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ASSESSMENT OF THE RELATIONSHIP BETWEEN TRACHEAL BREATHING SOUNDS AND LUNG VENTILATION DURING PHYSICAL EXERCISE

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Introduction. Assessment of the functional state of the respiratory system is a relevant task in the fields of sports, aerospace, and maritime medicine. Direct flowmetry methods cannot always be applied under conditions of a sealed enclosed environment. The recording and analysis of lung sounds appears to be a promising method for assessing the state of the respiratory system.

Objective. To assess the relationship between the amplitude characteristic of the recorded lung sound signal and the magnitude of pulmonary ventilation, as well as the applicability of the acoustic method for assessing the respiratory rate in healthy individuals during physical exercise, regardless of age and sex.

Materials and methods. The study involved 25 volunteers (20 male and 5 female) aged 23–59 years (mean age 35.5 ± 8.7 years). The participants were subjected to a stepwise increasing workload on an Ergoselect 200P cycle ergometer (Ergoline GmbH, Germany) up to submaximal heart rate levels, with simultaneous recording of respiratory sounds over the extrathoracic section of the trachea and measurement of respiratory flow via direct flowmetry using a Jaeger Oxycon Pro device. Statistical data processing was performed using the Statistica 13 software (StatSoft Inc., USA). To assess the relationship between respiratory sound power and pulmonary ventilation, a correlation analysis was conducted using Spearman's rank correlation coefficient (r_s).

Results. During the study, the achieved maximum power output for all participants ranged 105–240 W; only two subjects were capable of developing a power level exceeding 210 W. Dependencies of respiratory sound power on pulmonary ventilation were obtained. Spearman's rank correlation coefficient between the studied parameters was 0.58 ($p < 0.001$). Significant changes in the mean power of respiratory sounds were observed with an increase in load and pulmonary ventilation, already at the 30 W stage compared to the resting state (0 W) ($p < 0.0001$). The power of tracheal respiratory sounds also increased by 56% between the 120 W and 135 W load stages ($p = 0.023$) and by 75% between the 180 W and 195 W load stages ($p = 0.043$). No significant differences were found between respiratory rate assessments obtained by direct flowmetry and acoustic methods.

Conclusions. A statistically significant, moderate positive correlation was established between the magnitude of pulmonary ventilation and the mean power of respiratory sounds ($r_s = 0.58$; $p < 0.001$). For pulmonary ventilation values up to 60 L/min, the relationship between the mean power of tracheal sounds and pulmonary ventilation was found to be linear. A satisfactory agreement was determined between the acoustic assessment of respiratory rate and the data obtained by direct flowmetry methods. The analysis of respiratory sounds is capable of providing an indirect assessment of the state of the respiratory system.

Keywords: physical activity; lung sounds; cycle ergometry; pulmonary ventilation; respiratory system; respiratory acoustics

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Compliance with the ethical principles: the study was conducted in accordance with the principles of the Helsinki Declaration. All volunteers underwent medical selection by the Medical Expert Commission of the SSC RF — IBMP RAS, during which no diseases or pathologies preventing participation in the experiment were identified. All participants provided signed voluntary informed consent to participate in the study. The study was approved by the Biomedical Ethics Committee of the SSC RF — IBMP RAS (Protocols No. 520 of 25.07.2019, and No. 539 of 17.03.2020).

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ОЦЕНКА ЗАВИСИМОСТИ МОЩНОСТИ ТРАХЕАЛЬНЫХ ДЫХАТЕЛЬНЫХ ШУМОВ ОТ ЛЕГОЧНОЙ ВЕНТИЛЯЦИИ ПРИ ФИЗИЧЕСКОЙ НАГРУЗКЕ

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Введение. Оценка функционального состояния дыхательной системы является актуальной задачей в областях спортивной, космической и морской медицины. Использование методов прямой флоуметрии в условиях замкнутого гермообъекта не всегда возможно. Регистрация и анализ дыхательных шумов представляется перспективным способом оценки состояния респираторной системы.

