Biological age and vegetative regulation of heart rhythm in 8-year-old children residing in the European North of Russia

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Abstract. The second period of childhood is a crucial stage of ontogenesis which is characterized by the intensive morphofunctional development in the body. When children start school, the regulatory mechanisms for controlling visceral functions are still developing, under the influence of which adaptive responses to ambient factors form themselves. Parameters of physical development are reliable markers of adaptive processes. The functional state in children living in the European North of Russia at this age period is influenced by a combined set of specific ecological-climatic conditions and school-related stress exposure. The long-term studies undertaken by domestic and foreign research teams have so far focused on the effect of this complex set of factors on the morphofunctional development in children, targeting to determine the mechanisms for maintaining physical and mental health in schoolchildren. In this regard to the foreground comes the need of improving school environment in order to increase academic performance and reduce the increasing rates of stress, disadaptation and decompensation of physiological functions in children.

1. Introduction

The primary school period falls on one of the most important, crucial stages of human ontogenesis. It is known that the “tension” in puberty period and further life directly depends on the degree of well-being during the second childhood period. The junior school age is characterized by sharp morphological and functional reorganizations in the body, which put additional pressure on the physiological systems responsible for adaptation to ambient conditions. One of the criteria for childhood health, at the present stage of physiology, medicine and auxology, is the optimal level of achieved development (morphological, physical, mental, intellectual etc.) and the degree to which it corresponds to chronological age. In today’s ecological and social conditions, the number of retarded children and children with various deviations in morphofunctional and psychophysiological development increases [1,2]. According to the Academy of Medical Sciences’ National Medical Research Center for Children’s Health, about 90% of children have certain deviations in their health status, 30%-35% of children starting school have chronic diseases. The results of a number of studies indicate various deviations in maturation and functioning of mental sphere in junior schoolchildren [3].

The specific environment of the North (natural, anthropogenic, social) impose increased demands on physiological and mental systems in children, largely affecting the rate of morphofunctional maturation and causing delays in the development of certain systems or pathological deviations in physical and mental development [4]. The studies started as early as Rappoport’s (1979) show that
maturity indicators in children of the North are lagging the average of 1.5-2 years behind those of children in Central Russia. Therefore, the biological age of children of the North often does not coincide with chronological age.

It is known that well-performing adaptation mechanisms rely well-coordinated nervous, humoral, and information perception systems responsible for homeostasis and adaptive reactions. Each period of ontogenesis is characterized by specific neuroendocrine relationships ensuring reliability of physiological functions. Change in heart rate, according to R.M. Baevsky, is a holistic reaction of the body in response to external or internal effects, reflecting the result of numerous regulatory influences [5]. It has been found that the tension in physiological system in response to the excessive school load manifests itself in the increased sympathetic tonus and degree of rhythm centralization, whereas the completion of the adaptation process is marked by an increase in the number of children with vagotonic type nervous system. The studies undertaken by domestic and overseas researchers have shown the relationship between the level of heart rate centralization and the state of sympatho-adrenal and pituitary-adrenal systems, serving as a criterion for assessing adaptation levels in the body, especially in growing one. In children of younger school age, there are two periods of formation of the regulatory mechanisms of the autonomic nervous system: 1) 7-8 years, marked by sympathotonia and increased bioelectric and metabolic activity of the myocardium, 2) 9-10 years, marked by the growth of vagotonic influences and decrease in electrical and energy activity of the heart. Adaptation to learning process and physical stress results in restructured functions and transition to a new level of regulation; increased tolerance towards ambient factors; and actively responding cardiovascular system. The autoregulation of cerebral blood flow, which ensures adequate blood supply to the nervous tissue, depends on the initial tone of the arteries, which, in turn, depends on neurovegetative influences. With an increase in the intensity and duration of cognitive load, the efficiency of cerebral autoregulation decreases, resulting in passive peripheral blood flow increasing passively in response to changes in systemic hemodynamics [6]. It has been demonstrated that learning activity can have a negative impact on the child’s body, causing shifts in the state of neurohumoral regulation. At the initial stage of schooling, there is an imbalance in the vegetative regulation of rhythm, with sympathotonic effects prevailing. In children with high tonus in sympathetic nervous system, high level of norepinephrine excretion was detected, the adrenaline excretion being 1.5-2 times higher in ‘vagotonics’ than in ‘non-vagotonics’. More favorable dynamics in response to static load is observed in metabolic shifts of catecholamines and precursors. The least optimal reactivity of the sympatho-adrenal system was found in sympathotonic children showing compensatory system tension. The direction of the vegetative shift under load is determined by the background level of activity, which was not found in this study in children with sympathotonic regulation. The age-related changes in spectral power occurring after exposure to mental loads demonstrate a “delayed response”, expressed in incomplete restoration of the heart rate to the previous (background) level. In younger school age, significant changes in hemodynamics occur, which are associated with changes in the morphology of the heart and blood vessels. Some specific features of cardiovascular system performance in junior schoolchildren living in the European North have been found. They include high diastolic and medium dynamic pressure; low myocardial contractile activity; and increased tonus in peripheral vessels with low intensity of blood flow in them. At the same time, the actual pressure in the pulmonary artery does not differ in children living in the North and children from those in other regions of Russia [7]. The control over peripheral vasomotor baroreflex mechanisms belongs mainly to the sympathetic nervous system, which predominates in cardiac rhythm modulation at the beginning of primary school age, which explains the heterogeneity of data on blood pressure variability. In general, school environment has a de-adaptational effect associated with adverse impacts on the child’s body systems. The period of the second childhood among schoolchildren living in the European north of Russia is characterized by the combined effect of adverse climatic and ecological conditions, complemented by the specific set of factors relating to school environment.

