Effects of Normoxia and Hyperoxia on the Rate of Fatigue Development in Human Respiratory Muscles under Conditions of Intensive Resistive Load

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We evaluated the rate of fatigue development in the inspiratory muscles of healthy trained individuals during graded bicycle exercise and high resistive resistance to breath under conditions of normoxia and hyperoxia. Fatigue of the respiratory muscles was assessed by tension—time index ($TT_m=P_mI/P_mI_{max}xT_I/T_T$), by the dynamics of changes in the ratio of respiratory volume to inspiratory muscles force, and by ratio of the mean amplitudes of electrical activity in high and low frequency ranges. It was found that the limit of extreme working capacity in humans during heavy resistive load is related to fatigue of the inspiratory muscles developing with the same rate under conditions of normoxia or hyperoxia.

Key Words: *respiratory muscle fatigue; normoxia; hyperoxia; resistive load; extreme working capacity*

Biochemical and hystochemical properties of the majority of muscle fibers of the diaphragm and inspiratory muscles of the thorax (parasternal, sternocleidomastoid, scalene, *etc*.) and their excellent blood supply determine their capacity to permanently generate the pressure for adequate alveolar ventilation at rest and to maintain high pulmonary ventilation during long-term physical exercises [8,9]. However, even in healthy individuals fatigue of inspiratory muscles develops during heavy and/ or long-term physical exercises, especially in combination with breathing against additional resistive resistance [2,6]. This fatigue is defined as inability to maintain the pleural or transdiaphragmal pressure providing alveolar ventilation in accordance with energy expenditure. Working capacity of skeletal muscles, including respiratory muscles, largely depends on their energy supply. Hyperoxia is considered to increase diaphragm endurance and improve tolerance to low and moderate respiratory loads, thus delaying the development of respiratory musculature fatigue [1,3]. At the same time, there are data that fatigue of the inspiratory muscles is mediated by mechanisms insensitive to changes in blood oxygen level; this is true for breathing both hypoxic and hyperoxic gas mixtures [4].

The aim of this study was to compare the rate of fatigue development in inspiratory muscles of healthy individuals under conditions of high resistive resistance to breathing combined with progressive physical exercise.

MATERIALS AND METHODS

Five healthy men aging 19-27 years in good physical shape were included in the study. The examinees performed physical exercise on a Jaeger bicycle ergometer with load increment of 175 kg× m/min every 3 minutes under conditions of breathing against additional inspiratory-expiratory re-

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sistance of 40 cm H_2O/liter×sec^{-1} until they became unable to continue the experiment. Two experimental series were performed: the participants breathed either air (series 1) or oxygen (series 2). Experiments were carried out in different days in random manner. Each examinee participated in 3 experiments with air and in 3 experiments with oxygen, and the result of the experiment where maximum working capacity was achieved was used for statistical analysis. Pneumotachogram was continuously recorded and the data were used for calculation of volume—time ventilation parameters: respiratory volume (V_T), respiratory rate (f), duration of the inspiratory phase (T_I), and the duration of whole respiratory cycle (T_T); changes in Pco_2 in the alveolar gas were evaluated using an MX 6203 mass-spectrometer. The contraction force of inspiratory muscles was measured by peak values of mask (oral) pressure (P_{mI}). Total electrical activity (EMG) of the parasternal muscles was recorded using surface bipolar silver electrodes. Quantitative analysis of EMG was carried out using integrated activity peak value, spectral analysis of electrical activity of the parasternal muscles was also employed. To this end, amplified EMG-signals were digitized using an analog-to-digital converter and processed using VU POINT (version 1.27) software performing discrete Fourier transform and calculating the mean spectrum amplitude of EMG-signal in high (380-700 Hz) and low (50-200 Hz) frequency ranges. Load intensity was increased by 175 kg×m/min every 3 min.

Since the duration of work "to refusal" (*i.e.* maximum physical performance) in all experiments and for all participants was different, for leveling the individual differences statistical analysis was carried out with absolute values recorded at 10, 20, 30… 100% (refusal) of peak power achieved by a participant under specified conditions. The results were statistically analyzed and expressed as $M \pm m$. Significance of differences was evaluated using Student's *t* test and nonparametric Wilcoxon test for small samples. The differences were significant at $p<0.05$.

