Development of algorithm for analysis of sound fragments in medical information systems

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Abstract. The article is devoted to the recognition of sound signals, including cough jerks, using various mathematical methods. The paper presents an information system for the diagnosis of patients with pulmonary diseases. The main problem of this system is to determine the parameters of cough fragments in the monitoring record recorded with a dictaphone. Criteria of recognition of cough moments are given, the analysis of processing of sound record is carried out and results of research are systematized. This system can be used by doctors to diagnose the condition of patients, as well as to monitor the treatment process.

1. Introduction
Medical information systems (MIS) are the basis for monitoring human health. They perform a variety of tasks (data collection, diagnosis, monitoring and consultation, as well as ensuring the health care process). One of the ways to improve the efficiency of such systems is to expand the means of diagnosis and monitoring of patients. Obtaining objective characteristics of the disease allows the doctor to promptly adjust the treatment process. This is especially important for life-threatening diseases. These diseases include pulmonary diseases, which are among the top ten causes of death. In their treatment, the use of methods for objective control for medical reasons is often impossible. This is due to the use of specialized diagnostic procedures and examinations, which have restrictions on the frequency of use. It should also be borne in mind that diagnostic devices should not impose significant restrictions on the activities of patients. The severity of the disease for pulmonary diseases, doctors often determine the frequency of cough – the main symptom of respiratory pathologies. Therefore, as a parameter characterizing the condition of patients, the number of cough jerks for a certain time is often used. Therefore, the development of elements of systems that allow to monitor the condition of patients and record their coughs automatically, without significant restrictions of activity is relevant.

Currently, the assessment of cough frequency is used to objectively assess the condition of patients. At the moment, manual counting of cough jerks remains the benchmark, as compared to other tools, the human ear best detects cough. The rapid development of information systems requires automation of the process, in which restrictions on the actions of the patient would be minimal.

There are several cough monitoring systems that receive audio signals alone (contact microphone) or in combination with other sensors such as accelerometers, electromyography, electrodes, electrocardiography, induction, plethysmography and pulse oximeter, etc. It is established that the audio microphone is the best among the above sensors for cough detection. Thus, it is possible to divide exist-
ing cough frequency recognition systems into two sections: one uses only sound signals, and the other—mixed signals (sensor + microphone).

Consider such developments.

The HullAutomaticCoughCounter (pump) uses the microphone’s free field to record sound for about 24 hours. The System can mark coughs automatically, but the cough count is done manually. The sensitivity of NASS was 80% [4].

The LeicesterCoughMonitor consists of a microphone and a digital MP3 recorder. The sensitivity of the system is 91% [5].

A hybrid system including NAS and The LeicesterCoughMonitor, software for measuring cough rates in COPD exacerbation and recovery, was also used, and a sensitivity of 57.9% was achieved [6].

The VitaloJAKTM is a semi-automatic cough recording device with two sensors. This system is accurate but very time consuming and time consuming due to manual counting. The sensitivity level of this system is 99% [7].

Cough recognition system using mixed signals.

PulmoTrack-CC includes a piezoelectric belt to control the movement of the chest wall, one lapel microphone, and two contact microphones placed on the trachea and chest. The device reaches a sensitivity of 91% to detect explosive cough sounds. However, in a study led by Turner and Botami, the device had a sensitivity of 26% to detect cough identified by the ear [8].

To recognize the sound signal of cough, it is necessary to know the etymology of cough, i.e. its phase. There are three main phases: the first—corresponds to the rapid opening of the glottis; the second—corresponds to the exit of air from the lungs (longer); the third—corresponds to the closure of the glottis at the end of the cough (this phase may be absent). According to the table “Comparative characteristics of frequency-time parameters of cough sounds in healthy people and patients with AD” in [5], the second phase of cough is of particular interest. It is the longest and most informative for recognizing cough sounds.

