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Physiological Basis of Differences in the Body Tolerance to Submaximal Physical Load to Capacity in Healthy Young Individuals

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Abstract—A complex approach to studying the physiological basis of the individual and typological features of functional states and tolerance of physical load in healthy young individuals using superslow physiological processes (SSPP) was elaborated. Statistically significant differences were found in the values of central hemodynamics, physicochemical homeostasis, the level of oxygen consumption by the tissues, and general nonspecific adaptation reactions of the body. These reactions correlated with differences in the integral values of the wakefulness level, as judged by the SSPP data, in healthy individuals tolerant of physical fatigue and quickly fatigued individuals at rest and after a two-step individually submaximal physical stress to capacity. The possibilities of the use of this approach to substantiate the physiological significance of SSPP in the differential diagnosis of the optimal level of wakefulness, the state of physical tension, the state of fatigue, and asthenic states of a different degree of severity in healthy individuals with regulatory and homeostatic control inherent in these states were revealed.

The problem of functional states as a phenomenon revealing interactions of the body with the environment is most closely connected with the problems of biological and psychological stress.

Modern investigations in the field of functional states embrace a wide spectrum of methods and approaches to studying the mechanisms of intra- and intersystem interactions providing a diversity of types of adaptive human activity on body exposure to different stressors [1–13].

With multifactorial investigations in the field of the physiology of functional states, the notions of the physiological basis of differences in stressor resistance have not been outlined in sufficient detail thus far. It is common knowledge that the effects similar in intensity and duration may be stressors for one individual and may not possess these characteristics for another. The effects of exposure similar in intensity and duration may be likewise ambiguous in one individual in different functional states.

Our recent investigations theoretically substantiate the complex approach using superslow physiological processes that permit different levels of operative rest and active wakefulness of a man in health and pathology to be differentiated, and the physiological basis for differences in stressor resistance in normal and pathological states to be investigated [10, 14–16].

The essence of this approach consists in disclosing the basic role of superslow physiological processes (SSPP) of the brain and the other organs and tissues, commensurable with temporal parameters, in the mechanisms of neurohumoral regulation of interorgan and intersystem interactions forming the individual and typological features of the human psychoemotional and locomotor status, and determining the typology of adaptive behavior under ever-changing conditions of internal environment of the body and the multifactorial effect of the external environment [9, 10, 17].

This communication presents the results of a complex study of the physiological basis of individual and typological features of systemic control of the rest state and compensatory–adaptive reactions of the body under conditions of individually submaximal two-step physical load to capacity in healthy individuals aged 17 to 30 tolerant of stress and easily fatigued.

METHODS

The study included 87 subjects aged 17 to 30 years (47 men and 40 women) stated to be healthy by the results of prophylactic screening.

Two groups of subjects were singled out by the duration of exercise performance to capacity (running on the spot at an individually comfortable rate). In group I individuals, the duration of physical load varied from 20 to 45 min (70 individuals), which characterized their tolerance to such a load. For group II individuals (17 subjects), this value did not exceed 5–10 min, which gave evidence of their quick fatigability to this load [15, 18–20].

The duration value of exercise performance to capacity was used as one of the integral values of the subjects' resistance to this kind of stressor exposure.

The systemic level of physiological investigations included analysis of the generally accepted parameters of the state of the autonomic nervous system (the stress index, Kerdo's autonomic index); the external and tissue respiration (respiratory rate, tidal volume, the index of respiratory volume in 1 min, the level of oxygen consumption, the degree of oxygen extraction in the tissues); central hemodynamics (heart rate, mean arterial pressure, stroke volume, specific peripheral vascular resistance, minute blood volume); peripheral oxygenation (the degree of oxygen extraction in the tissues by oxygen arteriovenous difference value); acid–base (pH, pCO_2, buffer base shift) and energy (respiratory coefficient) homeostasis as well as adaptive reactions and nonspecific resistance of the body by the method of Garkavi *et al.* [21].

A stable potential of the millivolt range (Ω-potential) in the vertex–thenar lead of the right and left arm, respectively, was used as the basic integral value of the level of wakefulness, balance, or, on the contrary, imbalance of intersystem relations in the formation of compensatory–adaptive reactions of the body to stress exposure [14, 17, 22].

