QUANTITATIVE ASSESSMENT OF THE HOMEOSTATIC PROPERTIES OF THE OXYGEN TRANSPORT SYSTEM

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To assess the homeostatic properties of the oxygen transport system quantitatively it is suggested that a change in the state of the system be compared with the magnitude of the factor inducing it. Experiments to obtain such an assessment with the aid of a computer and a mathematical model of the respiratory, circulatory, and energy-metabolic systems linked with oxygen transport are described. Quantitative indices of homeostatic properties were found to vary with the conditions (rest, physical exertion). During physical exertion when the mechanisms of regulation are under strain, the homeostatic power of the system is reduced.

The homeostatic properties of physiological control systems [4, 9, 12] vary with the state of the animal and the external environmental conditions [1, 5, 6, 10]. The disturbing action of the environment leads to the creation of a transition process in the system followed by a new level of activity. The system is homeostatic if this new level is close to the old. The relationship between the force of disturbance and the magnitude of the response can be used as a measure of the homeostatic power of the organism [7, 10]. When the number of disturbing factors and of variables to be investigated is great, it is possible to make a combined evaluation of the effect of each disturbance on each variable (coefficient of sensitivity [2]), from which a mean assessment of homeostatic ability can be obtained [7].

This paper describes a computerized method of investigation of the oxygen transport system to obtain a quantitative assessment of the homeostatic properties of that system.

EXPERIMENTAL METHOD

A system of equations characterizing the combined function of the human respiratory, circulatory, and energy-metabolic systems based on mean statistical data was solved by the computer [8, 11]. The homeostatic properties were investigated for two conditions of oxygen consumption (W): in a state of rest (W = 225 ml/min) and in a state of intensive muscular work (W = 2600 ml/min). In both cases the oxygen consumption of the muscle tissue (W_1) and of nonmuscular tissues (W_2) was studied. The composition of the inspired air depended on two variables: the partial pressures of oxygen (V_1) and carbon dioxide (V_2). The following 14 variables of the internal milieu of the organism were determined during the experiments: the alveolar (U_1) and venous (U_2) partial pressures of oxygen, the partial pressure of oxygen in the muscular (U_3) and nonmuscular (U_4) tissues, the alveolar (U_5) and venous (U_6) partial pressures of carbon dioxide, the partial pressure of carbon dioxide in the muscular (U_7) and nonmuscular (U_8) tissues, the concentration of incompletely oxidized products in the muscular (U_9) and nonmuscular (U_{10}) tissues, the pulmonary ventilation (U_{11}), the blood flow through muscular (U_{12}) and nonmuscular (U_{13}) tissues, and the concentration of incompletely oxidized products in the arterial blood (U_{14}).

To assess the homeostatic properties of the system it is essential to have data on the effect of all the disturbing factors studied on the state of all the variables examined under the conditions specified. The coefficient of sensitivity – the ratio between the j-th variable of the internal milieu and the i-th variable of the external environment – is [7]

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$$Sij = \frac{Vi}{Uj} \cdot \frac{\Delta Uj}{\Delta Vi}; \quad \Delta Uj \to 0, \quad \Delta Vi \to 0,$$

where $\Delta Vi \to 0$ and $\Delta Uj \to 0$ signify that the values of ΔVi and ΔUj must be as small as possible. A change in the state of the system in response to the action of disturbing factors V_1 and V_2 was assessed jointly by the mean square coefficient of sensitivity:

$$S = \sqrt{\frac{1}{i \times j} \Sigma (Sij)^2}.$$

The value of $h = 1/S$, in accordance with data in the literature [7], can be called the index of homeostatic ability of the system for it characterizes the degree of maintenance of constancy of the internal milieu during the presence of variations in the external environment. It is difficult to obtain data for coefficients of sensitivity in the essential quantity and yet satisfying the requirement of smallness of the deviations by direct experiments on animals. However, an adequate mathematical model on which additional investigations can be carried out to determine the homeostatic properties of control systems can be based on the results of a large number of experimental investigations [3, 6, 13].

In the present investigation the values of V_1 and V_2 were changed in the course of the experiment so that $\Delta V_1 = 0.1\ V_1$ and $\Delta V_2 = 0.1\ V_2$. New values of all variables of the internal milieu and of their increases ΔUj were calculated, after which the coefficients of sensitivity could be determined.