2. Materials and methods
The study covered 8-year-old first-grade students in the city of Arkhangelsk and its municipalities – Pinega, Mezen and Onega – a total of 467 children (230 girls and 237 boys). The experiment was conducted in accordance with the ethical standards, represented in Helsinki Declaration and European Community directives (8/609 EC). Based on the tasks, the study was carried out in three stages:

a. Evaluation of biological maturity in children according to morphological criteria (body length, school maturity indicator, Philippine test, dental maturity, hand type, development option index). Body types were determined by method of V.G. Stefko and A.D. Ostrovsky.

b. Evaluation of children's biological maturity based on functional criteria (hand dynamometry, hemodynamic parameters (heart rate and blood pressure, heart rate variability)). The parameters were calculated by standard formulas for per minute blood flow volume and blood circulation index.

c. Evaluation of psychophysiological maturity (mental performance and concentration, level of development of visual perception, functional maturity of cerebral cortex).

Two-minute recordings were made on hardware-software facility "VNS-spectrum" (Neurosoft, Russia). Cardiac rhythm was recorded at rest (sitting position) and during two functional tests – orthostatic (transition from semi-vertical to vertical position) and cognitive (mathematical calculation). The results were processed in accordance with the international recommendations of The North American Society of Pacing and Electrophysiology (1996) [5].

Statistical data analysis was performed using SPSS for Windows 17.0 and included descriptive statistics (test for distribution normality); ANOVA tests to determine the statistical significance of differences; linear regression analysis under General Linear Model; correlation (Kendall) and factor analyses with varimax rotation. Statistically significant range was p <0.05.

3. Results and discussion

The study of the rate of biological maturation in children shows that the majority of Arkhangelsk first-graders of both sexes correspond, according to morphological criteria, to age-specific standards. However, in 7.92% to 22.91% of children the rate of morphological maturation was found to be below the age norm according to various criteria. This correlates with the studies of other authors, who note a decrease in morphometric parameters, a delay in somatic maturity and delayed development of morphofunctional systems in northern children [8,9]. The body type represents a set of stable morphofunctional features that are formed under the influence of genotype and modified by habitat.

The most proportional, i.e. corresponding to the reaction norm, is the muscular somatotype, which does not always dominate in the population [10]. Thoracic and muscular somatotype, which are dominant in the sample, are likely to be the ones that provide optimal adaptation to environmental influences in the North. The balanced morphological development is one of the most important criteria for the normal course of physical development, which is associated primarily with the shape and size of the body, as well as bodily proportions. Recently, there has been a frequent occurrence of cases of disharmonious development, expressed in musculoskeletal system developing disproportionately to the length of body, a process known as asthenization of younger schoolchildren. The level of balanced development varies in somatotypes, with the high proportion of disharmoniously developing children found in digestive somatotype. They account for 81.8%–91.3%. A consistently high proportion harmonious morphological development is noted in children of thoracic somatotype.