SSPP were recorded using a direct current amplifier with R_{BX} 100 MΩ [23]. To lead SSPP from the surface of the head or the body, liquid nonpolarizable silver–silver chloride electrodes were used [24]. The ω-potential sign and value (after the plateau was reached) were determined at rest. Psychomotor resistance and the capacity for spontaneous relaxation in individuals in the state of psychomotor stress or, on the contrary, development of psychomotor stress were judged by the time of the ω-potential initial values attaining the plateau and the intensity and direction of their dynamics [20, 23]. The character of compensatory–adaptive reactions of the main regulatory systems under these conditions was determined by type changes in the ω-potential at different time intervals after stress exercise [25].

The state of the compensation mechanisms intended to eliminate metabolic stress was judged by the amplitude, regularity, and stability of superslow potential fluctuations (SSPF) with $T = 2$–4; 6–8 s in the lead from the surface of the head and the body [11, 14, 17, 25, 26]. The regularity and stability of decasecond SSPF ($T =$ 30–40 s) appeared, by the existing notions, to be a physiological equivalent of the state of light drowsiness and sensory restriction [26]. Detection of SSPF with a period of 2–4 min allowed us to reveal fluctuations of accomplished and unaccomplished mental processes, including fluctuations of voluntary attention [26].

The standard package of programs—Graph Pad Instat, Copyright (©) 1990–1994, Graph Pad Software V. 2.05a, E. Zvartau, 942034—installed on IBM PC Pentium-166 was used for statistical analysis of the study results. The means and the standard mean error ($M \pm m$) of the variables studied were calculated. To assess the statistical significance of intergroup differences of the small-size sample values, nonparametric Dunn's test was used; in standard samples, Student's *t*-test was used.

RESULTS AND DISCUSSION

At rest, as judged by the subjective evaluation, the predominant majority of the subjects examined (67 individuals) had no complaints. They determined their state as normal and their well-being as good. Three subjects periodically noted a low mood and the feeling of fatigue. The objective examination revealed moderately severe signs of neurocirculatory dystonia in the form of hyperhydrosis of the extremities.

Virtually all group II subjects complained of general fatigue and a progressive low mood; 15 subjects noted the sensation of palpitations, sleep difficulties; 11 subjects complained of periodic headaches of different character occurring, as a rule, during physical and mental tension.

Tables 1A and 2A summarize the results of the study of systemic regulatory and homeostatic variables in group I and group II subjects at rest. It is seen that healthy individuals tolerant of a physical load at rest are characterized by balanced values of central and systemic hemodynamics, physicochemical homeostasis, tissue respiration, and general nonspecific adaptation reactions of the body (Table 1A).

The balance of the systemic variables studied was comparable with SSPP characteristics reflecting the optimal wakefulness level of group I individuals (Table 3A). This was reflected in the optimal ω-potential values (the mean background values 32.6 ± 8.7 mV) and irregular, moderately marked SSPF, which is, by the existing notions, characteristic of healthy individuals at rest [14, 17, 22, 25, 26].

With the presence of the signs of asthenia and neurocirculatory dystonia, all group II subjects showed an increased oxygen consumption by the tissues at rest under compensated metabolic acidosis conditions (Table 2A), the main compensatory systemic reaction aimed at correcting acidosis being a moderately marked hyperdymanic type of blood circulation.

The consistent pattern of systemic regulatory and homeostatic shifts was comparable with a decreased level of wakefulness, as evidenced by the data of the background ω-potential values (Table 4A). The background ω-potential values in this group of individuals did not exceed -12.5 ± 1.7 mV. Moreover, virtually all group II individuals revealed, as a rule, marked SSPF in the decasecond and minute range at rest, which, according to the existing notions, appeared to be a physiological equivalent of light drowsiness and sensory restriction at a decreased level of wakefulness [26].