In the course of diagnostic measures, the nature of the cough is determined. There are several subjective criteria for assessing the severity of cough, according to which the scheme of effective treatment is selected. To diagnose cough, such methods as visual analog scale, cough diaries, measurement of sensitivity of the cough reflex are used. These same methods are used as potential tools to assess the severity of disease diagnosis.

Despite the fact that both speech and cough belong to a person, mathematical methods used for speech recognition can not be used for sound recognition, because the informative parts of both signals are different.

In this regard, there is a need to develop an algorithm for isolating audio signals from a long recording.

It is necessary to develop a mathematical apparatus, allowing to distinguish high-quality audio signals; to develop an algorithm for recognition of sound signals on the basis of it to create non-invasive diagnostics of pulmonary diseases for decision support to the attending physician in diagnosis.

2. Materials and methods
The analysis of the main information flows MIS, the basic parameters of non-invasive monitoring of the treatment process (NMPL) lung diseases and its interaction with the elements of the system. Figure 1 presents a functional model of the NPL in the form of a context diagram based on the IDEF0 methodology.
The main objective of the module is to isolate from the monitoring recording sound fragments that have signs of cough and their classification by signal-to-noise type. The patient's cough at the beginning of the monitoring recording is selected by the attending physician as a cough template (ShK), with the help of which the classification of sound fragments by the type of cough-noise will be carried out. This ShK allows you to take into account the individual characteristics of the patient's cough (especially the vocal cords, type, severity of the disease, etc.). The studies have shown that the traditional method of estimation – by correlation coefficient-to determine the proximity of the amplitudes of the envelopes of the SHK and the studied signals in the time domain allows to correctly classify no more than 63 % of the selected fragments of the monitoring record. Therefore, a number of criteria are proposed that can be used to classify cough-noise.

The analysis of time characteristics showed that the fragments corresponding to coughs are characterized by a symmetric signal form, for part of the noise – asymmetric. The degree of symmetry was estimated by the criterion of integral error between the positive and negative parts of the envelope. The paper analyzed the influence of the width of the smoothing window on time in the construction of the envelope and the threshold value of the error, which allows to allocate fragments of coughs. The analysis of this criterion showed that the percentage of correctly recognized coughs is not less than 67 % of the selected fragments of the monitoring record.

The analysis of the spectral characteristics of the fragments of the recording using the algorithm of multi-signal classification (MUSIC) showed that in the considered fragments of coughs are allocated from two to four characteristic frequencies. In this case, the characteristics of peaks in frequency and amplitude for coughs and noises are quite close, which does not allow them to be divided into coughs and noises only on these grounds (figure 2).

The change in the amplitude of the sound signal in time at two frequencies characteristic of the first and second phases of cough was analyzed. This criterion (“correlation coefficient by time slice”) characterizes the proximity of the amplitude change in time in the ShK and the studied sound fragment. The percentage of correctly classified signals by cough-noise type is not less than 49 % of the selected fragments of the monitoring record.

Also, when analyzing spectrograms, it was found that there are regions for coughs and noises that differ significantly in amplitude from each other. Therefore, the criterion “average value of the spectrogram window” is proposed. This criterion calculates the average value of the amplitudes in the spectrogram window and compares it with the average value of the amplitudes of the SC in the same window. The position of the spectrogram Windows is selected according to the most informative cough phases, as shown in figure 3, a (window 1 and window 2). The percentage of correctly classified coughs is not less than 35 % of the selected fragments of the monitoring record.
Figure 2. Representation of characteristic frequencies, where $a$, $b$, $c$ – cough, $d$, $f$ – noises.

Figure 3. Spectrum: $a$ – cough, $b$ – noise.

On the basis of the presented types of criteria for classification of fragments of record it is offered to use system from 8 criteria. Five criteria for correlation coefficient, two criteria for the average value of the spectrogram window and one criterion – the integral error between the positive and negative parts of the envelope.

The application of criteria with accepted constants allows to classify the sound fragments of the monitoring recording by the cough-noise type up to 88 % of the selected fragments.

