Processing bronchial sonograms to detect respiratory cycle fragments

A Sh Bureev[1], D S Zhdanov[1], I Yu Zemlyakov[1], M V Svetlik[1]

[1] *Tomsk, 634055, Russia,* Diagnostika + Limited Liability Company

E-mail: D_S_Zhdanov@mail.ru

Abstract.

This article describes the authors' results of work on the development of a method for the automated assessment of the state of the human bronchopulmonary system based on acoustic data. In particular, the article covers the method of detecting breath sounds on bronchial sonograms obtained during the auscultation process.

Introduction

According to the data of the World Health Organization (2009), the global incidence of chronic obstructive lung diseases and bronchial asthma has become over 10 times higher since the beginning of 2000. The mortality rate for these conditions, including infectious diseases, takes the third place in Europe being inferior to cardiovascular and oncologic diseases. In Russia, the number of patients with bronchial asthma amounts approximately to 7 million people (2.2% of the population, the 18th place in the world); however, the country takes the second place in the world in terms of the number of lethal cases (28.6 per 100 thousand people). One of the key reasons for such a situation is late detection of the disease. The condition is diagnosed at the stages, when common therapeutic options cannot stop disease progression.

The simplest and the most common method to study the respiratory function is the auscultation (hearing) of breath sounds. The method was proposed by French physician R. Laennec in 1821. Despite the development of other diagnostic methods, this technique is still one of the most important patient examination methods. The key drawback of this technique is the subjectivity of a physicians' opinion during the analysis of these sounds – auscultation findings also depend on many hard-to-formalize factors, first of all, individual hearing parameters (musicality, hearing acuity, frequency range, physicians' age and gender). It is necessary to take into account the fact that a stethoscope might bring in inaccuracy, as it weakens the signals the frequency of which is higher than 120 Hz, and the human ear is characterized with poor sensitivity to low-frequency sounds [1-3].

Since the mid-1990s, scientists have been trying to make the methods of assessing normal and abnormal breath sounds more objective by means of bronchial sonography. The method's key idea implies recording and further analysis of patients' breath sounds and respiratory murmur. The most obvious solution is assessing the spectral density of sounds through time under the conditions of calm breathing and/ or forced expiration. In this connection, some authors [3-6] proposed new methods for acoustic lung diagnostics. They identified diagnostically significant objective signs: relations between the presence of sounds at the frequency of 0.2–1.2 kHz, 1.2–12.6 kHz and 1–12.6 kHz. The sensitivity of detecting bronchial obstruction with this method is 86.7%, the technique specificity is 86.5%.

Unfortunately, besides the statement of the fact of air obstruction in airways and quantitative assessment of this phenomenon, the models and methods described cannot provide any further information. According to many practicing physicians, one of the most important assessment parameters is the timbre nature of breath sounds and rattling from the viewpoint of their musicality: whether these sounds can be attributed to one of the common categories – rattling, sibilant rale, dry or moist rale, crepitation, pleural friction rubs, etc. [0, 0, 0]. It is exactly this identification of auscultative signs to be most subjective and often require a board of physicians to make a diagnosis.

Within the framework of State Contract No.2013-1.4-14-514-01 concluded between the Ministry of Education and Science of the Russian Federation and LLC Diagnostika + on the subject "Development and research on the methods of producing informational images of bronchial sonography signals and algorithms to detect pathological signs for more objective diagnostics of bronchopulmonary diseases in pediatrics", the authors developed an algorithm for the automated detection of respiratory cycles on patients' bronchial sonograms under study. Further analyses of the fragments detected allow building mathematic models to assess the state of the patients' bronchopulmonary system by means of specialized algorithms. The existing method including the algorithm for automated detection of respiratory cycles makes it possible to analyze patients' bronchopulmonary sounds in the automated mode most thoroughly, which allows significantly reducing the subjective component related to physicians' hearing peculiarities and personal experience when assessing patients' type of breathing. In addition, analyzing only significant fragments of the respiratory cycle makes it possible to detect bronchopulmonary diseases at the initial stages.

Theoretic rationale

The basis for the development of the algorithm to detect respiratory cycle fragments is bronchial sonograms recorded with a special model used to obtain auscultative signals from the patients' bronchopulmonary system.

