omega Tn}$$

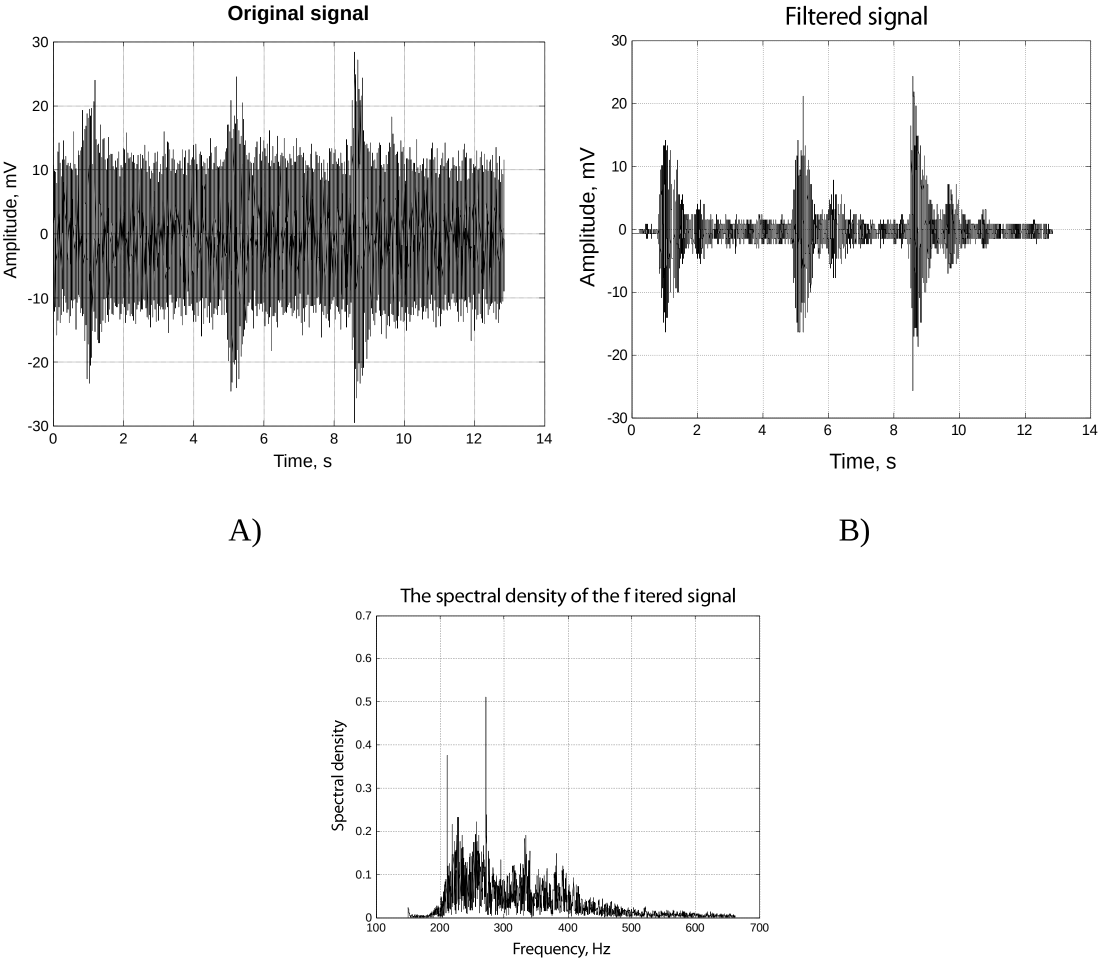
Signal measurement period $T = 1/f_d$ forms a connection between the spectral representations of analog incoming signals and discrete digitized signals ensuring a similar connection between their spectral densities.

Some part of reference signals was obtained from the library [18]. The file record format was compliant with the MP3 standard (monophonic, 16 bit, 44.1 kHz, bitrate 196 kBps), which allowed reproducing sounds with the frequency from 20 Hz to 16 kHz. The authors used physiological respiratory signals that matched the state of healthy people: vesicular respiration and bronchial respiration. Each file contained a record of five complete respiratory cycles (inspiration-expiration) in the quiet respiration mode.

