Increasing the Reliability of Human Respiration Pulmonograms Measured by Radio Wave Method

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Abstract

This article considers a device for monitoring the functioning of the bronchopulmonary system, including the study of human respiration by radio wave method. The principle of operation of the device is based on the emission of low-power radio waves by a generator and measurement of their level by a spectrum analyzer after passing through a person's lungs during breathing. A switched array of emitting and receiving antennas is used to cover the entire volume of the lungs. The result of the measurement is a pulmonogram – a record of the functioning of the entire lung volume in time. To achieve the practical applicability of the device, it is necessary to ensure the repeatability of the obtained pulmonograms after identical measurements, i.e. to increase the reliability of the results. The purpose of this work is to substantiate the applicability of pulmonograms reliability increasing methods through experiments and calculations. A method is proposed for calculating the required number of measurements at a given accuracy of the measuring device to match the required confidence interval. The article proposes a method for synchronizing breathing cycles by introducing a light indication into the device. This method will allow the use of the method of integration and averaging of pulmonograms in order to increase the reliability of the results.

Keywords

Pulmonogram, lung, breath, noninvasive, microwave, generator, antennas, spectrum analyzer, synchronization of breath cycles, increasing information content

1. Introduction

The study and evaluation of the human respiratory system is carried out by various devices and methods. In outpatient settings, functional pulmonary tests such as spirometry and pulse oximetry allow to quickly narrow down the differential diagnostic search for various pathologies and justify the choice of a further diagnostic method. To expand the limited capabilities of such devices and methods, it is necessary to develop devices based on other physical principles. Magnetic resonance imaging, computed tomography, fluorography methods have their advantages and disadvantages. We propose a non-invasive harmless investigation method with the possibility of frequent use as an express diagnosis.

This article presents a developed and patented device for monitoring the functioning of the bronchopulmonary system, including the study of human respiration [1]. The block diagram of the device operation is shown in Figure 1.

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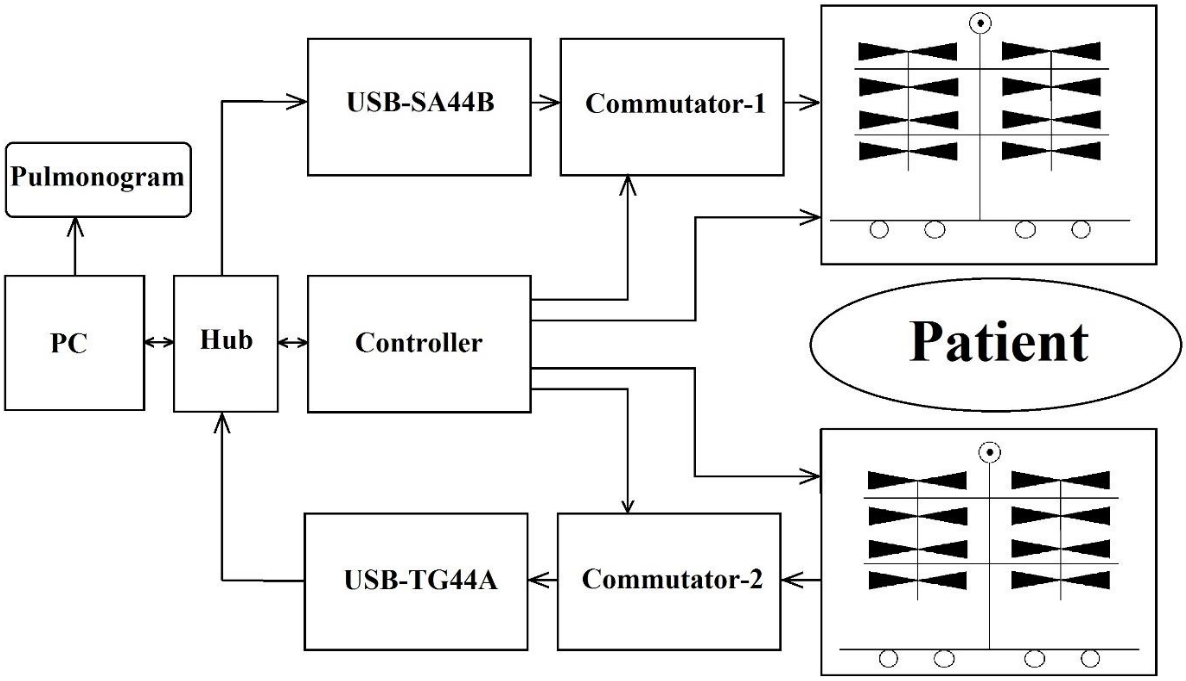