The authors used a binaural pediatric stethoscope as an acoustic detector. The Panasonic WM-61 microphone was installed into the sonic locator of the device. In order to exclude noises produced by the frictions of the sound-amplifying membrane on the patients' skin, the authors used an open funnel of the stethoscope. The microphone was glued into the opening bored in the place of bifurcation of the sound channels, straight across their axis. Then a shielded lead was welded on the microphone, and the entire node was covered with a 5-8 mm layer of the silicone sealer. Such a structure of the acoustic detector allows reducing the level of external noises at the frequency of 50-1,000 Hz by 10-12 dB.

Bronchial sonograms were recorded at the therapeutic wards of pediatric and adult pulmonology departments, i.e., under the conditions that were maximally close to the actual operating settings of the authors' end product – software and hardware complex for invasive automated express diagnostics of human bronchopulmonary diseases. Patients were aged from 3 to 30 y. o. As a result, the bronchial sonograms contained a lot of noises (other than breath sounds), which made it hard to diagnose the state of the patients' respiratory system. In order to eliminate these noises, the authors used specialized digital filters that allowed detecting specifically breath sounds in the bronchial sonograms recorded. For this purpose, the authors used the Embarcadero RAD Studio XE4 development framework (C++ programming language) to create an application that allowed studying the frequency composition of the bronchial sonograms under consideration based on the fast Fourier transform (FFT) method. The bronchial sonograms under study were divided into sections, the length of which was equal to the size of the FFT window (1,024 sections of the bronchial sonograms under study), the sections underwent FFT, and the results were normalized to the sampling frequency of the section obtained according to the formula $\frac{i*f_s}{Size}$, where i is the number of the FFT window element; f_s- sampling frequency of the bronchial sonogram, *Size* – size of the FFT window. The research on the spectral composition of 100 bronchial sonograms obtained in patients aged 3-30 y. o. revealed that diagnostically significant breath sounds lie within the frequency range of 80-500 Hz. These values are true for the analysis of bronchial sonograms obtained under the conditions of patients' calm breathing. Therefore, it is necessary to design a digital filter that will allow singling out the above-mentioned frequency range [1-6].

Due to the peculiarities of the acoustic detector used to record patients' bronchial sonograms, they do not contain sounds at the frequency over 700 Hz. Therefore, the authors took a decision to use a high-frequency digital filter and noise suppression in the area of the rejection band at the level of 30 dB.

The authors used their own application (developed by means of the Embarcadero RAD Studio XE4 development framework, C++ programming language) to analyze and develop digital filters with finite impulse response (FIR) and infinite impulse responses (IIR). The key goal is to choose the most optimal implementation (in terms of fast action at the level of software) and highest-quality method to eliminate low-frequency noises hindering the correct detection of respiratory cycle fragments.

As for the FIR filter, the authors analyzed the probability to implement it by calculating window coefficients with the Hann window function (it provides noise suppression at the rejection band at the level of 44 dB). The filter was calculated in two stages. At the first stage, the authors set its order and calculated an ideal impulse response for the filter:

$$h(n) = \begin{cases} 1 - \frac{\omega_c}{\pi}; & n = M \\ -\frac{\sin(\omega_c(n-M))}{\pi(n-M)}; & n \neq M, \end{cases} \qquad (1)$$

where $h(n)$ – element of the ideal impulse response of the filter, ω_c – cutoff frequency of the filter, n – number of the impulse response element of the filter, M – median element of the impulse response of the filter.

At the second stage, the authors calculated a window coefficient for the filter and corrected its ideal impulse response:

$$h(n) = h(n) * \left(0.5 * \left(1 - \cos\left(\frac{2\pi n}{N-1}\right)\right)\right), \qquad (2)$$

where N – filter order. This filter type did not allow eliminating low-frequency noises hindering the detection of breath sounds in the bronchial sonograms under study. Moreover, in order to implement this filter, it is necessary to use a larger filter order (set of impulse response characteristics), which affects the speed of the algorithm used to detect breath fragments and express diagnostics of the bronchopulmonary system. The type 1 Chebyshev IIR filter would allow completely eliminating low-frequency noises. The coefficients of this filter in response characteristics are calculated according to the following formula:

