Simulation of human external respiration

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Creating a new generation of life-support systems and the protection of human health is influenced by a number of factors including the increase in the number of objects with technical and technological resources that are close to the limit or completely exhausted, etc.

New types of personal protective equipment of human respiratory organs (HRO) and their components require testing, both at the stage of development, and at that of production. The primary testing tool for HRO, as well as their individual units is the Artificial Lung device (AL) [1,2].

Simulation of human breathing on the AL device in the test mode is defined by the following parameters: the depth of breathing V_d, dm^3; respiratory rate n, min^{-1}; pulmonary ventilation $W_l = V_d n$ dm ^{3}/min.

The volumetric flow of carbon dioxide during the test, dm3 / min simulates human emissions of carbon dioxide. This value determines the initial volume fraction of carbon dioxide in exhaled respiratory gas mixture (RGM) $C_{\mathrm{CO_2}}(0) = W_{\mathrm{CO_2}}(0)/W_l$, which depends on the supply amount of carbon dioxide in the initial time of the test and the pulmonary ventilation. [2]

It is important for simulation of respiration to have correct reproduction of the respiratory quotient $K_d = W_{\mathrm{CO_2}}(0)/W_{\mathrm{O_2}}$, which determines the level of oxygen consumption by human.

The calculation of the volume fraction of the N_2 in the RGM is based on the assumption that in the circuit "AL - HRO" only three-component mixture of CO_2, O_2, N_2 circulates. The volume fraction of nitrogen in an inhaled RGM is calculated as follows: $C_{\mathrm{N_2}}^{\mathrm{inh}} = 1 - C_{\mathrm{CO_2}}^{\mathrm{inh}} - C_{\mathrm{O_2}}^{\mathrm{inh}}$. Similarly, for the exhalation: $C_{\mathrm{N_2}}^{\mathrm{exh}} = 1 - C_{\mathrm{CO_2}}^{\mathrm{exh}} - C_{\mathrm{O_2}}^{\mathrm{exh}}$.

The amount of RGM to be removed at the inhale stage equals $W_{\mathrm{RGM}} = W_{\mathrm{CO_2}} / C_{\mathrm{O_2}}$ so as to ensure the removal of the required volume and mass of the O_2 from the system.

At the same time, nitrogen and carbon dioxide removed from the system together with the oxygen; the volume flow rate is determined on the basis of their the volume fractions in the discharged RGM:

$$W_{N_2}^{RGM} = C_{\mathrm{N_2}}^{\mathrm{inh}} W_{\mathrm{RGM}},\ W_{\mathrm{CO_2}}^{\mathrm{RGM}} = C_{\mathrm{CO_2}}^{\mathrm{inh}} W_{\mathrm{RGM}}$$

These amounts of CO_2 and N_2 must be returned to the system to maintain the material balance of these gases. The quantity of carbon dioxide and nitrogen is calculated using material balance equations, which allow calculating the amount of removed gases from the RGM system, and the amount of CO_2 and N_2, which must be returned to the system for different test modes IDA.

Thus, to fully simulate the oxygen consumption by the simulator it is necessary to remove the RGM with the following volume flow rate:

$$W_{\mathrm{RGM}} = W_{\mathrm{O_2}} C_{\mathrm{CO_2}}^{\mathrm{inh}} = W_{\mathrm{CO_2}}(0) / (K_{\mathrm{d}} C_{\mathrm{O_2}}^{\mathrm{inh}})$$

The described relationships make it possible to develop a mathematical model of human external respiration, describing the dynamic processes in the AL device, simulating various kinds of respiration pneumotachograms, oxygen consumption levels.

Gas flows in the device are modulated by respiration pneumotachograms,which perform modulating functions. A simulator drive acts as a modulator, specifying the frequency, depth and type of respiration pneumotachograms in the device.