In addition, the authors used several signals obtained under laboratory conditions from physiological experiments in volunteers of both genders, aged 19-52 y.o. and with the healthy bronchopulmonary system. These signals were recorded, when the volunteers stood still, and their breathing rhythm was 14-16 respiratory cycles per minute (quiet respiration). A standard piezoelectric contact microphone and laptop with a standard audio card were used to record these signals. In total, 29 experiments for the registration of physiological respiratory sounds through the mouth and nose were carried out, and 58 records were obtained. The signals were saved in the WAVE file format, with no loss in quality (16 bit, mono, 44.1 kHz).

Control over the quality of these signals was performed by means of the Wave Editor 3.3.2.0 sound file editor. This application was used to single out the fragments of respiratory sound records with the minimum level of disturbance, containing from 3 to 5 full respiratory cycles and more. Each fragment was saved as an individual file in the source format. All the actions for the preparation and analysis of signals, research and modeling were performed in MATLAB 2013b. 36 records of quiet nasal or mouth respiration characterized by an acceptable level of quality and minimum level of external noises were chosen to build the model.

At first, medium- and high-frequency signal components were singled out. In order to do this, the authors carried out band filtering by means of the 16th order Butterworth filter. As a result, all the sounds lower than 120 Hz and higher than 650 Hz were suppressed to the level of -60..-80 dB: the frequencies lower than 120 Hz contained heart tones and equipment noises, and the frequencies higher than 600 Hz contained external noises. A typical 12.6 second-long original signal of respiratory sounds, results of preliminary filtration and its spectral density are represented in Figure 1. Additional signal filtration was performed by means of Morlet wavelet transform.



A) B)

C)

Figure 1. Spectral characteristics of respiratory sounds obtained from experiments. A. Original signal registered under laboratory conditions. B. Signal after preliminary processing. C. Spectral density of the filtered signal.

An independent spectrogram in increments of 10 Hz was built for each filtered experimental signal within the range of 180-600 Hz. For each frequency, coefficient values were averaged, and mean values, dispersion and confidence intervals were calculated.

In order to form necessary frequencies for the signals that composed the model, the authors used an approach similar to that described in [6]. The following model parameters were set:

- $F_{\min}$, corner frequency for low- and medium-frequency asymptotes, 180 Hz;
- F_{int}, corner frequency for low- and high-frequency asymptotes, 250 Hz;
- P_{int}, spectral power density at frequency F_{int}, 0 dB;
- F_{max}, maximum frequency of registered signals at the amplitude of -60 dB (corresponds to the range of the analog-to-digital converter with the bit depth of 10 bits), 1,150 Hz;
- A_{low}, slope of low-frequency asymptote within the range from 75 Hz to F_{int}, -5 dB/octave;
- A_{high}, slope of high-frequency asymptote within the range from F_{int} to F_{max}, -15 dB/octave.

The arrangement of the adopted model parameters in the spectral plane is shown in Figure 2.

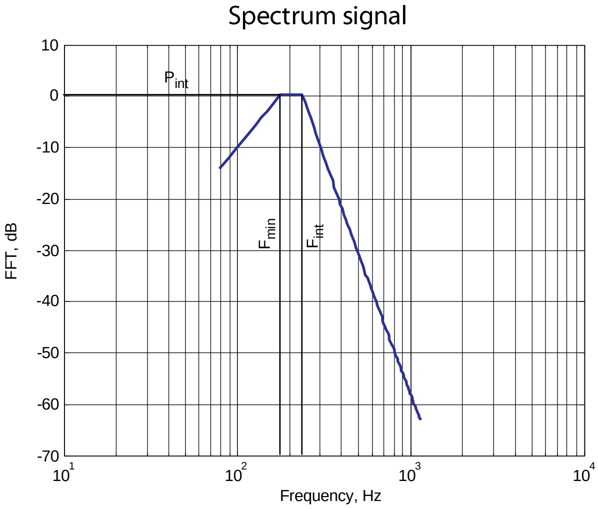


Figure 2. Arrangement of the frequency parameters of the signal model in the spectral plane