A quantitative analysis of the use of the proposed criteria was also carried out. To do this, the fragments of the monitoring record were sequentially classified by criterion 1, then by criterion 2. The table 1 shows the percentage of additionally correctly classified noises by one criterion compared to another criterion.

| Table 1. Comparison of additionally correctly classified noises by criteria. |
|-----------------|---|---|---|---|---|---|---|
|                | $R_2$ | $R_3$ | $R_4$ | $R_5$ | $\delta_6$ | $\delta_7$ | $\Lambda_8$ |
| $R_2$          |       | 5 %  | 7 %  | 2 %  | 3 %   | 11 %     | 3 %     |
| $R_3$          | 22 %  |      | 11 % | 12 % | 12 %  | 27 %     | 13 %    |
| $R_4$          | 25 %  | 34 % | 33 % | 12 % | 13 %  | 26 %     | 10 %    |
| $R_5$          | 41 %  |     | 12 % |     | 21 %  | 48 %     | 12 %    |
| $\delta_6$    | 45 %  | 38 % | 37 % | 25 % |      | 54 %     | 14 %    |
| $\delta_7$    | 5 %   | 4 %  | 1 %  | 3 %  | 6 %   |          | 3 %     |
| $\Lambda_8$   | 61 %  | 54 % | 50 % | 32 % | 30 %  | 67 %     |        |
To assess the quality of the system using criteria used fuzzy logic mechanism. In its application, three stages were used: the introduction of fuzziness (fuzzification), fuzzy inference, composition and reduction to clarity, or defasification.

To do this, a linguistic variable is introduced: $MFC(\xi)$ – the degree of belonging to the fuzzy set C (cough set). Then the fuzzy set $C = \{MFC(\xi)/\xi\}, MFC(\xi) [0,1]$. A value of $MFC(\xi) = 0$ means no affiliation to a set of coughs, 1 means full affiliation [9].

The criteria listed above are accepted as linguistic variables. Linguistic variable is represented by a set of variables $(N, T, \Xi, G)$, where $N$ is the name of the criterion, $\Xi$ is a universal set (the scope of the reasoning $[0,1]$), $T$ – fuzzy set in $\Xi$ (cough noise), $G$ is a syntactic rule (IF a BPV is done THEN "maybe the cough" or "noise"), where BPV (basic rule) identifies the criteria above.

To bring the obtained experimental data to a General form, normalization on the interval scale was carried out. The following algorithm was used to obtain a logical conclusion. Gasification was carried out for each criterion and the membership functions were constructed for each linguistic variable. As a result, we obtain the degrees of membership for each rule by the formula

$$A_{ik}(x_k), \quad i = 1..m; \quad k = 1..n,$$

where $A_{ki}$ is the degree of truth; $x$ is the sound segment to be processed; $i$ is the criterion number; $k$ is the segment number.

Fuzzy inference was performed by determining the level of "cut-off" on the schedule of membership function of each criteria, and then based on the projection "truncated" membership functions on the graph of defazifikatsii each criterion [10].

Next, the composition of the obtained "truncated" membership functions was carried out. For this purpose the maximal composition of fuzzy sets by the formula was used

$$\mu_{general}(\xi) = \max(B_i(\xi)).$$

where $\mu_{general}$ – membership function of the resulting fuzzy set; $B_i$ – "truncated" membership functions; $\xi$ – the argument of the membership function.

At the stage of defuzzification method has been used average. The result of the final fuzzy inference on Mamdani is presented in figure 4.