Цель. Выявление возможного характера зависимости между амплитудной характеристикой регистрируемого сигнала дыхательных шумов и величиной легочной вентиляции, а также степени применимости акустического метода для оценки частоты дыхания у здоровых людей при выполнении физической нагрузки независимо от возраста и пола.

Материалы и методы. В исследовании приняли участие 25 добровольцев (20 мужчин и 5 женщин) в возрасте 23–59 лет (средний возраст 35,5 ± 8,7 года). Обследуемые выполняли ступенчато-возрастающую нагрузку на велоэргометре Ergoselect 200P (Ergoline GmbH, Германия) до субмаксимальных величин частоты сердечных сокращений с одновременной регистрацией дыхательных шумов над внегрудным участком трахеи, а также величины дыхательного потока методом прямой флоуметрии на приборе Jaeger Oxycon Pro. Статистическая обработка данных проводилась с помощью программного обеспечения Statistica 13 (StatSoft Inc., США). Для оценки взаимосвязи мощности дыхательных шумов и вентиляции легких проведен корреляционный анализ с использованием коэффициента ранговой корреляции Спирмена (r_s).

Результаты. В ходе исследования у всех испытуемых достигнутые величины максимальной мощности находились в диапазоне 105–240 Вт; мощность свыше 210 Вт смогли развить только 2 испытуемых. Получены зависимости величины мощности шумов от легочной вентиляции. Коэффициент ранговой корреляции Спирмена между изучаемыми параметрами равен 0,58 (p < 0,001). Отмечены значимые изменения средней мощности дыхательных шумов при росте нагрузки и легочной вентиляции уже на ступени 30 Вт относительно состояния покоя (0 Вт) (p < 0,0001). Мощность трахеальных дыхательных шумов также увеличивалась на 56% между ступенями нагрузки 120 и 135 Вт (p = 0,023) и на 75% при нагрузке 180 и 195 Вт (p = 0,043). Значимых различий между оценками частоты дыхания методом прямой флоуметрии и акустическим способом не выявлено.

Выводы. Установлена статистически значимая умеренная положительная корреляционная взаимосвязь между величиной легочной вентиляции и средней мощностью дыхательных шумов (r_s = 0,58; p < 0,001). При значениях легочной вентиляции до 60 л/мин характер зависимости средней мощности трахеальных шумов от легочной вентиляции является линейным. Установлено удовлетворительное соответствие акустической оценки частоты дыхания данным, полученным методами прямой флоуметрии; анализ дыхательных шумов способен дать косвенную оценку состояния дыхательной системы.

Ключевые слова: физическая нагрузка; дыхательные шумы; велоэргометрия; легочная вентиляция; дыхательная система; респираторная акустика

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Соответствие принципам этики: исследование проведено в соответствии с принципами Хельсинкской декларации. Все добровольцы проходили медицинский отбор врачебной экспертной комиссией ГНЦ РФ — ИМБП РАН, в ходе которого заболеваний и патологий, препятствующих участию в эксперименте, выявлено не было. Все участники подписали добровольное информированное согласие на участие в исследовании. Исследование одобрено Комиссией по биомедицинской этике ГНЦ РФ — ИМБП РАН (протоколы № 520 от 25.07.2019, № 539 от 17.03.2020).

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INTRODUCTION

In sports, aerospace, and maritime medicine, as well as in somnology studies, the issue of assessing the functional state of the human respiratory system is rather acute. This issue is addressed using the methods of direct flowmetry, which measure the magnitude of the respiratory flow. However, in a sealed enclosed environment (e.g., an orbital station or a spacesuit), direct flowmetry may not be possible or practical. In the search for a more compact and autonomous method for monitoring and assessing the state of the respiratory system, methods of respiratory acoustics are being investigated, which involve the recording and analysis of sounds generated during breathing [1–3].

The auscultation method is widely used in clinical medicine for an indirect assessment of pathological conditions of the lungs, at the same time as finding application in the field of maritime medicine [4, 5]. During spaceflight, including during physical exercise, monitoring the functional state of the respiratory organs to prevent bronchopulmonary diseases is of primary importance. In such conditions, astronauts experience changes in the shape of the chest, a cranial shift of the diaphragm, and a decrease in the functional residual lung capacity [6–8]. These phenomena affect the dimensions of the airways, leading to changes in the acoustic characteristics of lung sounds.