Figure 1: Block diagram of the device for investigating the functioning of the bronchopulmonary system by radio wave method

The operation of the device is based on the method of measuring the level of the signal that has passed through a person's lungs during breathing. The method is a non-ionizing method of measurement, since the power range of the generator radiation is safe: from -30 dBm to -10 dBm. The curve of the signal amplitude change recorded by the spectrum analyzer – a pulmonogram – corresponds to the attenuation of the electromagnetic radiation energy depending on the change in the medium. The name pulmonogram, proposed by the second author of this article (Latin pulmo, pulmonis lung + Greek gramma recording) by analogy with an electrocardiogram. During the measurement, the signal propagation medium changes corresponding to the variation in the amount of air entering the lungs. We have proposed a model of the medium for an electromagnetic signal - a serial connection of three capacitors. The first capacitor is the part of the body before the lungs, the second capacitor is the lungs and the third capacitor is the part of the body behind the lungs. Changing the amount of air in the lungs changes the resistance of the second capacitor, leaving almost unchanged the resistance of the first and third capacitors. On the pulmonogram, the intake of air into the lungs is shown by a proportional decrease in the signal level compared to the lungs without air.

2. Description of the device

For practical implementation and recognition as a full-fledged new additional way of studying the functioning of human respiration, it was necessary to overcome a fundamental difficulty. The disadvantage of the prototypes of this device was that measurements could be carried out only in certain areas of the lungs, moving the receiving and transmitting antennas on both opposite sides of the lungs and thereby analyzing only a separate section [2-3]. In the developed device, the decision on the use of electronic commuting, i.e. sequential spatial switching of the antennas of corresponding generator and receiver in the matrix of transmitting and receiving antennas allowed scanning to cover the entire volume of the lungs in a short time, during which the change in air movement is insignificant. Pulmonograms of a larger number of lung sections obtained simultaneously allow us to identify the features of filling the lungs with air as a whole and continue measurements over time without interrupting the human breathing process.

There are two main electromagnetic research methods: obtaining information from a backscattered wave or from a transmitted through i.e. attenuated wave. To identify diagnostic information from a wave that has been influenced by a biological object – the lungs, it is necessary to identify the features of the mechanism of its propagation in biological objects in both cases.

A frequency of 1220 MHz was used in the device for experiments. At such a frequency, it is advisable to use the method of measuring the signal that has passed through a person, and not the backscattered signal. This is confirmed by the fact that in [4] the author found out that for an elongated spheroidal lung model, the backscattered microwave energy at a frequency of 2450 MHz is less than one tenth of the forward-scattered component, and the backscattered microwave energy at a frequency of 915 MHz is of the same order of magnitude with the forward-scattered component. Above 915 MHz, the forward energy of the scattered component prevails.

An electromagnetic wave propagates in a material medium at a speed of:

$$\upsilon = \frac{1}{\sqrt{\mu\varepsilon}} \tag{1}$$

where μ - magnetic permeability of the medium, ε - dielectric constant of the medium. Biological materials are lossy dielectrics for electromagnetic radiation, so the magnetic permeability of the medium is equal to the value in free space and does not depend on frequency. The dielectric constant of biological tissues depends on the frequency. The approximate permittivity of the lungs at a frequency of 1220 MHz is 34 [4]. Thus, the measurement resolution increases to 4.22 cm in body (lung) compared to the wavelength of 24.59 cm in open space.

