Forced expiratory (FE) noise is powerful bioacoustic signal, carrying information on human lung function. FE noise differs from sounds of quiet breathing by increasing an intensity of the broadband component and by appearance of narrowband components. When recording FE respiratory noise with a sensor on the neck, above trachea, there are two mechanisms of origin of recorded signal. The first one “acoustic” is determined by superposition of acoustic noises emitted through airway lumen, and assumes sound propagation from distant sources located inside the bronchial tree. The second one “hydrodynamic” is due to the pseudo-sound effect of turbulent pressure pulsations in the vortex flow on the inner wall of trachea. Estimates of Reynolds numbers in the average model of bronchial tree for healthy adults indicate that the developed turbulence is achieved in trachea lumen, thus an existence of the second mechanism is unquestionable. As for the first mechanism, a turbulent flow (broadband component), shedding of vortices or self-oscillatory effects (narrowband components) may be involved to form sources of powerful sound emission inside airway lumen. Approximate estimates show that these effects can be observed no further than in the 10-th level of bronchial tree branching. A variety of identified sound and pseudo-sound FE effects opens new opportunities for diagnostic applications. The method of medical diagnosis of human lung function is developed. Forced expiratory noise time (FETa) in the frequency band 200-2000 Hz is justified as the acoustic predictor. The correlation between FETa and aerodynamic resistance of the respiratory tract is found experimentally. A sufficiently high sensitivity and specificity of the method (near 90%) and an ability to detect hidden bronchial obstruction not revealed by spirometry as well as possibilities to monitor lung function under diving and simulation weightlessness are demonstrated.

Keywords: respiratory acoustics, forced exhalation, apparatus, biomechanics, diagnostics
2. An origin of forced expiratory noises

A simplified scheme demonstrated forced expiratory signal origin and its recording above trachea is shown in Fig. 1. During signal sound registration by a microphone, equipped with stethoscope head, FE tracheal noises may appear in two ways [2]. The first one is a superposition of the acoustic noises emitted in Airways lumen. This mechanism involves a propagation of acoustic signals from the distant intrabronchial sources (Fig. 1) through the Airways of bronchial tree resulting in formation of acoustic pressure ($p_a$) inside the trachea lumen. The second mechanism is hydrodynamic or so-called pseudo-sound effect of turbulent pressure pulsations of the airflow vortices to the trachea inner wall. This effect results in average hydrodynamic pressure ($p_{hd}$). Unlike the first (acoustic) mechanism in this case there is no requirement of the air medium compressibility and the recorded signals are proportional to the hydrodynamic pressure in the turbulent flow averaged through the projection of the acoustic sensor perception. Due to the physics of its operation stethoscope sensor does not distinguish these mechanisms of pressure changes on the trachea inner wall and registers these signal components outside (on the neck) equally.

![Figure 1: A schematic configuration of measurements.](image)

FEWs may be divided into sounds generated by flow-dependent mechanisms (shedding vortices, forced dynamic flutter) and flow-independent self-oscillatory mechanisms (self-oscillatory flutter, oscillation in the closing of the mucous tissue). An origin of the most powerful mid-frequency FEWs (400-600 Hz) is associated with 0-th – 3rd levels of branching of the bronchial tree, whereas high-frequency FEWs (above 600-700 Hz) may be connected with 2-nd – 6-th levels of bronchial tree branching [3].

3. Method and apparatus

A variety of identified sound and pseudo-sound FE effects opens new opportunities for diagnostic applications. The acoustic method of diagnostics of lung function is developed which is based on estimation of time noise parameters of human forced exhalation, recorded above trachea (Fig. 2). Forced expiratory noise time in the total frequency range of 200-2000 Hz (FETa), recorded at the lateral neck surface (above trachea) is suggested as the diagnostic parameter as well as 200-Hz signal durations and relative energies into total frequency range [4]. The apparatus is developed, which includes acoustic sensor – electret microphone with stethoscope head and special software to evaluate FETa and its derivatives automatically [5].

During measurements the sensor is attached to lateral neck surface and the subject holds the box with his hand pressing stethoscope head to the body, nose-clamp is used. The subject performs a
forced exhalation maneuver from maximal inspiration. A delay of about 0.5 s is made between inspiration and exhalation. In order to carry out the maneuver properly, a maximum sharp and complete exhalation is required.

Figure 2: An appearance of the forced expiratory noise signal in the window of PPhT soft (Pacific Oceanological Institute, RF): green – time series, red – envelope, blue – start and finish of the noise process used to measure FETa.

4. Acoustical-biomechanical relations of forced exhalation

The main method of study is a comparison of the FE tracheal noise acoustic parameters with the results of the evaluation of biomechanical indicators of human lung function, which were first time obtained not only by means of spirometry, but also with body plethysmography (MasterScreen Body, Jager). The sample consisting of 230 volunteers was studied, which include healthy subjects, persons with risk factors for chronic respiratory diseases, patients with bronchial asthma (BA) and chronic obstructive pulmonary disease (COPD).

By means of nonparametric ANOVA analysis, a statistically significant bidirectional effect of the factor of occurrence and severity of bronchial obstruction on the FE acoustic parameters and the lung function biomechanical indicators was revealed. Using the statistical model characterized by a significant gradual increase in bronchial resistance and residual lung volume it is found the FETa and band energies of FE tracheal noise are coordinated both with the resistance of a calm exhalation and with the residual volume of the lungs, which confirms the developed model considerations of FE noise production in healthy and in individuals with bronchial obstruction (Fig. 3) [5]. The frequency selectivity of the dependence of acoustic durations and energies on the factor of occurrence and severity of bronchial obstruction was found.