In this study, we set out to establish the presence and nature of relationships between the amplitude characteristic of the recorded lung sound signal and the magnitude of ventilation during physical exercise in healthy human participants, regardless of age and gender. Furthermore, we analyze the applicability of the acoustic method for assessing the respiratory rate.

MATERIALS AND METHODS

The study involved 25 volunteers (20 males and 5 females) aged 23–59 years (mean age 35.5 ± 8.7 years). The height ranged 165–189 cm (mean 178 ± 6.6 cm), and body weight ranged 56–104 kg (mean 79.2 ± 11.3 kg). All the participants were non-smokers and had no history of bronchopulmonary diseases. The volunteers underwent medical selection by an expert medical commission, during which no diseases or pathologies preventing participation in the experiment were identified. All the participants signed voluntary informed consent to participate in the study and for the use of their anonymized data.

The participants were subjected to a stepwise increase in physical workload on an Ergoselect 200P cycle ergometer (Ergoline GmbH, Germany). The initial workload stage was 30 W followed by a 15 W increase in each stage, which lasted for 1 min. The study was conducted until a submaximal heart rate[1] was reached under laboratory conditions with optimal ambient microclimate and atmospheric composition [9].

The participants breathed through a mouthpiece connected to the following pneumatic circuit: a tube with a saliva trap; an individual disposable filter; the measurement unit of the Jaeger Oxycon Pro system (Germany), which includes a rotary air flow sensor (turbine) and tubes for sampling exhaled air for breath-by-breath gas analysis.

Lung sounds over the extrathoracic section of the trachea and the magnitude of the respiratory flow were continuously recorded by the direct flowmetry method using a Jaeger Oxycon Pro device. Based on the respiratory flow dynamics, the built-in device software determined the values of pulmonary ventilation and respiratory rate, which were further analyzed.

Recording of lung sounds was carried out using equipment comprising a lightweight accelerometer, a power supply unit, a voice recorder, and cables [10–12]. The PCB 333B52 accelerometer (USA) was placed over the extrathoracic section of the trachea on the subject's neck and secured to the skin surface using a Velcro