Studies are conducted on the classification and study of various types of breathing by different authors [5-7]. The pulmonograms obtained by the proposed method make it possible to analyze the functioning of a person's lungs with calm breathing and under various breathing conditions. Variations in the levels and forms of pulmonograms can give different information about pathological changes in the lungs, about the types of respiratory disorders to identify the corresponding diseases. Covering the entire volume of the lungs will allow to explore the features of the functioning of various parts of the lungs.

Detailed characteristics of the tracking generator and spectrum analyzer are presented in Tables 1 and 2.

Table 1
Characteristics of the USB-TG44A tracking generator

Frequency range	from 10 Hz to 4.4 GHz
Frequency accuracy	±1·10-6
Frequency steps	19 step sizes to choose from 10 Hz to 10 MHz
Amplitude range	from -30 dBmW to -10 dBmW
Absolute amplitude accuracy	±2 dB
Amplitude steps	1 dB
Harmonics	< -10 dBc for typical use

Table 2
Characteristics of the spectrum analyzer/measuring receiver USB-SA44B

As a spectrum analyzer	
Frequency range	from 1 Hz to 4.4 GHz (without RF preamp) from 500 kHz to 4.4 GHz (with RF preamp)
Accuracy of the internal reference frequency	±1·10-6
Counter accuracy	±(1 Hz + reference time error)
Resolution band	from 0.1 Hz to 250 kHz and 5 MHz
Average noise level	for frequencies from 1 GHz to 2.6 GHz: -139 dBmW (without RF preamp) -151 dBmW (with RF preamp)

Range of measured amplitude	from +10 dBmW up to an average noise level
Absolute accuracy	±1.5 dB (from 0 dBmW up to an average noise level); ±2.0 dB (from +10 dBmW to > 0 dBmW)
Relative accuracy	±0.25 dB (from 0 dBmW up to an average noise level)
As a measuring receiver	
Operating frequencies	from 150 kHz to 4.4 GHz
Accuracy of FM	±1 % for typical use
Accuracy of AM	±1 % for typical use
Synchronous detector level	±0.25 dBc for frequencies from 150 kHz to 1 GHz: from 0 dBmW to -125 dBmW for frequencies from 1 GHz to 4.4 GHz: from 0 dBmW to -115 dBmW

Figure 2: Tracking generator and spectrum analyzer

Figure 2 shows a photo of the device, consisting of a USB-TG44A tracking generator, a USB-SA44B spectrum analyzer, a laptop with an installed program for displaying measurement results – pulmonograms, a controller, two stands with antenna arrays, switches and synchronization light indicators.

3. The method of calculating the required number of measurements at a given relative accuracy of the measuring device

Here presented the determination of the number of measurements that must be averaged to correspond to the confidence interval $CONF_{95\,\%}\{\bar{x}-k \le \mu \le \bar{x}+k\}$ with a relative accuracy of the measuring device of 0.25 dB (Table 2). Standard deviation index is set as c=1.960, corresponding to the confidence level for experiments γ=95 %. Standard deviation (σ) calculation of the results of measurements for a given relative accuracy of the measuring device presented by formula 2.

$$
\begin{aligned}
&0.25\,dB = 10\times\log_{10}\frac{P_1}{P_2}\\
&\frac{P_1}{P_2} = 10^{0.025}\approx 1.059\\
&\sigma = \frac{P_1-P_2}{P_2} = \frac{P_1}{P_2}-1 = 1.059-1 = 0.059
\end{aligned}
\tag{2}
$$

Confidence interval determination is carried out by setting the maximum sampling error equal to 0.5 dB (3).

$$
\begin{aligned}
&0.5\,dB = 10\times\log_{10}\frac{P_1}{P_2}\\
&\frac{P_1}{P_2} = 10^{0.05}\approx 1.122\\
&1.122-1 = 0.122\%\\
&k = 0.122
\end{aligned}
\tag{3}
$$

The required number of measurements required to match the value of the confidence interval is determined by the formula (4).

$$
n = \left(\frac{c\times\sigma}{k}\right)^2 = \left(\frac{1.960\times 0.059}{0.122}\right)^2 \approx 1 \tag{4}
$$

The calculation shows that for a given accuracy of the spectrum analyzer, 1 measurement is sufficient. In addition. averaging the results of more measurements can increase the accuracy of the results by using the same spectrum analyzer.