$$H(z) = H_0 * (-1)^{N-M} * \frac{1}{\prod_{k=1}^{N}(1-p_k)} * (1+z^{-1})^{N-M} * \frac{\prod_{k=1}^{M}(1-z^{-1})}{\prod_{k=1}^{N}\left(1-\frac{1+p_k}{1-p_k}z^{-1}\right)}, \qquad (3)$$

where H_0 – constant calculated for the high-frequency type 1 Chebyshev filter, N – filter order, M – number of poles for the analogue prototype of the low-frequency filter, p_k – frequency of the pole. Following the elimination of noises, breath fragments that are significant assessing the state of the human bronchopulmonary system are singled out by means of the autocorrelation function. For this purpose, the autocorrelation function between the sections of the bronchial sonograms under study is calculated according to the following formula:

$$A(\tau) = \int f(t)f(t-\tau)dt, \qquad (4)$$

where τ – offset value of the bronchial sonogram section; $f(t)$ – section of the bronchial sonogram; $f(t-\tau)$ – copy of the bronchial sonogram section shifted relatively to itself by τ.

Results and considerations

The authors developed specialized software able to automatically detect diagnostically significant sections of patients' bronchial sonograms. The theoretical data presented in the previous section and implemented in the software application developed were used to process 100 bronchial sonograms of patients aged 3-30 y. o. The method proposed is illustrated by the example of a 3-year-old girl's

bronchial sonogram. A WAVE file with the sampling frequency of 10 kHz and duration of 9.5 seconds was chosen for processing. Figure 1 demonstrates the graphic representation of this record.
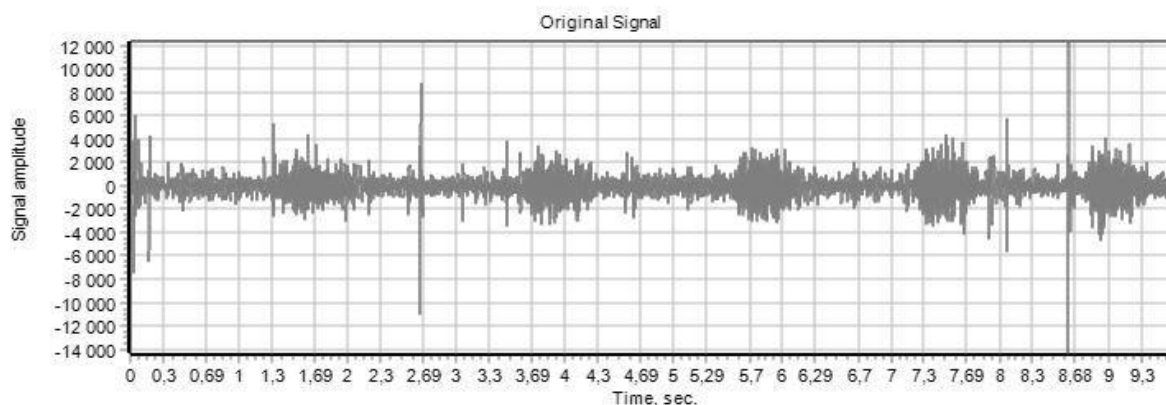

Figure 1. Graphic representation of the initial bronchial sonogram.