RESULTS

During exposure of the respiratory system to heavy resistive load, the peak power of muscle activity achieved during oxygen inhalation was 831.5±43.4 kg×m/min, which did not significantly differ from the control (air breathing) 815.6±45.1 kg×m/min. Minute respiratory volume (V_E) increased with increasing muscle activity during breathing both oxygen and air, but this increase was inadequate to the increased ventilation demands. Limited increase in V_E led to a decrease in CO_2 elimination rate and to the development of pronounced hypercapnia (under conditions of normoxia and hyperoxia P_{ACO2} at the moment of refusal was 69.8±2.8 and 72.4±3.1 mm Hg, respectively). In all participants, the increase in V_E during submaximal and maximal exercise was provided exceptionally by increasing the respiratory rate, while V_T decreased in both experimental series. The dynamics of V_T and P_{mI} ratio with increasing the load under conditions of both oxygen and air breathing suggests that V_T values gradually increased after the start of the experiment, then were maintained at a constant level, and considerably decreased 3-5 minutes before refusal. At the

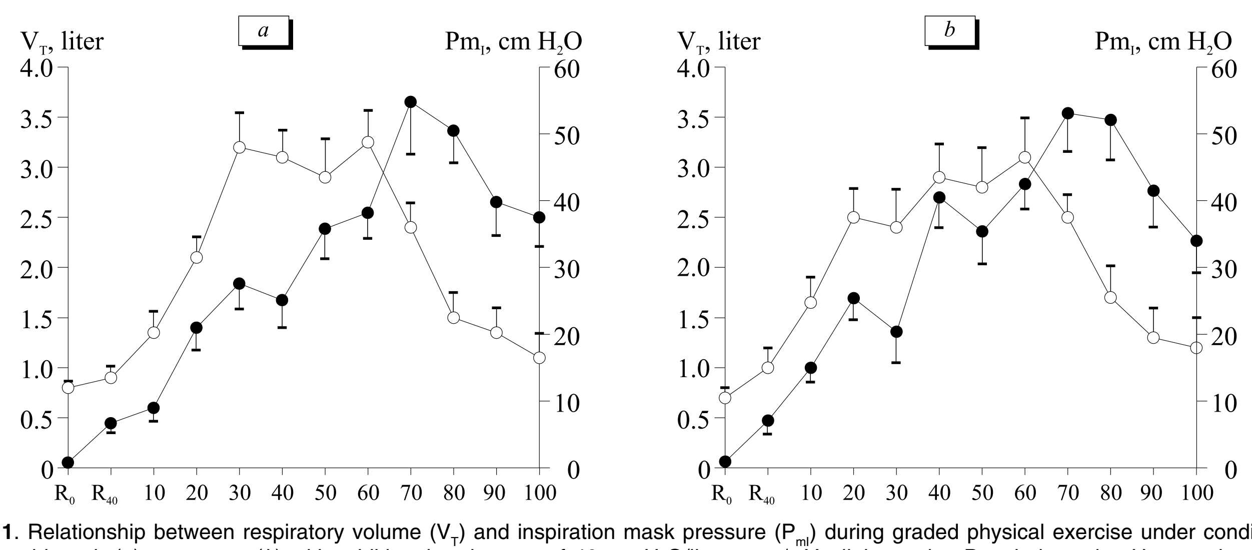

Fig. 1. Relationship between respiratory volume (V_T) and inspiration mask pressure (P_{mI}) during graded physical exercise under conditions of breathing air (*a*) or oxygen (*b*) with additional resistance of 40 cm H_2O/liter×sec^{-1}. V_T: light marks, P_{mI}: dark marks. Here and on Fig. 2: abscissa: physical performance,% of maximum value. R_0: at rest with quiet respiration, R_{40}: at rest with breathing against additional resistance of 40 cm H_2O/liter×sec^{-1}.

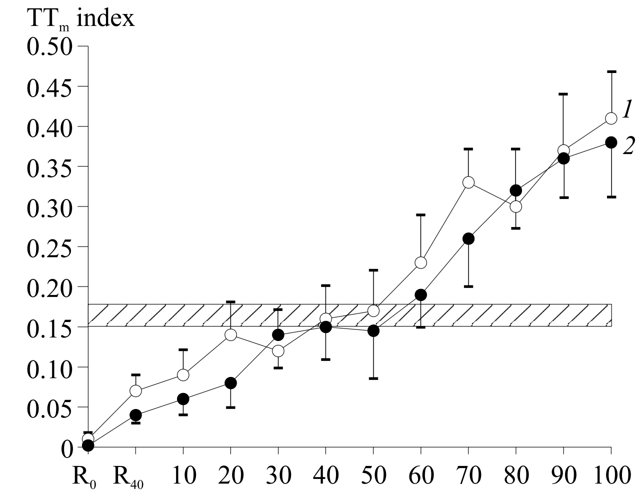

Fig. 2. Dependence of tension—time index on physical performance under conditions of resistive resistance of 40 cm H_2O/liter×sec^{-1} to breathing air (*1*) and oxygen (*2*). Shaded area: fatigue zone (TT_m=0.15-0.18).