4. Introduction of a synchronization indicator to enable the use of integration and averaging of pulmonograms

A significant limitation for the implementation of the method based on measuring the level of the signal passed through the lungs of a person is that the signal experiences numerous re-reflections inside and around a person. Minor changes in the position of a person during the measurement also affect the level of recorded signals. Multipath propagation of the signal reduces the signal-to-noise ratio and thereby reduces the reliability, stability and informativeness of pulmonograms.

To solve this problem, the method of integration and averaging of measurement results is used. Authors of the article [8] applied the method of integration and averaging for positioning problems in enclosed spaces. The result was an increase in the stability of measurements. Integration and averaging will increase the signal-to-noise ratio and increase the reliability, stability and informativeness of the measurement results – pulmonograms also for the tasks of studying respiration by radio wave method. Signals with an amplitude equal to one after M multiple summation will have an amplitude of M . Noise with a standard deviation equal to one before integration after M multiple summation will have a standard deviation of $\sqrt{M}$. Thereby improving of the signal-to-noise ratio in terms of voltage:

$$\frac{S}{N} = \frac{M}{\sqrt{M}} = \sqrt{M} \tag{5}$$

In terms of power, the signal improves M times.

To implement the method of integration of measurement results and averaging, a series of experiments was carried out. Figure 3 shows the dimensions of the antenna array, adjusted to the complexion of the person being examined.

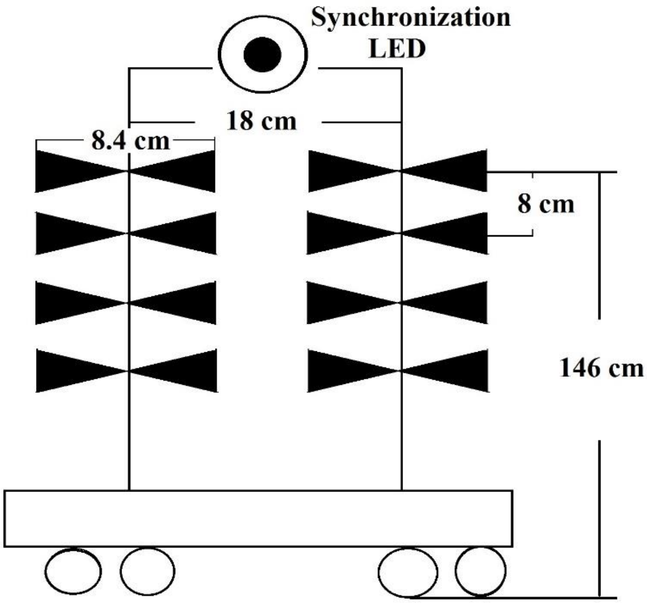

Figure 3: The dimensions of the antenna array stand before the experiment, adjusted to the height and complexion of the person being examined

In this article pulmonograms of breathing of one real person are presented.

To study the breathing of a person with a height of 165 cm the geometric parameters of the device were adjusted to it and equal to the following values:

- distance between stands with arrays of emitting and receiving antennas: 60 cm (far zone);
- in each matrix, the distance between vertical antennas: 18 cm;
- distance between horizontal antennas: 8 cm;
- height of the topmost antennas from the ground: 146 cm.

The stand of matrices with antennas was adjusted to the complexion of the examined person according to the data of the reference books on pulmonology [9-10] to take into account the boundaries of the lungs in the human body.

The technical parameters of the device for experiments were chosen equal to the following values:

- USB-TG44A generator frequency: 1220 MHz;
- relative accuracy of the USB-SA44B spectrum analyzer: 0.25 dB.

The mutual influence of antennas during radiation was studied and modeled in the MMANA-GAL software environment. The results of solving this problem were given in the article [11].

Figure 4 shows a photograph of the person being examined, located between stands with antenna arrays.

Authors of the article [12] claimed that they carried out from 10 to 40 averaging of the results of experimental measurements. But the authors of mentioned article do not indicate how the integration of measurement results and averaging were carried out.