The study has revealed the features of morphological maturation rate in first-graders, according to various indicators. Thus, in terms of body length, it was found that 44.97 ± 2.31% of children are above the age norm. The studies by a number of authors have shown that the accelerated rate of body length formation leads to disbalanced physical development, accompanied by strain in all the processes occurring in the body and health impairments [11,12]. According to the results of the Philippine test, 19.92 ± 1.85% of children have the rate of morphological maturation below the age norm; we have not observed any cases of advanced morphological maturation. Children with negative Philippine test result experience the greatest morphofunctional stress, which can lead to a decrease in their performance. In terms of dental maturity, which demonstrates the degree of maturation of
childhood skeletal system during critical periods, a significant number of first-grade students (45.82 ± 2.27%) have the rate of morphological maturation below the age norm, which is a marker of poor health [13]. The results of our research objectively confirm, based on dental maturity analysis, the existence of delays in somatic maturity in children living in the circumpolar region [14]. The study has shown that the ulnar type of hand and the slow-paced development (in terms of IVR) among children in the circumpolar region is observed quite often (19.49 ± 2.50% and 22.91 ± 1.95%, respectively). This correlates with the data from a number of authors on lesser maturity degree in children with such features [15,16].

Our analysis of the rate of maturation in first-graders, according to functional criteria, indicates that the majority of the children surveyed do comply with age standards in terms of hemodynamic parameters. Yet, 22.48 ± 1.93% of children have heart rate above the age norm, which leads to functional stress in cardiac muscle performance, limiting the compensatory abilities of the body [17]. Tachycardia is an adaptive reaction of the circulatory system to the increased needs for oxygen, contributing to increased blood supply to organs and tissues. In addition, tachycardia indicates the intense activity of sympathetic division of autonomic nervous system and tension in the regulation of circulatory system [18]. It has been found that among children of the circumpolar region, lower values of systolic pressure (33.83 ± 2.19%) and increased values of diastolic pressure (20.98 ± 1.88%) are more common. Lower systolic pressure leads to a lack of oxygen in the tissues of the body and a drop in the intensity of metabolic processes in them, which may indicate a slowdown in biological maturation [19]. Increased diastolic blood pressure can be caused by the influence of local photoperiodicity [7], as well as adverse anthropogenic factors, which include exposure to school-related stress [20].

Based on the results of ANS reactivity in our orthostatic test, the participants were divided into 2 adaptation groups (group 1 with satisfactory adaptation reserve, and group 2 with unsatisfactory one). The distribution of children among adaptation groups according to somatotypes turned out to be unequal. A high proportion of students with unsatisfactory adaptation reserve were observed in groups of boys of digestive and thoracic types, where there is 1.5–1.6 times more of children with unsatisfactory adaptation reserve. In girls, the risk group was asthenic body type, where tension in adaptive mechanisms was recorded 1.8 times higher than in girls with satisfactory levels of adaptation. Using the linear regression method, it was revealed that the type of body does not have any pronounced effect on HRV parameters, which is confirmed by the results of our correlation analysis. However, the one-dimensional analysis of variance confirmed some of the differences between the variability of R-R time series and the body type. Based on these data, we can conclude that girls of thoracic somatotype constitute risk group, running a higher risk of maladaptation to school environment. For example, mental arithmetic in some of the girls in this group caused centralization index (IC) to increase 4.78 times, compared with the background IC. The intra-group HRV analysis also showed that the risk group includes children of digestive somatotype (reduced KVS functionality, reduced variability of R-R series, high background IC), but the adverse changes are not aggravated in the state of mental stress in them, unlike in girls of thoracic type. The dispersion analysis of muscular somatotype group has identified particular statistical gender differences in HRV and hemodynamic parameters. Note that the functional state of this group of children can be considered meeting the nosological norm. The predominant type of hemodynamics is hyperkinetic: blood circulation index in girls is 17.7% higher than in boys (p <0.01). Diastolic pressure in boys is 9.6% higher, and the magnitude of IC is 9% lower than in girls (p <0.05). At similar values of initial vegetative background (LF / HF = 0.78), boys and girls show different ANS reactivity in orthostat. In boys, there is a 2.09 times increase in LF/HF frequency ratio, whereas in girls it is only 1.82 times (p <0.05). In the course of cognitive activity, regardless of gender, a number of common reactions has been noted – decreased R-R range variability and total spectral power (TP); increased sympathotonic activity; decreased vagal control; increased Amo, heart rate; and decreased Mo. However, there are also differences in HRV indicators noted during the exposure to cognitive activity. In particular, girls react to the process of counting with a sharper decrease in TP – 1.45 times lower than boys. In boys, sympathotonia (LF,%)
in the process of cognitive activity is more pronounced - 18.4% relative to the background, compared to 7.4% in girls (p <0.05). In the process of counting, some children show moderate tachycardia (up to 107 beats/min); cardiac rate increases in girls occurs by 5%, in boys only by 2.3% (p <0.001). The integrative indicator characterizing tension in regulatory mechanisms is IC. The analysis shows that girls of muscular somatotype experience a significantly greater stress in adaptation mechanisms (IC = 1.47 ± 0.96) than boys (IC = 1.24 ± 0.64). The correlation analysis has revealed a significant dependence of IC during mental arithmetic on the initial vegetative status in girls (R = 0.72, p <0.01); no such dynamics was observed in boys. It has been revealed that in a significant number of first-graders the strength of right hand muscles is lower than the age standards, while the strength in muscles of the left hand is reduced in more than half of the children. A significant number of children with reduced dynamometry of the hands reflects a delay in maturation of musculoskeletal system in children living in the North, which characterizes the reduction in their nonspecific resistance.