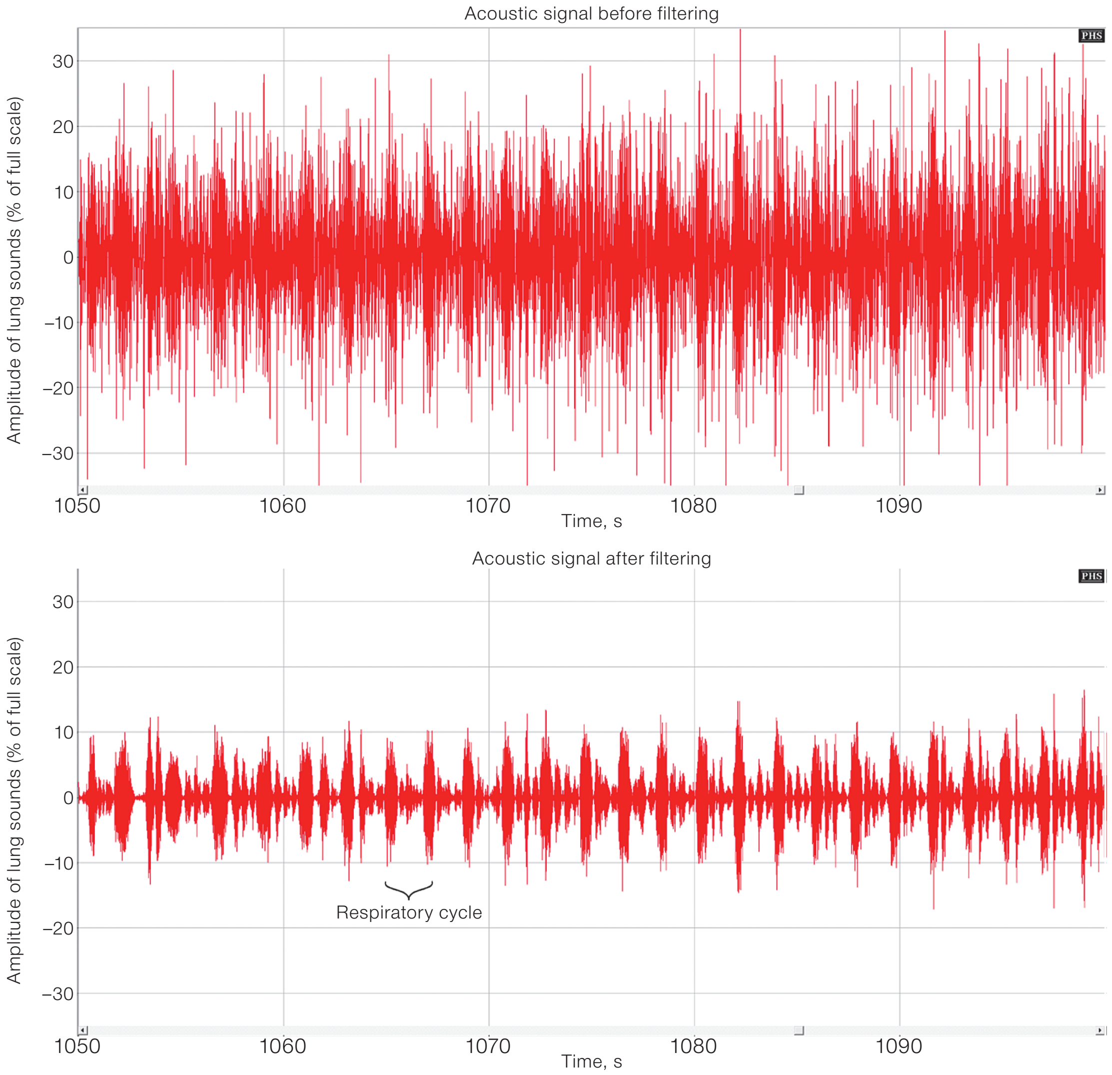

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Fig. 1. Filtering of the lung sound signal: *x*-axis — time (sec); *y*-axis — amplitude of lung sounds (% of full scale)

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[1] Bystrova AG, Kovaleva IO, Kuz'mina AYu, Parnes EYa, Potievsky BG, Erenburg IV, et al. Cycle ergometry in civil aviation aeromedical expertise. Manual. Moscow: RMANPO; 2020.

elastic strap. The accelerometer signal was digitized at a frequency of 48 kHz.

In order to attenuate background noise and the cardiac artifact, band-pass filtering was applied (Fig. 1). The acoustic signal was processed using an algorithm similar to that described in [11]. The lung sound recordings were processed by the SpectraPLUS 5.0 software (USA) using a band-pass filter in the frequency range of 200–1000 Hz to remove cardiac and muscle noises, which are typically observed at frequencies below 200 Hz, as well as high-frequency interference with frequencies above 1000 Hz [13].

The distance between adjacent peaks characterizing expiratory noises was considered the duration of the respiratory cycle, allowing an acoustic assessment of the respiratory rate (RR) and the period of the respiratory cycle. Furthermore, the SpectraPLUS software was used to determine the root mean square (RMS) value of the lung sound (RS) amplitude, taking into account each digitized value of the accelerometer signal corresponding to the load stages. This value is conventionally referred to as the mean power of lung sounds and is expressed as a percentage (%) of the full scale, i.e., the maximum signal amplitude value [11, 13–15].

Statistical data analysis was performed using the Statistica 13 (StatSoft Inc., USA) and Microsoft Excel (Microsoft, USA) software packages. To assess the dynamics of the parameters, non-parametric analysis of variance (Friedman ANOVA) was applied; changes in the studied parameters were evaluated using the Wilcoxon test (for RS power and pulmonary ventilation) and the Mann–Whitney U test (for comparing the acoustic assessment of RR and flowmetry data). To assess the relationship between RS power and pulmonary ventilation, a correlation analysis was conducted using Spearman's rank correlation coefficient (r_s) [16]. To establish the dependence of RS power on pulmonary ventilation, linear regression analysis was applied.

