ACOUSTIC METHODS OF MONITORING RESPIRATORY SYSTEM OF SCUBA DIVERS DURING AND AFTER UNDERWATER MISSIONS

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Abstract: *Monitoring of diver's respiratory system status remains an urgent problem. The study of respiratory noises revealed new acoustic approaches to its solution. An application of wearable hydrophone as well as external one is verified for monitoring the status of divers under water. The respiration rate and its dynamics, the ratio of inhalation and exhalation times, evaluated in the characteristic frequency bands, are supposed as monitored parameters for wearable hydrophone. Usage of external hydrophone provided an ability to evaluate a breathing rate of scuba diver at the distances up to 30 m by exhalation noises. After underwater missions it is suggested to monitor dynamics of tracheal forced expiratory noise time (FETa) measured in the frequency band of 200-2000 Hz. For group of 6 divers, performed wet submersions in modern closed type breathing apparatus, statistically significant increase of FETa was found in relation to background status before dive. This response may be treated as an adverse influence of even a short hyperbaric hyperoxia on bronchial resistance. Developed methods are promising to monitor respiratory system of scuba divers during and after underwater missions.*

Keywords: *Diver, respiration, acoustics, monitoring*

1. INTRODUCTION

Divers in underwater submersion conditions are affected by additional barometric pressure, increasing oxygen partial pressure (hyperbaric hyperoxia), enlarging respiratory resistance and temperature influences. Multiple studies of divers' lung function (for example [1]) showed that mentioned factors provided the development of transient failures of respiration, resulted in an increase of fatigue and reducing physical ability, as well as delayed changes, fraught with serious consequences for health and life. For these reasons, monitoring the state of the respiratory system of divers remains an urgent problem.

Previously a cardiac function was primarily controlled in this application. A monitoring of the respiratory system, sometimes used, included only flow-volumetric control methods. Whereas bio-acoustic signals associated with respiratory noise are considered promising for monitoring the state of the respiratory system for many years. However there are certain problems in research and development of highly informative acoustic apparatus for monitoring respiratory system of divers during and after underwater submersions having sufficient noise immunity to process in field conditions.

We developed new acoustic method and apparatus for study of human respiratory system which provided a possibility to monitor a diver respiratory status promptly during underwater submersion as well as after it. These methods may be divided into acoustic monitoring of the respiratory system by the noise of quiet breathing recorded at the chest wall surface and acoustic monitoring of the respiratory system by the forced exhalation noise recorded above trachea. Pilot results of both methods application are presented.

2. ACOUSTIC MONITORING OF RESPIRATORY SYSTEM OF DIVER BY THE NOISE OF QUIET BREATHING

Respiratory sounds of divers were recorded during wet shallow-water submersions in the Peter the Great Bay near Vladivostok. The breath noises were recorded by inner acoustic sensor worn under diving suit, which was made on the basis of the H1 voice recorder (ZOOM Corporation, Japan), as well as by the external hydrophone.

The frequency of quiet breathing (respiratory rhythm) determined by the envelope of respiratory noises, its dynamics, as well as the ratio of durations of inspiratory and expiratory phases, found in characteristic frequency bands, are suggested as a controlled parameters for the wearable acoustic sensor (Fig. 1).

For example, for the diver in normal status the ratio of inhalation and exhalation times was 1:2.5, and the respiratory rhythm was 10.3 breaths per minute. However for the diver who had problems with equipment and demanded finishing his mission in stress condition the breathing rhythm was 18 breaths per minute, and the ratio of inhalation and exhalation times was 1:1.3 (before evacuation from water). The last values are significantly different with the normal respiratory status.

A possibility of remote determination of the respiratory rhythm for scuba diver by the noise of exhalations using the external hydrophone is demonstrated (Fig. 2). In accordance with the spectrograms (Fig. 2), the characteristic vertical bands (green colored) in the frequency range of 50-700 Hz, corresponding to the exhalations of the diver, may be traced in the response of the second hydrophone (the bottom graph) during the entire time of travelling the diver from the first hydrophone (upper graph) to the second one and vice versa. Hydrophones are installed at the sea bottom at depths of about 8 m and are separated by the distance of 30 m.