The analysis of the rate of psychophysiological maturation in first-graders of Arkhangelsk region indicates delays in the formation of the psychophysiological functions under study. Thus, half of the first-graders surveyed have low-speed indicators of mental activity, more than half of the children show less accuracy mental performance. It should be noted that children with low initial level of performance tend to get tired more quickly, even from simple and short assignments, experiencing greater difficulty adapting to regular learning.

Similar results were found when assessing levels of visual perception. In 37.31 ± 2.27% of the examined children, the rate of maturity of visual perception corresponds to the age norm. This indicates that, despite progressive development, the system of perception in first-graders has not yet reached level of maturity high enough to ensure uninterrupted functioning [1].

The final stage of our study targeted the relationship between parameters of morphofunctional and psychophysiological maturity and their hierarchy in children (Figures 1 and 2).

**Figure 1**: Structural correlation of biological maturity indicators in first-grade students.

DM - dental maturity, TH – type of hand, BL – body length, ID – indicator of developmental variant, ISM – indicator of school maturity, PT – Philippine test, PLH – power of the left hand, PRH – power of the right hand, HR – heart rate, DBP – diastolic blood pressure, SBP – systolic blood pressure, RMP – rate of mental performance, C – concentration, VP – visual perception.
The analysis of the structural correlation among the indicators of biological maturity enables a conclusion that the transformations occurring in the system responsible for biological maturity among 8-year-old first-graders of different sexes are directed differently (Figure 2). Thus, in boys, the most intense re-adjustments target the morphological substrate of biological maturation, while in girls they occur already at the functional and psychophysiological levels. This conclusion agrees with the commonly recognized opinion that girls at this age show higher levels of psychophysiological maturation [4], while boys have a more intense morphological maturation. The results of our factor analysis testify to similarity of factor models for ensuring biological maturity in children of different sexes: the general factor is dynamometric, the factor 2 is mainly hemodynamic, and the factor 3 is morphological.

This indicates that there is a common tendency for the maturation processes in the child's body to follow (Figure 1). The inclusion into the presented system of the parameters of psychophysiological maturity confirms the opinion about the specific nature of cognitive functions in boys and girls. In girls, the indicator of attention concentration is more important, and in boys - visual perception. These
data correspond with the opinion of a number of researchers that at the age of 7 girls outperform boys in intellectual development, while boys have more developed age-specific visual-spatial abilities [4,20].

4. Conclusion

The rates of biological maturation in first-grade students living in the circumpolar region correspond to age standards for most of the parameters studied. The largest number of mature children was found in terms of school maturity, developmental variant index, Philippine test, heart rate, diastolic blood pressure and attention concentration. Girls of thoracic somatotype are identified as a risk group in terms of acute maladjustment to school setting. Data analysis has revealed the absence of any significant relationship between HRV indicators and the type of body at this stage of ontogenesis. A close relationship was found between these indicators and the overall level of adaptation, and the predominant influence of ANS.

The system-forming complexes – morphological, dynamometric and hemodynamic – have been identified in the structure of biological maturity indicators in all children. In a significant proportion of children, the largest degree of dispersion belongs to dynamometric complex. The overall biological maturity of children at this age is marked by low performance of psychophysiological maturation parameters.

The analysis of sex differences showed the diversity and heterogeneity of the maturation process in girls and boys. While girls show greater degree of maturity in terms of tooth age, strength in left hand muscles, and systolic blood pressure, boys in terms of visual perception.

The structural correlation found among the indicators of biological maturity, as well as the results of factor analysis, have shown that in boys the most intense re-adjustments target the morphological substrate of biological maturation, while in girls they take place at the functional and psychophysiological levels.

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