By means of nonparametric correlation analysis in the sample, significant interrelations between acoustic durations and energies of the FE tracheal noises and the biomechanical indicators of the lung function were revealed. Moreover, the strongest correlation links are noted between time acoustic parameters and resistances, reflecting primarily the functioning of large airways, as well as with the residual volume of the lungs and its ratio to the total lung capacity that characterize the state of small airways. The significant bidirectional correlation between the acoustic FE tracheal parameters and biomechanical indices were revealed in specific groups the sample (subjects and patients).
1 – healthy, 2 – subjects with risk factors, 3 – spirometry negative bronchial asthma (BA), 4 – spirometry confirmed bronchial asthma (BA), 5 – chronic obstruction pulmonary disease (COPD).

5. FE acoustic parameters in diagnosis and monitoring lung function

Our many-years clinical investigations of FE acoustic parameters demonstrated a sufficiently effective acoustic diagnosis of bronchial obstruction in patients with bronchial asthma with usage FETa – FE noise duration in the frequency range 200-2000 Hz (sensitivity and specificity of about 90%), as well as the possibility of early detection of hidden bronchial obstruction not revealed by traditional spirometry [6].

In head-down -6° test simulation of the space weightlessness, the group as a whole showed a statistically significant lengthening of the FETa in comparison with the initial background values (Fig. 5 – **). For the subgroup remaining in this position until the end of the experiment (exp_1), further significant growth of the acoustic parameter FETa was established (Fig. 5 – **). By means of a 2-dimensional ANOVA, a significantly greater group FETa (Fig. 5 – *) was found in this subgroup in comparison with another subgroup where lunar gravity was simulated by head-up +9.6° test (exp_2). Spirometry indexes did not reveal these differences between subgroups. By acoustical-biomechanical considerations, the prolongation of FETa in the weightlessness model may be explained by an additional increase in the aerodynamic resistance of respiratory tract with respect to a lunar gravity model.

An application of the developed method to divers (48 subjects) revealed transient bronchial obstruction features in 13 subjects (27%) after single shallow-water sea submersion with the closed-type breathing apparatus IDA-71 (Russia). The effect is probably caused by the development of inflammation of bronchial mucosa and accompanying edema due to toxic effect of hyperbaric hyperoxia in combination with small doses of the regenerative substance vapor [7]. These signs of toxic damage of the pulmonary system appeared in time intervals not exceeding the permissible period of diving operation with oxygen. The observation dictates a necessity to provide individual control of divers lung function during training process in closed-type breathing apparatus in order to prevent accidents and to achieve a professional longevity.

It was supposed that modern closed-type breathing apparatus would not have such influence on human lung function. To test the supposition a group of 6 divers (Fig. 4), performed single shallow-water sea submersion (less than 1 hour) in modern closed-type breathing apparatus Amphora (Aqualung). The statistically significant increase of FETa was found in relation to background status (Wilcoxon p=0.042). This response may be treated as an adverse influence of even a short hyperbaric hyperoxia on aerodynamic resistance of bronchial tree. This effect is consistent with those obtained for closed-type breathing apparatus of previous generation [7] despite of using modern
diving apparatus. Thus the phenomenon revealed das not depend on the type of closed-type breathing apparatus.

![Image](image1.png)

**Figure 4:** Applications of FETa evaluation for monitoring an influence of postural model of lunar gravity (left) and underwater diving (right) on lung function.

![Image](image2.png)

**Figure 5:** “Box and whiskers” diagram of FETa (weighted means with limits of 95% CI) for exp_1 – circles, exp_2 – squares, by days of study; *,**,*** – significant differences detailed in the text.

**Table 1:** Individual acoustic reply to single shallow water wet sea submersion for 6 divers equipped with closed type breathing apparatus Amphora (Aqualung)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No</td>
</tr>
<tr>
<td>1.99*CV(FETa)_{before},%</td>
<td>23</td>
</tr>
<tr>
<td>ΔFETa,%</td>
<td>27</td>
</tr>
</tbody>
</table>

The individual dynamics of acoustic parameter ΔFETa = (FETa_{after} - FETa_{before})/FETa_{before} to single dive may be evaluated in comparison with individual threshold determined as intra-individual variability 1.99*CV(FETa)_{before}. The index allows to monitor individual features of lung function dynamics undetectable by spirometry (Table 1). It is seen significant (p<0.01) reply of FETa in 4
subjects (printed with red numbers) – increase for 3 divers and decrease only for 1 of them. While in other 2 subjects the reply in not significant (black numbers).

Thus, a set of the above mentioned proposals, developed methods and results of research is promising for solving the problem of acoustic monitoring of divers during and after underwater missions. The developed methods are promising to monitor human respiratory system status in other extreme conditions, including applications implying usage of special and insulating equipment.

6. Conclusions

A refined model of noise production in human respiratory system under forced exhalation is developed. The relations between the acoustic characteristics of forced exhalation and the biomechanics of the respiratory system are revealed. Informative acoustic parameters of the forced exhalation noise, suitable for diagnostics of lung function are found. A portable hardware-software complex is developed that implements noise recording and evaluation of the proposed acoustic parameters. It is demonstrated that evaluating the duration of forced expiratory tracheal noise in the frequency range of 200-2000 Hz can be used as a simple, affordable and highly sensitive tool for assessing lung ventilation function and monitoring the effects of extreme factors (including weightlessness and diving modeling) on human respiratory system.

The study was partially supported by the Program of basic research of Far Eastern Branch of Russian Academy of Sciences (the project state registration No. AAAA-A17-117030110041-5).

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