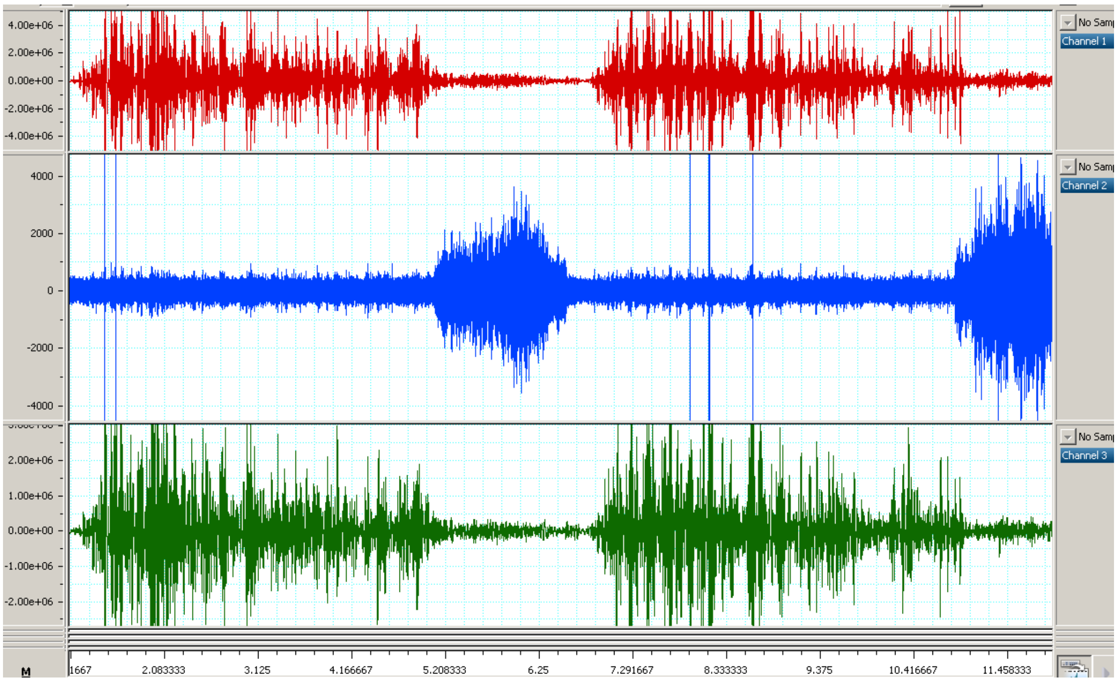

Fig.1: Time series of 2 cycles of scuba diver respiration: upper channel – original respiratory noise, recorded under diving suit, mid channel – inspiratory noise in the frequency band above 1 kHz, bottom channel – expiratory noise in the frequency band below 500 Гц; abscissa - time (min), ordinate - amplitude (relative units).

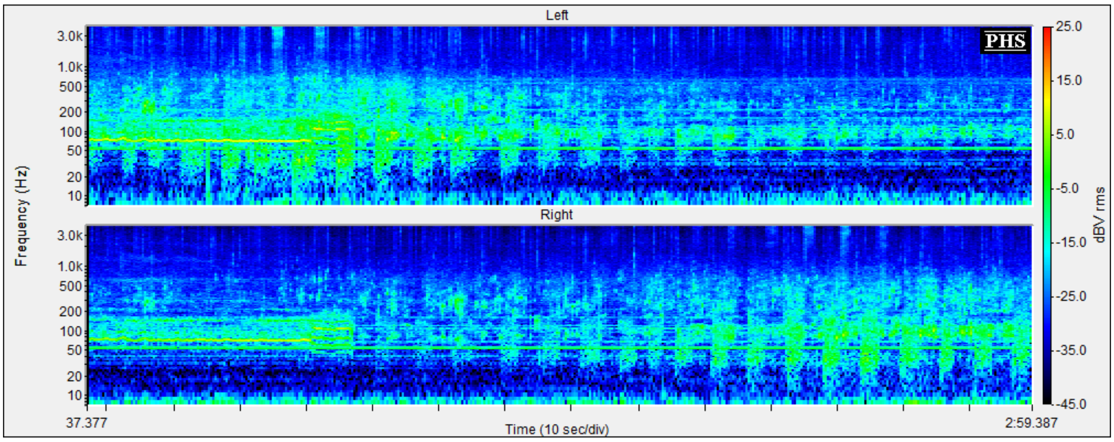

Fig.2: Spectrograms of respiratory noises of the scuba diver recorded during his passing between two hydrophones, distanced at 30 m; abscissa – time (sec), ordinate – frequency (Hz), colour represents noise spectral density (relative units, log scale).