The amplitudes of the frequencies $F_{\min}$ to F_{int} were maximum and equal to 0 dB. The amplitudes of the frequencies lower than $F_{\min}$ decreased with the rate $A_{\mathrm{low}} = –5$ dB/octave or 25 dB/decade to the frequency of 75 Hz. The amplitudes of the frequencies higher than F_{int} reduced with the rate $A_{\mathrm{high}} = –15$ dB/octave or 75 dB/decade to the level of -60 dB, which corresponded to the frequency of 1,150 Hz. In order to obtain a satisfactory description of the tracheal component of respiratory sounds, the frequencies of the signal components generated had to lie within the range of 70-1,150 Hz. In total, 108 frequencies in increments of 10 Hz were used to synthesize signals. At the same time, it was assumed that the only source of sound is side-wall turbulence, and the linear air flow velocity is not higher than 0.6 m/s, which eliminated the possibility of time shifting for frequency characteristics.

The frequency model of signals obtained represents a system of three non-linear algebraic equations and can be represented in the following way in the logarithmical form (4).

$$\begin{cases} \log(P_{low}) = \dfrac{A_{low}}{20\log(2)}\log(F) + \log\left(\dfrac{P_{int}}{\mathrm{F}_{\min}\left(\dfrac{A_{low}}{20\log(2)}\right)}\right), \\ \log(P_{mid}) = \dfrac{\log(F_{min})}{20\log(2)}, \\ \log\left(P_{high}\right) = \dfrac{\log(F_{min})}{20\log(2)} + \log(F)\log\left(\dfrac{P_{int}}{F_{int}\left(\dfrac{A_{int}}{20\log(2)}\right)}\right), \end{cases} \tag{2}$$

where P_{low}, P_{mid} and P_{high} – spectral power density of the signals generated in the zones of low, medium and high frequencies, respectively. The authors elaborated the behavior of low- and high-frequency asymptotes and specified their trajectories in corresponding frequency zones. In order to increase the plausibility of synthesized signals in the form of the inspiration-expiration cycle, parameter values can be represented as functions of the time of the respiratory cycle.

The synthesis of signals based on the model proposed (4) was carried out by means of a specially created MATLAB script. The calculation of the spectral power density of respiratory sounds based on this model is shown in Figure 3.

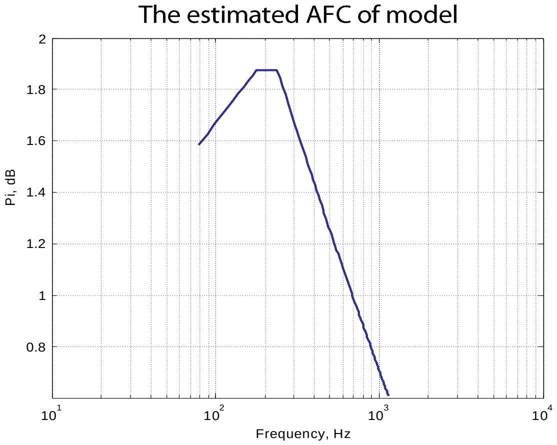


Figure 3. Calculated values of the spectral power density of respiratory sounds.

According to available data [3, 15, 17], a reduction in the amplitude-frequency characteristics of respiratory sounds at the rate of -5 dB/octave was modelled at the level of low frequencies (from 70 Hz to 180 Hz). Some authors believe that this range is of little importance to clinical trials [3, 17], but it can be very valuable for artificial respiration, when the air flow rate is quite low in the trachea. In addition, energy characteristics of signals are used to register respiratory acts, which also requires the presence of the low-frequency components of signals.