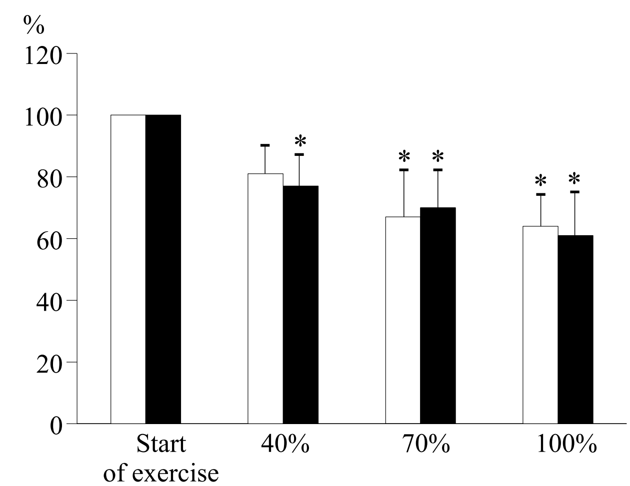

Fig. 3. Dynamics of HF/LF ratio at different stages of exercise testing (% of maximum performance) under conditions of additional resistance of 40 cm H_2O/liter×sec^{-1} to breathing air (dark bars) and oxygen (light bars). HF/LF at the start of exercise testing=100%. Abscissa: stages of exercise in % of maximum performance. *$p<0.05$ compared to the start of muscular work.

same time P_{mI} values reflecting the effort of respiratory muscles required for providing constant and then decreased V_T values steadily increase. However, during the last minutes of work, the contracting force of the respiratory muscles does not increase, but even decreased (Fig. 1) despite high hypercapnic stimulation and voluntary efforts of the participants to increase lung ventilation under conditions of both normoxia and hyperoxia.

The major criterion of respiratory muscle fatigue is the tension—time index ($TT_m=P_mI/P_mI_{max}\times T_I/T_T$) reflecting force and temporal characteristics of muscle contraction [5,7]. Our findings suggest that TT_m values simultaneously attained the threshold of the fatigue zone in practically all participants breathing air or oxygen and then significantly exceeded it (Fig. 2).

For the diagnostics of respiratory muscles fatigue, changes in frequency compositions of the EMG spectrum are evaluated. It was empirically established that fatigue is associated with an increase in the amplitude of low-frequency (LF) and a decrease in high-frequency (HF) components of the EMG spectrum, which manifests in reduced HF/LF ratio. In this study, marked decrease in HF/LF ratio with increasing working activity was also observed in all participants both during breathing air and oxygen; moreover, at the moment of refusal, the HF/LF ratio dropped by 36 and 39%, respectively in comparison with the initial HF/LF values ($p<0.05$, Fig. 3).

Thus, improved energy supply in the form of breathing pure oxygen during heavy resistive load in combination by progressively increasing muscle work had no beneficial effect on general working capacity of the examinees and on endurance of their respiratory muscles. Limited working capacity in trained men under conditions of heavy resistive load is related to respiratory muscle fatigue; the rate of the development of this fatigue is similar under conditions of normoxia and hyperoxia. It was assumed that during forced respiration caused by progressive exercise testing with high additional resistance to gas flow, the blood supply to the respiratory muscles is impaired. Under these conditions, powerful muscle contractions compress the intramuscular vascular network, thus reducing or even arresting blood flow (complete occlusion of arterial vessels in respiratory muscle at high $P_m/_{Pm\ max}$ values) and the duration of effective T_I/T_T cycle exceeds 0.5 (reduced relaxation period during inspiration phase). Due to mechanical blood flow disturbances, even inhalation of 100% oxygen has no beneficial effect on energy supply to the respiratory muscles and the rate of fatigue development. Rapid fatigue is promoted by marked hypercapnia and high blood concentration of acid metabolites inevitably appearing during combination of heavy resistive load and physical exercise.

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