Figure 5 shows the result of measuring 16 breathing cycles of the examined person. The results of measuring the respiration of the right and left parts of the lungs are presented almost simultaneously. The respiration cycle was set to 6. The spectrum analyzer measured 15 samples per second. Thus, along the abscissa axis, 16 breathing cycles of 6 seconds and 15 samples per second are represented by 1440 samples. The ordinate axis shows the signal levels in ADC units.

In this experiment, the examined person was instructed to breathe evenly. The graphs show that the signal level is not always uniform.

To increase the signal-to-noise ratio, the averaging method was then applied to these results. The results of averaging in dB are shown in Figure 6.

Figure 4: The location of the person being examined during the experiment

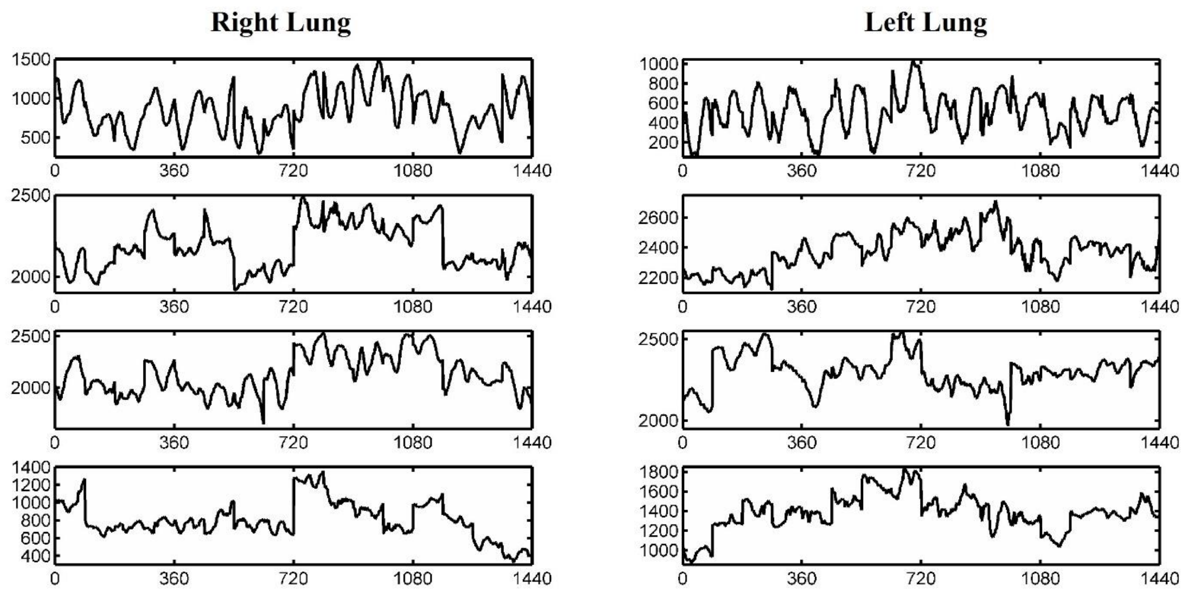

Figure 5: 16 breathing cycles of the examined person without the use of a synchronization indicator (in ADC units)