Table 1. Features of the dynamics of systemic and homeostatic values in healthy individuals tolerant of physical fatigue at rest (A) and after two-step individually submaximal physical exercise before the first (B) and second refusal (C) ($M \pm m$)

Variables	A	B	C
Central and systemic hemodynamics: heart rate, min	76.0 ± 0.6**	148.6 ± 4.8	128.4 ± 0.9**
mean arterial pressure, mm Hg	84.4 ± 0.5**	122.4 ± 1.2*	114.8 ± 0.9*
stroke volume, ml	76.8 ± 1.3**	117.5 ± 1.2	118.5 ± 2.1*
specific peripheral vascular resistance, dyne s cm^{-5} m^2	1274.2 ± 53.6*	1032.6 ± 27.8*	1093.6 ± 326.5*
minute blood volume, ml/min	4.8 ± 0.1**	12.4 ± 0.3	10.7 ± 0.2
Physicochemical homeostasis and tissue respiration: blood pH, u	7.39 ± 0.004	7.38 ± 0.004**	7.36 ± 0.002**
buffer base shift, mmol/l	–1.4 ± 0.6**	–3.8 ± 0.2**	–4.6 ± 0.4**
degree of oxygen extraction in the tissues by $AVDO_2$, ml O_2/100 ml blood	4.5 ± 0.006*	8.9 ± 0.2*	8.2 ± 0.1*
General nonspecific adaptation reactions: leukocyte count, 1×10^9 in mm^3	7.5 ± 0.2**	12.6 ± 0.3**	16.5 ± 0.5**
lymphocyte content, %	33.6 ± 0.3**	42.5 ± 0.6**	44.2 ± 0.6**
coagulation time, min	6.2 ± 0.3**	8.2 ± 0.3**	6.3 ± 0.2**
fibrinolytic activity, %	24.2 ± 0.4**	29.3 ± 0.63**	26.7 ± 1.2**

Note: Here and in Table 2, the significance of intergroup differences by A, B, and C * $p < 0.05$; ** $p < 0.001$ (t-test).

Table 2. Features of the dynamics of systemic and homeostatic values in easily fatigued individuals at rest (A) and after two-step individually submaximal physical exercise before the first (B) and second refusal (C) ($M \pm m$)

Variables	A	B	C
Central and systemic hemodynamics: heart rate, min	63.2 ± 0.9**	154.3 ± 0.8	110.3 ± 1.1**
mean arterial pressure, mm Hg	75.2 ± 1.1**	134.5 ± 3.9*	111.2 ± 1.1*
stroke volume, ml	102.5 ± 0.7**	108.4 ± 5.0	104.2 ± 4.8*
specific peripheral vascular resistance, dyne s cm^{-5} m^2	1327.5 ± 172.3*	1641.1 ± 247.4**	2223.4 ± 116.3*
minute blood volume, ml/min	6.9 ± 0.2**	10.4 ± 1.2	10.8 ± 0.9
Physicochemical homeostasis and tissue respiration: blood pH, u	7.38 ± 0.008	7.34 ± 0.001**	7.30 ± 0.005**
buffer base shift, mmol/l	–4.6 ± 0.4**	–6.3 ± 0.3**	–7.4 ± 0.3**
degree of oxygen extraction in the tissues by $AVDO_2$, ml O_2/100 ml blood	6.6 ± 0.04*	6.7 ± 0.5*	6.1 ± 0.6*
General nonspecific adaptation reactions: leukocyte count, 1×10^9 in mm^3	4.2 ± 0.3**	4.4 ± 0.2**	4.5 ± 0.2**
lymphocyte content, %	28.3 ± 0.5**	26.1 ± 0.8**	24.4 ± 1.0**
coagulation time, min	3.8 ± 0.3**	4.5 ± 0.4**	3.2 ± 0.2**
fibrinolytic activity, %	13.7 ± 1.2**	11.6 ± 1.8**	9.5 ± 1.7**

Table 3. Features of the dynamics of superslow physiological processes (SSPP) in healthy individuals tolerant of physical fatigue at rest (A) and after two-step individual submaximal physical exercise before the first (B) and second refusal (C) ($M \pm m$)

SSPP variables	A	B	C
I. The Ω-potential sign and background values, mV	–32.6 ± 8.7*	–52.2 ± 0.9**	–22.7 ± 0.8**
II. Superslow potential fluctuations (ζ- and τ-waves)	7.8 ± 0.9*	13.9 ± 0.2*	5.2 ± 0.3*
III. SSPP entropy, u	1.6 ± 0.05**	2.2 ± 0.3**	2.3 ± 0.08**

Note: II. The number of ζ- and τ-waves during 8.3 min was calculated. III. To determine the degree of SSPP organization, entropy was calculated using Shannon's formula. The significance of intergroup differences: I. A–C, * $p < 0.05$; B–A, C, ** $p < 0.001$ (t-test); II. B–A, * $p < 0.05$; B–C, ** $p < 0.001$ (t-test); III. A–B, C, * $p < 0.05$ (t-test).