RESULTS AND DISCUSSION

During the study, the achieved maximum power output for all subjects ranged 105–240 W. However, only two individuals were capable of achieving a power output exceeding 210 W. In order to obtain more accurate data, the statistical analysis was limited to the power range of up to 210 W.

Dependencies of the mean lung sound (LS) power and the magnitude of pulmonary ventilation on the magnitude of physical load were obtained (Fig. 2).

A significant increase in the mean RS power from 0.0004 to 0.0009% was observed already at the 30 W stage compared to the resting state (0 W) ($p < 0.0001$). Furthermore, the power of lung sounds also increased by 56% between the 120 W and 135 W load stages ($p = 0.023$), and by 75% between the 180 W and 195 W load stages ($p = 0.043$).

The increase in RMS with an increase in physical load (Fig. 2) indicates a rise in the amplitude of lung sounds. The conducted correlation analysis established a statistically significant, moderate positive relationship between the absolute values of pulmonary ventilation and lung sound power ($r_s = 0.58$; $p < 0.001$).

The nature of the presumed relationship between RMS and the magnitude of pulmonary ventilation was analyzed by a linear regression analysis across the entire dataset (Fig. 3). Under an increase in the pulmonary ventilation volume, a scatter in the individual noise power values was observed. It appears that a single linear dependence cannot describe all individual parameters.

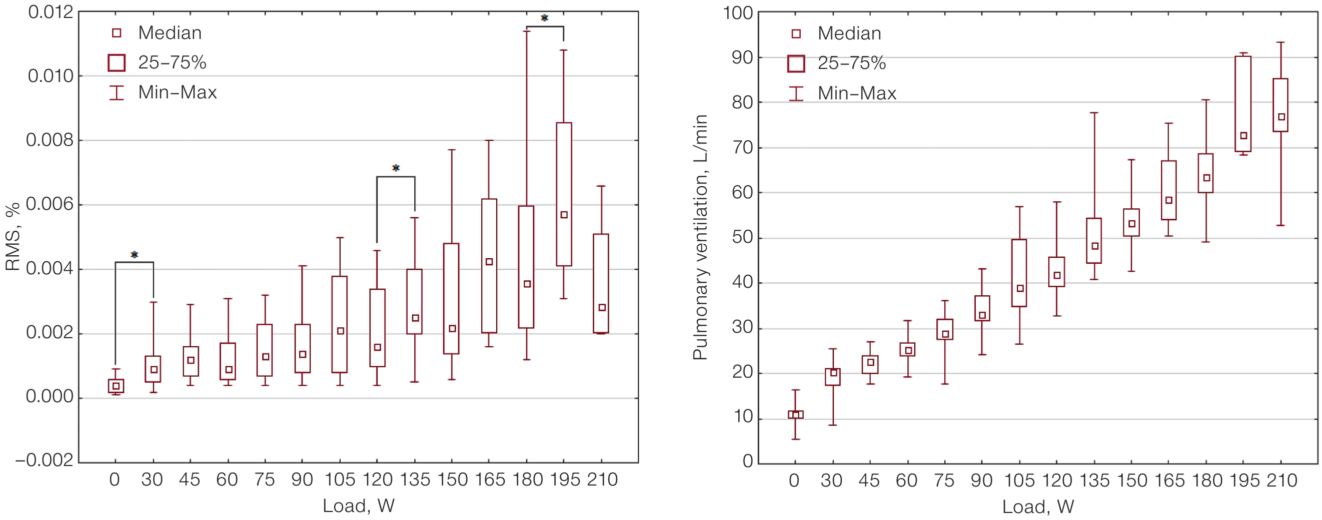

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Fig. 2. Dependence of the mean lung sound power and pulmonary ventilation on the magnitude of stepwise increasing physical load

Note: RMS — root mean square value of the lung sound amplitude; * — statistically significant changes ($p < 0.05$).

Significant individual differences and the non-linearity of the relationship between noise power and pulmonary ventilation led to data scatter and a low coefficient of determination value of $R^2 = 0.35$.