The basic relations of the mathematical model of human respiration simulation include: changes in the volume of gases at the inhale stage, for example, when implementing sinusoidal pneumotachogram:

- The volume of inhaled gases is as follows:

$$\begin{cases} dV_{CO_2}^{AL} / dt = W_{CO_2}^{AL} F^{\sin}; \\ dV_{O_2}^{AL} / dt = W_{O_2}^{AL} F^{\sin}; \\ dV_{N_2}^{AL} / dt = W_{N_2}^{AL} F^{\sin}; \end{cases}$$

- The volume of discharged RGM: $V_{RGM} = S_p X_p$; the returns of discharged N_2 and CO_2 gases from the cylinder, where X is calculated by the following equations:

$$dX_{п} / dt = (1/S_p) W_{RGM} F^{\sin}, \quad X_p^{\min} \le X_p \le X_p^{\max}, \quad \left|\dot{X}_p\right| \le \dot{X}_p^{\max}$$

$$\begin{cases} dV_{CO_2} / dt = W_{CO_2} F^{\sin}; \\ dV_{N_2} / dt = W_{N_2} F^{\sin}; \end{cases}$$

- O_2 consumption: $dV_{O_2} / dt = W_{CO_2}(0) / K_{д} F^{\sin}$. Change in the concentration of gases in the AL device at the inhale stage when implementing sinusoidal pneumotachogram:

$$\begin{cases} \frac{d}{dt} C_{CO_2}^{AL} = \left[\left(W_{CO_2}(0) + W_{CO_2}^{AL}\right)\left(V_{O_2} K_d + V_{AL} + V_{RGM}^{inh}\right) - \left(V_{O_2} K_d + C_{CO_2}^{(0)} V_{AL} + V_{CO_2}^{AL}\right) \times \right. \\ \qquad \times \left(W_{CO_2}(0) + W_{CO_2}^{AL} + W_{O_2}^{AL} + W_{N_2}^{AL}\right) F^{\sin} / \left(V_{O_2} K_d + V_{AL} + V_{RGM}^{inh}\right)^2; \\ \frac{d}{dt} C_{O_2}^{AL} = \left[\left(W_{O_2}^{AL}\left(V_{O_2} K_d + V_{AL} + V_{RGM}^{inh}\right) - \left(C_{O_2}^{(0)} V_{AL} K_d + V_{CO_2}^{AL}\right) \times \right.\right. \\ \qquad \times \left(W_{CO_2}(0) + W_{CO_2}^{AL} + W_{O_2}^{AL} + W_{N_2}^{AL}\right) F^{\sin} / \left(V_{O_2} K_d + V_{AL} + V_{RGM}^{inh}\right)^2; \\ \frac{d}{dt} C_{N_2}^{AL} = \frac{d}{dt} C_{CO_2}^{AL} - \frac{d}{dt} C_{O_2}^{AL}. \end{cases}$$

Flows of gases entering the respiration simulation unit simulate respiration in the AL device can be written as follows (dm^3 / min):

$$\begin{cases} W_{CO_2}^{AL} = C_{CO_2}^{AL} V_d n; \\ W_{O_2}^{AL} = C_{O_2}^{inh} V_d n - W_{O_2}; \\ W_{N_2}^{AL} = C_{N_2}^{inh} V_d n. \end{cases}$$

These equations with the initial conditions are the mathematical model of the human respiration simulation.

From the analysis of the results of simulation studies, we can conclude that the values of the amount of discharged RGM and carbon dioxide and nitrogen supply instead of those removed when simulating oxygen consumption are the most sensitive to the changes in the position of piston feeder plunger for RGM discharge, changes in the degree of opening of valves supplying CO_2 and N_2, respectively, thus, indicating the possibility of implementing all of the tested respiratory modes.

To simulate various human psycho-physiological states the simulator drive sets various combinations of respiration pneumotachogram and all metering devices (RGM discharge, CO_2 and N_2 supply) must operate synchronously with it.

References

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