Table 4. Features of the dynamics of superslow physiological processes (SSPP) in easily fatigued individuals at rest (A) and after two-step individually submaximal physical exercise before the first (B) and second refusal (C) ($M \pm m$)

SSPP variables	A	B	C
I. The Ω-potential sign and background values, mV	–12.5 ± 1.7**	–11.4 ± 0.9**	–7.1 ± 0.8**
II. Superslow potential fluctuations (ζ- and τ-waves)	13.8 ± 0.8**	8.2 ± 0.3*	4.5 ± 0.8**
III. SSPP entropy, u	2.7 ± 0.08**	1.2 ± 0.8**	0.9 ± 0.1**

Note: The significance of intergroup differences: I. C–A, B, ** $p < 0.001$ (t-test); II. A–C, ** $p < 0.001$; A–B, * $p < 0.05$; B–C, * $p < 0.05$ (t-test); III. A–B, C, ** $p < 0.001$ (t-test).

Thus, significant differences were revealed in the values of central and systemic hemodynamics, physicochemical homeostasis, the level of oxygen consumption by the tissues as well as the values of general nonspecific adaptation reactivity of the body at rest in healthy individuals tolerant of physical stress and age-matched easily fatigued individuals. The balance of homeostatic and regulatory values studied in subjects tolerant of physical stress was comparable with physiological criteria of the optimal level of wakefulness, as evidenced by the omegametric data. The behavioral signs of asthenia with the characteristic features of systemic regulatory and homeostatic changes as well as with a decreased level of general nonspecific adaptation reactions of the body in easily fatigued individuals were comparable with a decreased level of wakefulness, light drowsiness, and sensory restriction as shown by SSPF.

The subjects of both groups revealed differences in the dynamics of duration of physical exercise performance at an individually comfortable rate to capacity under conditions of its repeated accomplishment at a 20–25-min interval. It was found that, in the individuals tolerant of physical exercise, the duration of their performance was 20–45 min. When the same type of stress exercise was performed a second time, the onset time of the second rejection was shortened to 18–25 min.

In the group of easily fatigued individuals, the first refusal to perform stress exercise at an individually comfortable rate was observed at 5–10 min, they refused the second stress exercise after 3–5 min.

Changes in the duration of exercise performance at an individually comfortable rate until the first and second rejection revealed in group I and group II subjects were regarded as the integral behavioral equivalents of the features of the compensatory–adaptive possibilities of the contingents of subjects examined under these conditions.

The main regularities of intra- and intersystem rearrangements under stressor exposure conditions were revealed in healthy individuals with the initially different regulatory and homeostatic control of the wakefulness level.

Systemic tension-type shifts of the compensatory–adaptive character occurred in the individuals tolerant of physical stress after the first refusal to work (Table 1B). Thus, an increased consumption of oxygen by the tissues and a marked hyperdynamic type of blood circulation associated with decreased total peripheral resistance reflected the adequacy of hemodynamic and oxygen-transport compensation of oxygen debt and lactic acidosis under these conditions [27]. The systemic compensatory–adaptive tension-like shifts described above manifested themselves at the behavioral level by the occurrence of subjective sensations of internal tension, accelerated respiration (dyspnea), and palpitations. Within SSPP parameters, this was reflected in an increased negativity of the initially optimal background ω-potential values (up to –52.2 ± 0.9 mV) and markedly increased regular SSPF of the predominantly second range (Table 3B).