Literature sources present various methods for describing the relationship between respiratory flow and the amplitude of lung sounds [17]. Banaszak et al. described a linear relationship between instantaneous flow and breath sound amplitude measured over the chest wall [18]. Shykoff et al. utilized a quadratic function [14, 19]. Gavriely et al. characterized a power-law function, with the group-averaged exponent being 1.66 ± 0.35, which, in their view, is significantly less than the presumed second power [20, 21].

As noted above, the relationship between individual noise power values and pulmonary ventilation is characterized by a large scatter of noise power at a given level of pulmonary ventilation (Fig. 3). This scatter appears to be related to the significant differences in the geometry of the airway tree among the group participants. It can be assumed that in a more homogeneous group of subjects (by sex, age, height, body weight, physical fitness, etc.), the scatter would be smaller. Selecting homogeneous groups is a potential direction for future research in this field of respiratory acoustics. Furthermore, the search for individual regression dependencies is a promising avenue.

It can be assumed that the influence of individual differences on the relationship under study becomes smoother when transitioning from individual data to averaged values. Therefore, a regression analysis was performed on the averaged values of RS power and pulmonary ventilation parameters at each load stage. However, when considering the entire range of achieved pulmonary ventilation values up to 100 L/min, the coefficient of determination is only 0.68. This is likely due to the manifestation of a non-linear relationship between RS power and pulmonary ventilation magnitude, as well as individual differences across the larger range of pulmonary ventilation data. Consequently, the search for a linear regression dependence should limit the range of pulmonary ventilation (to 60 L/min) (Fig. 4). In this case, the coefficient of determination R^2 increased significantly to 0.93. Beyond this point, the relationship deviated from linearity, and data scatter increased substantially, leading to a decrease in R^2. In a similar manner, the correlation coefficient r_s decreased. This may be caused by the aforementioned non-linear phenomena and individual differences.

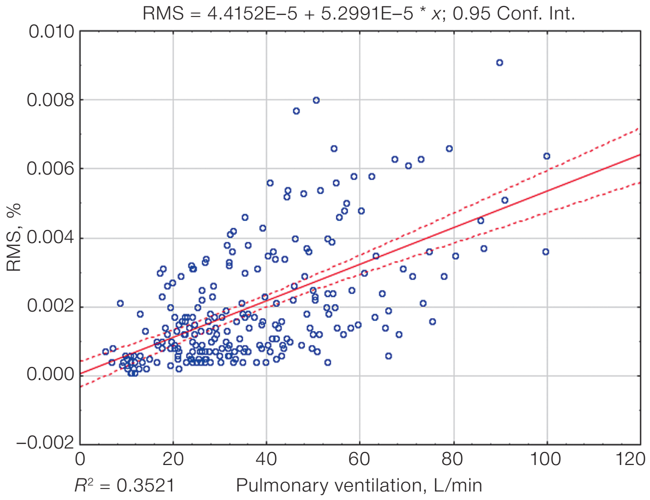

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Fig. 3. Relationship between individual values of mean lung sound power and pulmonary ventilation parameters

Note: RMS — root mean square value of the lung sound amplitude.