Then, in order to eliminate low-frequency ambient noises, the authors used the type 1 Chebyshev IIR high-frequency filter. Figure 2 demonstrates the results.
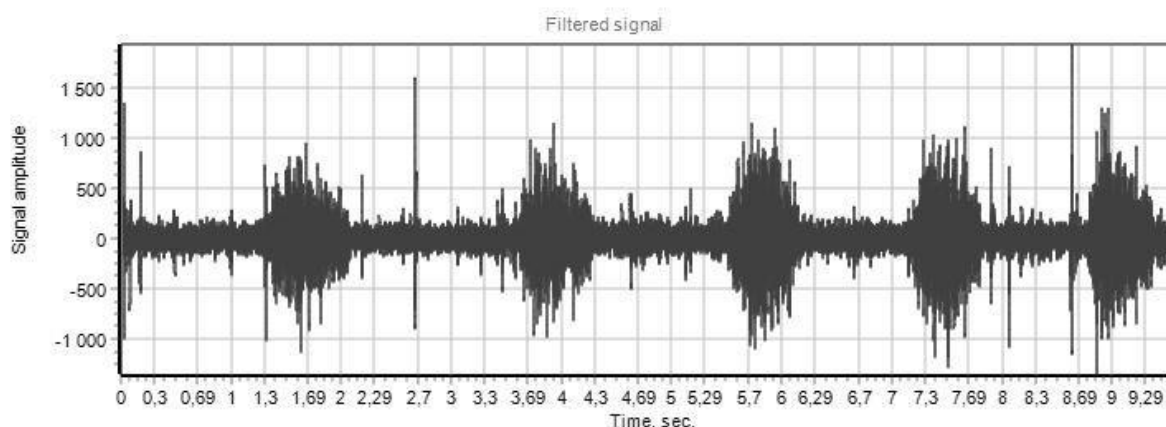

Figure 2. Graphic representation of the bronchial sonogram after eliminating low-frequency noises.

The graphic representation of the bronchial sonogram freed from low-frequency noises shown on Figure 2 allows one to see that noises hindering auscultation were eliminated. There are only clearly pronounced clicks caused by the contact between the acoustic detector and patients' skin. These clicks are not critical for the authors' method used to detect clinically significant breath sounds with the use of the autocorrelation function. The final automatically detected findings are represented on Figure 3.

The detected fragments of the respiratory cycle can be described as mathematic models for the purpose of further express diagnostics of bronchopulmonary diseases in patients of a varying age. Nowadays the authors are performing activities meant to describe various pathological conditions of the human bronchopulmonary system.
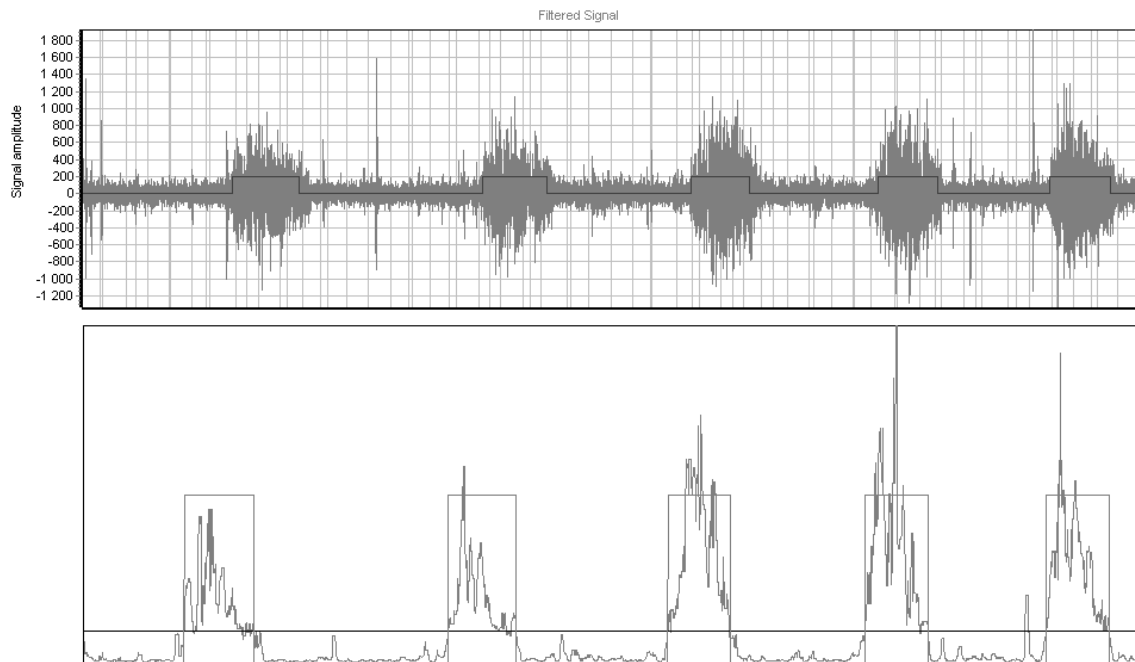
Figure 3. Graphic representation of detected clinically significant breath fragments.

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