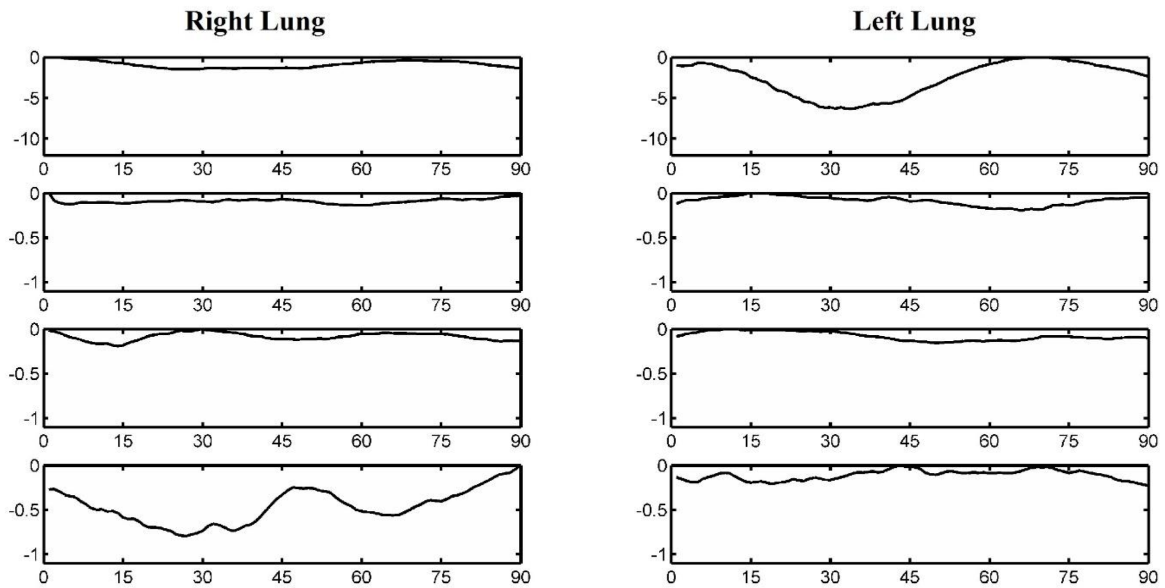

Figure 6: Integration and averaging of 16 breathing cycles without the use of a synchronization indicator (in dB)

The results in Figure 6 show that integration and averaging did not increase the signal-to-noise ratio.

The mistake here is that the pulmonograms of different cycles have different durations.

To implement the method of integration of measurement results, it is necessary to add up the measurement results of the same duration corresponding to one complete cycle of breathing. The beginning of inhalation and the end of exhalation of individual measurement results on the pulmonogram do not always coincide in duration. A person during breathing alone cannot accurately observe the duration of the breathing cycle.

To overcome this difficulty, a method of synchronizing human breathing cycles was proposed. Two LEDs were added to the device. Light-on of the LED indicates to the person the time of the beginning of inhalation, and light-off of the LED indicates to the person the time of exhalation. Both duration of the times when LED in on position and in off position corresponds to the duration of the full cycle of human respiration. The duration of the cycle can be selected according to convenience. Figure 7 shows the results of measurements using synchronization.