In the authors' opinion, the AFC of the signal within the frequency range of 180-250 Hz should be practically horizontal, as the air flow rate does not change in the trachea during the expiration phase. Consequently, sound oscillations generation should also have several constant parameters, e.g., amplitude and spectrum.

The reasons for a relatively rapid falloff of the spectrogram in the zone of high frequencies were rather thoroughly examined in [17], and the authors do not have any comments on this matter.

In order to verify the model, the authors additionally examined the spectral density of these signals. The amplitudes of component frequencies were calculated in the MATLAB environment in accordance with the model provided (4). The results of the spectral representation of the reference and synthesized signals are shown in Figure 4. Curve A of the spectral density chart corresponds to the spectrum of the signal obtained from the physiological experiment. The first peak of the spectral density within the range of 230-250 Hz corresponds to the spectrum of expiratory respiration sounds. Specifically this phase is registered in patients during artificial respiration.

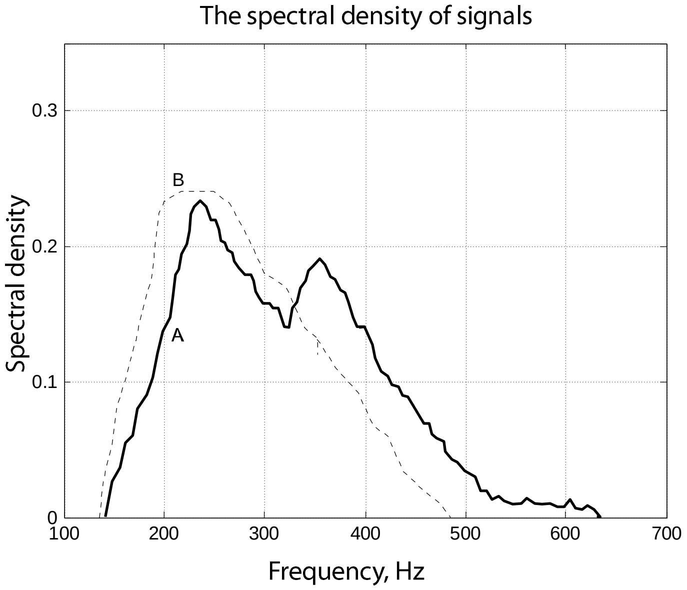


Figure 4. Charts of the spectral density of respiratory sound signals. A. Respiratory sounds obtained from the physiological experiment. B. Signal synthesized under the initial model parameters.

CONCLUSION

Despite the fact that the simple model proposed imitates only one peak of spectral density, the signal synthesized by means of this model is sufficient to perfect the respiratory sound detection algorithm. It is noteworthy that the synthesized and original signals have similar qualitative characteristics in the low-frequency zone.

In the authors' opinion, it is unnecessary to imitate inspiratory signals (peak of the spectral density – 340-400 Hz) for artificial respiration, although this model can theoretically be developed in such way without any problems.

In order to synthesize a model of respiratory sound that will take into account not only frequency characteristics but also amplitude-time characteristics of signals, the authors are going to introduce several new parameters responsible for changes in the amplitude of signals with time. In addition, it is necessary to create a model for the frequency characteristics of the second spectral peak. It can be represented as some function $f(t)$ that should integrate at least four exponents in its simplest form. However, this task requires a new research study to be carried out.

ACKNOWLEDGMENTS

The study was performed within the framework of the Agreement #14.578.21.0078 (unique identifier for the project – RFMEFI57814X0078) entitled "The device for monitoring CPR procedures of a human being", signed between National Research Tomsk State University and the Ministry of Education and Science of the Russian Federation.

REFERENCES

[1] 3M Littmann Stethoscopes: Basic Lung Sounds Tutorial. 50 Heart and Lung Sounds Library. Retrieved February 18, 2016, from solutions.3m.com/wps/portal/3M/en_EU/3M-Littmann-EMEA/stethoscope/littmann-learning-institute/heart-lung-sounds/heart-lung-sound-library/ .