TABLE 1. Determination of Coefficients of Sensitivity in the Resting State

Variables of internal milieu	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}	U_{14} (in mg %)
	in mm Hg								in mg %		in liters/min			
Initial value	112	40	40	40	41,3	44,5	60	60	26,6	12,5	3,33	1,31	3,19	15
Value during variation of V_1	99,8	40,8	38,5	36,3	37,8	40,5	51,8	54	29,2	14,4	3,3	1,67	3,31	16,6
Coefficient of sensitivity	1,09	0,19	0,38	0,92	0,85	0,91	1,36	0,99	0,97	1,9	0,02	2,27	1,36	1,05
Value during variation of V_2	110	40,6	39,5	39,9	42,7	45,8	59,8	61,4	27,3	12,7	3,22	1,4	3,2	15,3
Coefficient of sensitivity	0,2	0,15	0,12	0,02	0,3	0,3	0,03	0,23	0,26	0,15	0,3	0,73	0,05	0,2

TABLE 2. Determination of Coefficients of Sensitivity in a State of Physical Exertion

Variables of internal milieu	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9	U_{10}	U_{11}	U_{12}	U_{13}	U_{14} (in mg %)
	in mm Hg								in mg %		in liters/min			
Initial value	107	44,2	38,6	31,2	45,1	51,4	60,2	64,4	144	101	35,3	17,8	8,54	122
Value during variation of V_1	97,7	48,6	35,7	27,7	39,7	44,8	51,4	55,5	184	156	43,5	23,3	12	170
Coefficient of sensitivity	0,9	1	0,75	1,1	1,2	1,28	1,47	1,4	2,74	5,54	2,32	3,12	4,02	3,93
Value during variation of V_2	107,4	44,6	38,6	30,7	45	51,5	60,1	64,4	146	114	37,9	18,1	9,4	130
Coefficient of sensitivity	0,01	0,09	0,01	0,16	0,02	0,02	0,01	0,01	0,13	1,34	0,73	0,15	1	0,65

EXPERIMENTAL RESULTS

Values of all variables and coefficients of sensitivity for cases of variation in V_1 and V_2 in a state of basal metabolism $W = 225$ ml O_2/min ($W_1 = 65$ ml/min; $W_2 = 160$ ml/min) are given in Table 1. The mean square coefficient of sensitivity S in this case was 0.83 and the index of homeostatic ability h was 1.2.

Table 2 gives the same values for the case of intensive physical exertion $W = 2600$ ml/min ($W_1 = 1800$ ml/min, $W_2 = 800$ ml/min). In this case the values of S and h were 1.89 and 0.53, respectively.

During physical exertion the system is thus more sensitive to variations in the environment than in the state of basal metabolism. This worsening of the state is reflected in a decrease in the index of homeostatic ability from 1.2 under basal metabolic conditions to 0.53 under conditions of physical exertion.

LITERATURE CITED

1. V. N. Beklemishev, Byull. Moskovsk. Obshch. Ispyt. Prirody. Otdel. Biol., 64, No. 2, 24 (1964).

2. M. L. Bykhovskii, Cybernetic Systems in Medicine [in Russian], Moscow (1971).
3. E. J. Van Liere and J. C. Stickney, Hypoxia, University of Chicago Press (1963).
4. S. Goldman, in: Cell-Organizing Systems [Russian translation], Moscow (1964), p. 151.
5. V. S. Zav'yalov, in: Problems in Cybernetics [in Russian], Moscow (1966), p. 76.
6. The Oxygen Regime of the Organism and Its Regulation [in Russian], Kiev (1966).
7. V. N. Novosel'tsev, Avtomat. i Telemekhan., No. 7, 139 (1972).
8. B. V. Petrovskii, V. I. Shumakov, V. N. Novosel'tsev, et al., in: Bioelectrical Control. Man and Automatic Systems [in Russian], Moscow (1970), p. 278.
9. R. Rosen, The Optimality Principle in Biology [Russian translation], Moscow (1969).
10. V. V. Frol'kis, in: The Regulation of Functions at Different Age Periods [in Russian], Kiev (1966), p. 11.
11. V. I. Shumakov, V. N. Novosel'tsev, M. P. Sakharov, et al., Simulation of Physiological Systems of the Organism [in Russian], Moscow (1971).
12. W. B. Cannon, The Wisdom of the Body, London (1932).
13. H. Rahn and W. O. Fenn, A Graphical Analysis of the Respiratory Gas Exchange: The O_2-CO_2 Diagram, Washington (1955).