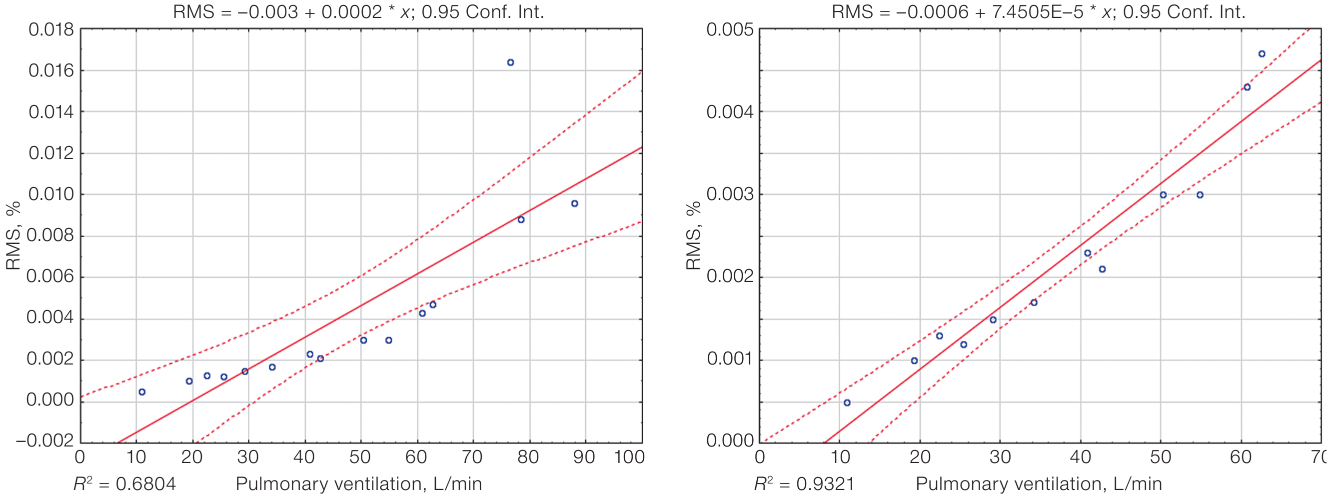

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Fig. 4. Dependence of lung sound power on pulmonary ventilation magnitude based on average parameter values

Note: RMS — root mean square value of the lung sound amplitude.

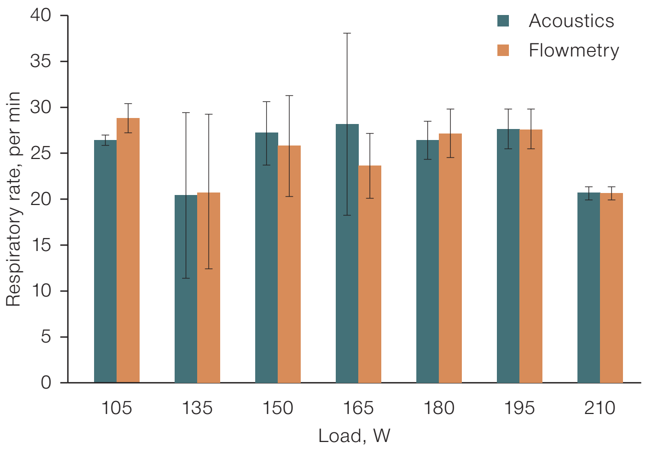

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Fig. 5. Comparison of respiratory rate values obtained by the acoustic method with those by direct flowmetry at various levels of stepwise increasing physical load

The practical significance of the obtained regression dependence lies in the possibility of assessing the magnitude of pulmonary ventilation based on lung sounds.

To identify the degree of agreement between the respiratory rate (RR) values obtained by the acoustic method and those from direct flowmetry, a comparison was made between the acoustic assessment of RR and the flowmetric parameter (Fig. 5).

Figure 5 shows that at a load of 135 W, the RR according to acoustic data was minimal, while at a stepwise increase in physical load to 165 W, it was maximal. It appears that these extreme values are more influenced by individual variations in the parameters. No significant differences were found between the RR values obtained by the two methods. The scatter in the values may be explained by differences in individual characteristics of the respiratory system.

CONCLUSIONS

1. A statistically significant, moderate positive correlation was established between the magnitude of pulmonary ventilation and the mean power of lung sounds ($r_s = 0.58$; $p < 0.001$).

2. For pulmonary ventilation values up to 60 L/min, the relationship between the mean power of tracheal sounds and pulmonary ventilation is linear. However, when this value is exceeded, additional non-linear processes are likely to contribute, altering the relationship. One such non-linear process could be the transition from laminar to turbulent airflow in the airways as the flow rate increases.

3. A comparison of the acoustic assessments of the respiratory system state with values based on direct flowmetry of respiratory flow showed satisfactory agreement. Consequently, the acoustic method can be considered an alternative to direct flowmetry in cases where the conventional approach is not applicable.

4. A potential direction for future research is the search for individual regression relationships and/or dependencies between the amplitude characteristic of the recorded lung sound signal and the magnitude of pulmonary ventilation in more homogeneous groups of subjects.

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