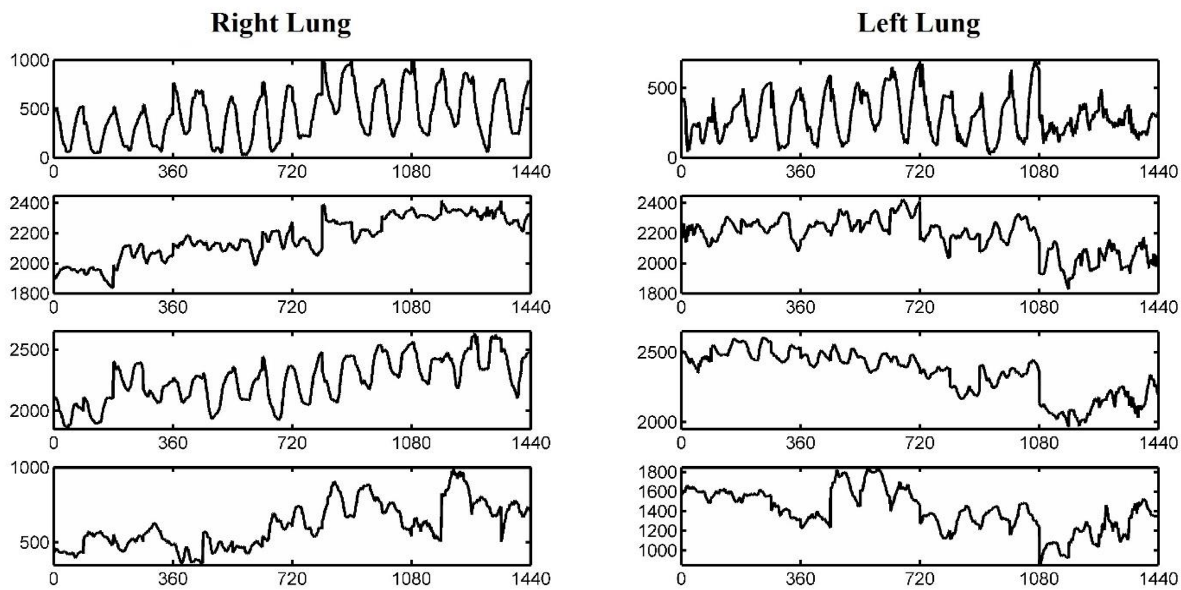

Figure 7: 16 breathing cycles of the examined person with the use of a synchronization indicator (in ADC units)

Figure 7 shows that although the signal levels are not the same, the breathing cycles correspond to 6 seconds.

Figure 8 shows the results of averaging in dB.

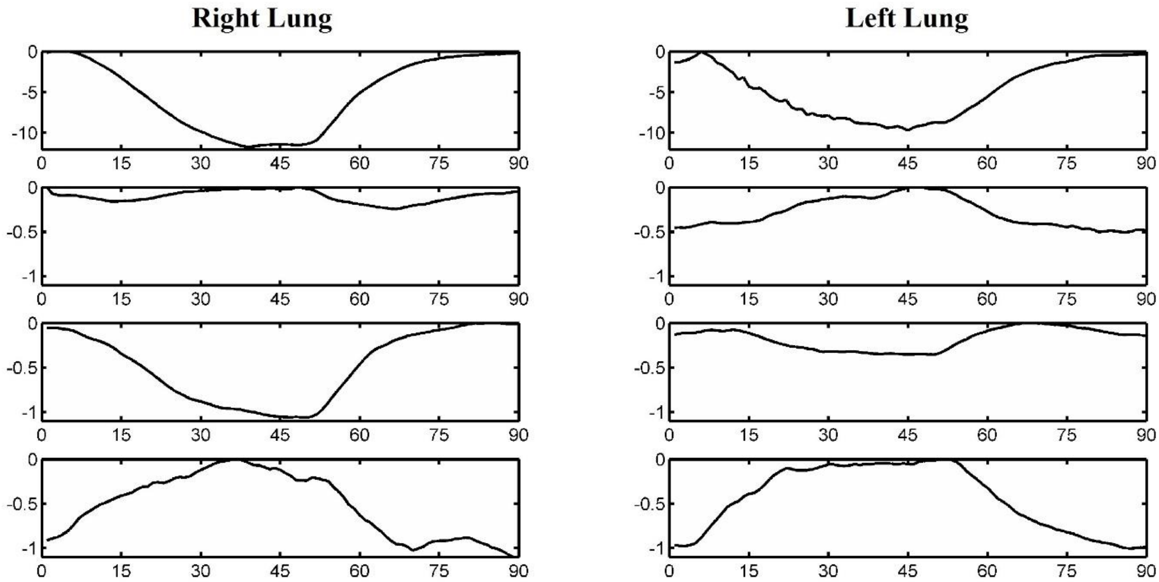

Figure 8: Integration and averaging of 16 breathing cycles using a synchronization indicator (in dB)

The results in Figure 8 show that the signal-to-noise ratio has increased, and thereby the stability, reliability and informativeness of the measurement results – pulmonograms have increased. The results show that the pulmonograms obtained by the described method and device offer more information about changes in human breathing. For comparison, there are breathing charts obtained by other methods, including radar in [13-22].

5. Conclusions

In this paper investigation is carried out in order to increase the reliability of human respiration pulmonograms measured by radio wave device intended for monitoring of bronchopulmonary system functioning, including the study of human respiration. Investigation is carried out through experiments and calculations.

Method is proposed for calculating the required number of measurements at a given accuracy of the measuring device to match the required confidence interval.

In addition, method for synchronizing breathing cycles by introducing a light indication into the device is proposed. This method will allow the use of the method of integration and averaging of pulmonograms, which is necessary to increase the stability, reliability and informativeness of the results.

6. Acknowledgements

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