In quickly fatigued individuals under conditions of the first refusal to perform stress exercise at an individually comfortable rate, the signs of imbalance of systemic compensatory–adaptive reactions appeared in parallel with deterioration of the signs of asthenization (increased general fatigue and headaches) (Table 2B). This was reflected in the onset of vasoconstriction with an insignificant increase in the initially high stroke volume of the heart and minute blood volume against the background of severe arterial hypertension and tachycardia (Table 2B). After the first refusal to perform physical exercise, this group revealed the signs of transient respiratory and circulatory hypoxia and transient acidosis (decreased pH and an increased deficiency of buffer bases). An increase in hypercoagulation and suppression of the blood fibrinolytic activity indirectly indicated a functional deficit of the hypophyseoadrenocortical system (Table 2B). The restriction of hemodynamic and oxygen-transport compensation of lactic acidosis and oxygen debt occurred in untrained or asthenic healthy individuals even after brief physical exercise [27].

According to the SSPP data, after the first rejection of exercise performance, quickly fatigued individuals retained low negative ω-potential values (–11.4 ± 0.9 mV), which was the physiological equivalent of retaining low-level wakefulness, a substantial decrease in the severity and regularity of SSPF of the ζ- and τ-range being observed, which showed that the mechanisms of compensation of metabolic and regulatory disorders deteriorated under these conditions (Table 4B).

Table 5. Characteristic of the states of rest, physical tension, and fatigue according to the data of superslow physiological processes in healthy individuals tolerant of physical load ($M \pm m$)

Functional states	Superslow physiological processes		Subjective appraisal of the state	Features of regulatory and homeostatic control
	Ω-potential, mV	SSPF***		
Rest	−32.6 ± 8.7*	7.8 ± 0.9*	Normal state, good well-being	Balance of the values of central and systemic hemodynamics, physicochemical homeostasis, external and tissue respiration, and nonspecific adaptation reactions
Physical tension	−52.2 ± 0.9**	13.9 ± 0.2*	Sensation of mental tension, dyspnea	Sympathoadrenal pattern of the cardiovascular and respiratory system reactions, appearance of signs of the hyperdynamic type of blood circulation, dynamic arterial hypertension, a marked increase in oxygen consumption by the tissues
Fatigue	−22.7 ± 0.8**	5.2 ± 0.3*	Sensation of fatigue	Shortening of the performance time of an individually submaximal physical exercise to capacity to 18–25 min, with the sympathoadrenal pattern of the cardiovascular and respiratory system reactions being retained and their severity being ameliorated. An increased oxygen consumption by the tissues is retained, the appearance of slightly marked signs of metabolic acidosis is observed

Note: Here and in Table 6, SSPF denotes superslow potential fluctuations,(*** the number of ζ- and τ-waves during 8.3 min). The significance of intergroup differences * $p < 0.05$; ** $p < 0.001$ (t-test).

The features of changes in the systemic and integral values of the state of group II subjects were comparable with the results of clinical and physiological studies of patients with asthenoautonomic disorders [28]. In other words, the regulatory and homeostatic changes revealed after exercise performance at an individually comfortable rate until the first refusal in easily fatigued individuals were equivalent to clinical and physiological manifestations of asthenoautonomic disorders at the systemic and bodily level. This was confirmed by the deterioration of systemic regulatory disorders after repeated exercise performance until the second refusal manifested itself by the appearance of signs of decompensated metabolic acidosis under respiratory and circulatory hypoxia and increased vasoconstriction conditions (Table 2C).

According to the literature data, these systemic shifts occur due to insufficient oxygen transport and hemodynamic compensation of oxygen debt and lactacidemia [27].

According to SSPP data, a more markedly pronounced decrease in the level of wakefulness comparable with deterioration of the asthenia signs and the onset of drowsiness was discovered (Table 4C), the disappearance of SSPF of the ζ- and τ-range being a physiological index of the areactivity of the mechanisms of compensation of metabolic and regulatory disorders under these conditions.

In the individuals tolerant of physical fatigue, repeated performance of physical exercise to capacity at an individually comfortable rate did not substantially change the pattern of autonomic control of cardiovascular reactions except for their mild attenuation (Table 1C). In this case, an increased oxygen consumption by the tissues in the hyperdynamic type of circulation was retained. However, an increased deficiency of buffer bases and the appearance of insignificant shifts in the blood pH toward a decrease indicated the appearance of mild signs of metabolic acidosis under these conditions (Table 1C). According to the SSPP data, a decrease in the level of wakefulness comparable with an intensified subjective feeling of fatigue was revealed under the same conditions (Table 3C).