![Figure 4. Final conclusion on Mamdani.](image)

The membership function of this graph is described below

$$\mu_{general}(\xi) = \begin{cases} 
0, & \xi \leq 0.6, \\
4\xi - 2.4, & 0.6 < \xi \leq 0.625, \\
0.1, & 0.625 < \xi \leq 0.7, \\
27\xi - 18.94, & 0.7 < \xi \leq 0.725, \\
0.78, & 0.725 < \xi \leq 0.85, \\
4.8\xi - 3.3, & 0.85 < \xi \leq 0.875, \\
0.9, & \xi > 0.875.
\end{cases}$$
- The resulting fuzzy membership function suggests that it is close enough to a clear membership function. This observation suggests that the developed system of criteria based on fuzzy logic gives a minimum percentage of error up to 7.5%.
- The algorithm of operation of the program (figure 5) in the analysis of sound recording is sequential processing.
- Pre-processing of the original audio signal and encoding into the desired format (WAV, monographic and single-channel recording).
- Selection of segments of a given length, which may be coughs during pretreatment. Here, high-frequency filtering is carried out and segments that do not meet the frequency characteristics are cut off.
- Calculation criteria, carrying out fuzzy inference and classification of signals.
- Analysis and visualization of results.

The projected element of the information system assumes an interactive mode of work of the researcher, including the formulation of rules of varying degrees of complexity, representing logical expressions.

The main functions of the developed element of the information system are: loading the daily record; splitting it into sound segments; entering and editing rules based on the implemented criteria; visualization of the result of the received classification (figure 6).

The first block of the scheme describes the process of obtaining the original audio signal, followed by its modulation and encoding into wav-format. Unfortunately, the use of equipment for polyphonic recording of an audio signal, which, of course, carries a large useful information load, is impossible due to its bulkiness, so the information system is designed exclusively for monophonic recordings. The use of multiple channels in the original daily patient record is not possible without prior decoding by discarding one of the channels.

The second block of the diagram illustrates a subsystem that produces a selection from a long record of short segments of a given length that satisfy some General condition. As a result, after numerous experiments, it was proposed to use the moment of exceeding the threshold value of the amplitude in the amount of 70% of the maximum value.

Also, in this unit, high-frequency filtering is carried out, since high-frequency noise falls on the sound recording. Segments that do not meet the frequency characteristics are cut off. Envelopes are built along all the remaining sound segments, which are then divided into two components. In the future, using either the original signal or the envelope of the original signal, or the envelope of the two components lying above and below the x-axis, for simplicity, further we will call them positive and negative parts of the envelope.
In the third unit is the analysis and processing of audio signals. Various mathematical methods based on correlation analysis, Bayesian estimation, fast Fourier transform, and criteria using integral estimates and standard deviation have been considered and analyzed to recognize cough sound signals.

In block four, the result is displayed. At this stage of the IC work, the results are displayed, which is a list of selected sound segments with notes to which class (cough or noise) this segment was assigned in accordance with the current set of criteria.

3. Results and discussion

As a result of the study, an algorithm was developed that allows to allocate high-quality sound segments, which is based on 8 criteria. On the basis of the developed algorithm the system of diagnostics of pulmonary diseases is designed to support decision-making by the attending physician at diagnosis and monitoring of the patient's condition.

The developed information system allows:
- to increase the recognition rate to 92.5%;
- increase the processing speed of long-term recording by 6 times;
- handle long-term records of a large amount of information.

4. Conclusion

Thus, the development of a non-invasive system of diagnosis of pulmonary diseases to support the decision of the attending physician in the diagnosis and treatment regimen of the patient is presented. This system is based on criteria to obtain objective data about the patient's condition. This makes it possible to completely eliminate human involvement. The system provides a sufficiently high accuracy of cough detection.

The algorithm of information processing of monitoring record for allocation of possible cough fragments and their classification by type cough-noise using preliminary signal processing, allocation of fragments of record which can be cough, rules of fuzzy logic on the basis of the developed criteria is offered. The use of fuzzy logic methods showed that despite a sufficiently large number of criteria used, the classification of signals by the cough-noise type is quite close to clear logic (the error does not exceed 7.5%).
The structure of the software for processing of monitoring sound information of coughs of patients with pulmonary diseases for obtaining objective information on their condition, using the module of noninvasive monitoring of pulmonary diseases, allowing to reduce time of processing of monitoring record and practically does not impose restrictions on activity of the patient is developed.

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