3. ACOUSTIC MONITORING OF RESPIRATORY SYSTEM OF DIVER BY THE NOISE OF FORCED EXHALATION

It is suggested to monitor dynamics of acoustic parameters of forced expiratory noise after underwater missions. This method is more informative than quiet breathing noise analysis; however it is impossible under diving insulation suit.

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. 3).

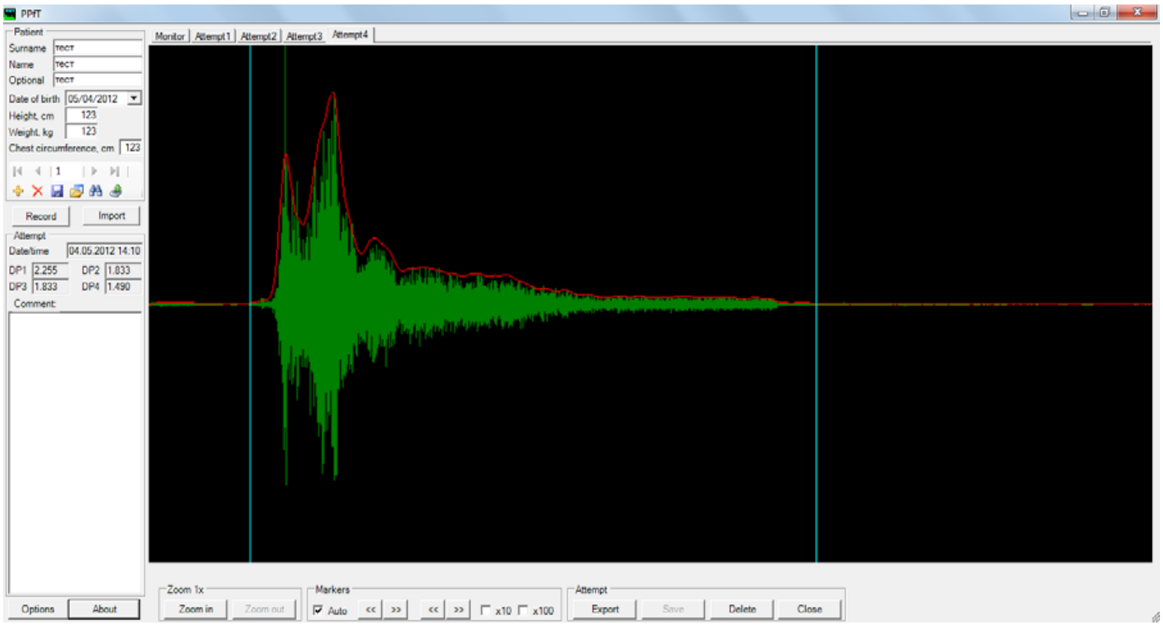

Fig.3: Appearance of forced expiratory noise in the window of PPhT soft (Pacific Oceanological Institute, RF): green – time series, red – envelope, blue – start and finish of the noise process.

Forced expiatory noise time in the frequency band of 200-2000 Hz (FETa), recorded at the lateral neck surface (above trachea) is suggested as the diagnostic parameter [2], The apparatus is developed [3], which includes acoustic sensor – electret microphone with stethoscopic head and special software to evaluate FETa automatically. An interdependence of FETa with aerodynamic airway (bronchial) resistance has been proved experimentally. The sufficiently high diagnostic sensitivity and specificity (near 90%) and an ability to reveal hidden (spirometry negative) bronchial obstruction as well as an applicability of the method to monitor lung function dynamics in extreme conditions have been demonstrated [2, 1].

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 (RF). 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 [1]. 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.

For group of 6 divers, performed single shallow-water sea submersion (less than 1 hour) in modern closed-type breathing apparatus Amphora (AquaLung) 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 [1] despite of using evaluation of individual dynamics of acoustic parameter $\Delta FETa = (FETa_{after} - FETa_{before})/FETa_{before}$ to single dive in comparison with individual threshold evaluated as intra-individual variability $1.99*CV_{before}$ allows to monitor individual features of pulmonary 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).

Parameter	Subjects					
No	*1*	*2*	*3*	*4*	*5*	*6*
$1.99*CV_{before}$,%	23	3	6	20	18	32
ΔFETa,%	27	45	-13	22	-17	12

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

Thus the 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 a usage of special and insulating equipment.

4. ACKNOWLEDGEMENTS

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