Less markedly pronounced SSPF of the second and decasecond range in the same subjects gave evidence of the compensatory mechanisms of metabolic and regulatory changes tending to be impaired under these conditions (Table 3C).

Generalization of the study results allowed us to reveal statistically significant differences in the relationships between the integral values of the wakefulness level (according to the data of SSPP dynamics) and the systemic regulatory and homeostatic values of the present functional state of young healthy individuals tolerant of physical load and easily fatigued.

The regularities revealed allowed the differences in regulatory and homeostatic control to be physiologically substantiated: (a) the optimal level of wakefulness at rest in healthy individuals tolerant of physical stress, (b) the state of physical tension in the same individuals, and (c) the state of fatigue in the same group of individuals (Table 5).

To expand the notions of the pathophysiological basis of asthenic states, the discovery of regular relations between the integral values of a decreased level of wakefulness (based on SSPP data) and the individual and typological features of systemic regulatory and homeostatic disorders in easily fatigued individuals at rest

Table 6. Physiological equivalents of asthenic states of different degree of severity with their inherent regulatory and homeostatic disorders in easily fatigued individuals at rest and after two-step physical exercise to capacity ($M \pm m$)

Functional states	Superslow physiological processes		Subjective appraisal of the state	Features of regulatory and homeostatic control
	Ω-potential, mV	SSPF***		
Asthenic state	−12.5 ± 1.7*	13.8 ± 0.8**	Complaints of general malaise, low mood, sensation of palpitations, periodic headaches triggered, as a rule, by physical and mental stress	Signs of neurocirculatory dystonia, hyperhydrosis of the extremities. Hyperdynamic type of blood circulation under arterial hypotension and increased oxygen consumption by the tissue conditions, signs of acidosis, impairment of general nonspecific reactions
Progression of asthenia	−11.4 ± 0.9**	8.2 ± 0.3*	Increased fatigue and more severe headaches	Signs of imbalance of compensatory–adaptive reactions. The appearance of vasoconstriction with an insignificant increase in the initially high stroke volume of the heart and minute blood volume against the background of markedly pronounced arterial hypertension and tachycardia. Signs of transient respiratory hypoxia and transient metabolic acidosis (decreased pH and an increased deficiency of buffer bases)
Astheno-autonomic syndrome	−7.1 ± 0.8**	Virtually absent	The feeling of feebleness, drowsiness, weakness, more severe headaches	Signs of decompensated metabolic acidosis under respiratory and circulatory hypoxia conditions, increased vasoconstriction and the appearance of the initial signs of heart failure associated with physical load

before physical load is of great importance (Table 6). Two-step physical exercise performed to capacity at an individually comfortable rate in easily fatigued individuals allowed us to trace progression of asthenization (according to SSPP data), an impairment of compensation processes associated with systemic disorders characteristic of the asthenoautonomic syndrome (Table 6). In our opinion, the results of these investigations are of fundamental importance in terms of theoretical substantiation of extending the use of superslow physiological processes for express diagnosis of functional states in young individuals at risk for neuroses and neurosis-like diseases.

CONCLUSION

(1) A complex approach was developed to the study of the physiological mechanisms of individual and typological features of functional states and tolerance of physical load in young healthy individuals with the use of superslow physiological processes as an integral parameter of the level of wakefulness.

(2) Statistically significant differences were revealed in the values of central and systemic hemodynamics, external and tissue respiration, physicochemical homeostasis, the level of oxygen consumption by the tissues, and general nonspecific adaptation reactions of the body correlating with differences in the integral values of the level of wakefulness, as evidenced by SSPF, in healthy young individuals tolerant of physical fatigue and easily fatigued individuals at rest and after two-step individually submaximal physical exercise performed to capacity.

(3) Based on the approach developed, the parameters of the optimal level of wakefulness at rest, the state of physical tension, and the state of fatigue with the features of their regulatory and homeostatic control were determined in young healthy individuals tolerant of physical stress, as evidenced by SSPF data.

(4) Based on the results of complex investigations, the physiological equivalents of (a) the asthenic state with a decreased level of wakefulness and inherent regulatory and homeostatic disorders at rest and (b) progression of asthenization with compromised compensatory processes and more markedly pronounced symptoms of asthenoautonomic disorders after the two-step individually submaximal physical exercise to capacity were determined.

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