[2] I.V. Vovk, V.T. Grinchenko, L.G. Krasnyi and A.P. Makarenkov, "Breath sounds: recording and classification problems". Acoustical Physics, vol. 40, no. 1, pp. 50-56, 1994.

[3] V.I. Korenbaum, Yu.V. Kulakov and A.A. Tagiltsev, "The origin of vesicular respiratory sounds". Human Physiology, vol. 23, no. 4, pp. 133-135, 1997.

[4] A.Sh. Bureev, D.S. Zhdanov, I.Yu. Zemlyakov and M.V. Svetlik, "Processing bronchial sonograms to detect respiratory cycle fragments". IOP Conf. Series: Materials Science and Engineering, vol. 66, pp. 12-18, 2014.

[5] F. Dalmay, M.T. Antonini, P. Marquet and R. Menier, "Acoustic properties of the normal chest". Eur. Resp. J., vol. 8, pp. 1761-1769, 1995.

[6] S. Fahr, "The Acoustic of Bronchial Breath Sounds". Arch. Inten. Med, vol. 4, pp. 288, 1926.

[7] P. Martini, and H. Meuller, “Über das Bronhialtmen”. Dtsh. Arch. F. Klin. Med., vol. 143, pp. 159-172, 1923.

[8] S.V. Gorbachev, D.S. Zhdanov, I.Yu. Zemlyakov and M.V. Svetlik, “Improvement in the accuracy of the detection of bronchopulmonary diseases based on the phase-time analysis of brochophonograms”. Proceedings of the universities. Physics, vol. 6, no. 10-2, pp. 18-24, 2013.

[9] D.S. Zhdanov, I.Yu. Zemlyakov, M.V. Svetlik and V.I. Syriamkin, “Potential use of the spectral characteristics of respiratory sounds for the express assessment of the bronchopulmonary system”. Telecommunications, vol. 6, pp. 42-46, 2014.

[10] M. Golabbakhsh, and Z. Moussavi, “Relationship Between Airflow And Frequency-Based Features Of Tracheal Respiratory Sound”. Electrical and Computer Engineering. Canadian Conference on., IEEE, vol. 2, pp. 751-754, 2004.

[11] H., Pasterkamp, R.S. Kraman and G.R. Wodicka, “Respiratory Sounds”. American Journal of Respiratory and Critical Care Medicine, vol. 156, no. 3, pp. 974-987, 1997.

[12] J. Xi, X. Si, J.W. Kim and G. Su, “Modeling the pharyngeal anatomical effects on breathing resistance and aerodynamically generated sound”. Med. Biol. Eng. Comp., vol. 52, no. 7, pp. 567-577, 2014.

[13] B.A. Reyes, S. Charleston-Villalobos, R. González-Camarena and T. Aljama-Corrales, “Assessment of time–frequency representation techniques for thoracic sounds analysis”. Comp. Meth. Prog. Biomed., vol. 114, no. 3, pp. 276, 2014.

[14] V.J. Mussel, and Y. Miyamoto, “Comparison of normal respiratory sounds recorded from the chest and trachea at various respiratory and flow levels”. Front. Med. Biol. Eng., vol. 2, no. 4, pp. 73-85, 1992.

[15] N. Gavrielly, N. Nissan, A.E. Pubin and D.W. Cugell, “Spectral characteristic of chest wall breath sounds in normal subjects. Thorax, vol. 50, pp. 1292-1300, 1995.

[16] A. Guseinov, “Bronchophonography: acoustic criteria for the diagnostics of obstructive pulmonary diseases”. Fundamental Research, vol. 2, pp. 55-59, 2011.

[17] V.I. Korenbaum, I.A. Pochekutova and A.A. Tagiltsev, “Regression modeling of the acousto-biomechanical characteristics of wheezes during human forced expiration”. Fluid Dynamics, vol. 38, no. 6, pp. 882-888, 2003.

[18] P. Safar, and N. Bircher, “Cardiovascular and cerebral resuscitation”. Moscow: Medicine, pp. 552, 2003.