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Theory of Functional Systems in the Scientific School of P.K. Anokhin

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In this paper we present brief biographical data of the outstanding Russian physiologist P.K. Anokhin and the stages of formation of the theory of functional systems, proposed by him. Furthermore we will deal with the architectonics of system organization of behavioral acts, underlying principles of the theory of functional systems as a part of the general theory of systems and the evolution of the theory of functional systems in the Anokhin Scientific School.

Keywords P.K. Anokhin, functional system theory, systemogenesis, systemoquantum, holographic principle, scientific school

Pyotr Kuzmich Anokhin (1898–1974) one of I.P. Pavlov's pupils may be considered an outstanding Russian physiologist.[1] On the grounds of a creative development of scientific ideas of his predecessors I.M. Sechenov, I.P. Pavlov, and A.A. Ukhtomsky, he formulated an original theory of functional systems, which as a matter of fact laid the foundation of a new integrative physiology and medicine. The necessity of an integrative approach in physiology was persistently proclaimed only in recent years beginning at the 32nd Congress of International Union of Physiological Sciences (IUPS), Glasgow 1993.

The theory of functional systems allowed regarding behavior, organization of visceral functions, and brain activity of humans and animals in quite a new way.

Anokhin belonged to an extraordinary galaxy of scientists who on an apt remark of Hans Selye was "discoverer of problems," revealing new tendencies in science by intuition. He was a man of wide scientific interests and great erudition. He felt himself quite confident in many different domains of science, literature, and art. He can be put, by right, in a rank of outstanding scientists of encyclopedic knowledge.

In his plenary lecture at the Congress of the IUPS in New Delhi in 1974, Professor Samuel Corson from the United States declared that Anokhin was by right the founder of physiological cybernetics.

[1]At the end of his career he was academic of the USSR Academy of Medical sciences (1945) and the Academy of Science (1966), professor, the Knight of the I.P. Pavlov Gold Medal of the USSR Academy of Science (1968), Laureate of the Lenin Prize (1972). Furthermore he was Member of the Hungarian Academy of Science, Honorary Doctor of Leipzig and Budapest Universities; Honorary member of Czechoslovakian Ja. Purkinje Medical Society, Member of International Brain Research Organization (IBRO), Corresponding Member of International Society of biological psychiatry, Member of American National Pavlovian Society, and Member of American Geographic National Society.

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The Road to Science

Anokhin was born in Tzaritzin (Stalingrad, now Volgograd). The father of the scientist to be, a kozak from Don, came to Tzaritzin to work as a laborer at the railway station. His mother from Penza Province, an amiable person, liked all kinds of merriments and songs. As a grader and then a scholar of a land-surveyor-agricultural college, Pyotr Anokhin was keen on mathematics and philosophy, literature, and music.

In 1918–1921 he took an active part in establishing a soviet regime on the Don: he was a soldier of a Don-Stavropol partisan division, participated in the defense of Tzaritzin and was an inspector of fortification of the defense headquarters of the town. In 1920 he was appointed Commissar of Press of the Don region, Head of the Press Center in Novocherkassk and subsequently Editor-in-Chief of the newspaper *The Red Don*.

However, the interest in natural sciences, a keen desire to understand the sense of the coming and developing events and to comprehend the motives and behavior of the fellows fighting side by side, made him seriously think about "inward springs" driving human's behavior. So his interest in the study of human brain and philosophy was aroused.

However, as he confessed, he badly felt the lack of thorough knowledge. On his request he was sent to Leningrad (now St. Petersburg) to the Institute of Medical Sciences, at that time headed by V.M. Bekhterev, the famous Russian neurologist and psychiatrist. Anokhin started his research work under the guidance of Bekhterev from the first semester. As Anokhin admitted later, Bekhterev was the first great scientist he met on his way to science who determined his future course of life. By his ingenious pedagogical insight, Bekhterev linked the young scientist to the problem of brain research forever. But after a year Anokhin realized that, as he himself recalled, "my road did not lie in the range of psychiatry where as it seemed to me that there were a lot of wordy, obscure, and simply helpless ideas with regard to the understanding of psychosis. I was more interested in experiments on animals' brain." The work at the neurological clinic did not satisfy the searching mind of the youngster anymore and he exchanged the clinic for the laboratory of I.P. Pavlov.

As a student he was greatly impressed by Pavlov's lectures at the Medico-surgical Academy in 1922. It was in that year that Anokhin and Pavlov met (Fig. 1). From that time, Anokhin participated in very difficult, "damned" experiments, as Pavlov called them, on the mechanisms of internal inhibition and development of conditioned reflex. Anokhin ardently began to investigate conditioned reflexes. However, very soon he was unsatisfied with the approach to the study of higher nervous activity when an animal's response of the salivary glands provoked by external (conditioned) stimuli was studied. At that time the intimate mechanisms of the brain remained unclear. Anokhin continued to research the internal mechanisms of the brain determining behavior and psychic activity of humans and animals. In 1930, at the recommendation of Pavlov, he was elected Head of the Department of Physiology of Medical faculty at the University of Nizhny Novgorod where his original understanding of physiological processes began to take shape. First of all he studied in depth the role of the periphery in the formation of brain functions.

The Discovery of Functional Systems

To reveal the role of afferentation ascending to the brain from the periphery, a method of heterogenic anastomosis of nerves was used (Anokhin, 1935). The method of heterogenic anastomosis consisted of a section of nerve trunks followed by suturing the proximal end of the nerve to the distal end of another sectioned nerve. As a result, neurofibrils of the

Figure 1. In Pavlov's laboratory: Anokhin on the left and Pavlov on the right side.

proximal nerve grew through the other distal nerve; in the periphery, afferent fibers made new contacts with inadequate sensory receptors and efferent fibers established functional contacts with muscle, glandular, or nerve tissue inadequate for the corresponding nerve center. As a consequence, a peculiar experimental "chimeras" appeared in which, by irritation of peripheral receptors, inadequate reactions for the previously linked nerve center could originate and at the same time inadequate efferent reactions with respect to the former nerve center could be observed in animals.

Anastomosis of the proximal end of the right vagus nerve (VN), cut on the neck, was studied in more detail in Anokhin's lab. These experiments and some other made Anokhin pay special attention to the decisive role of afferentation coming from the periphery in the recovery of nerve center functions. In the 1930s, on the basis of these experiments, Anokhin formulated the notion of a "functional system." In a preface to the monograph *Problem of Center and Periphery in Physiology of Nervous Activity* (1935), Anokhin presented his first definition of a functional system:

> Under functional system we understand a range of definite physiological acts related to a certain function (act of respiration, act of swallowing, locomotor act, etc.). Every functional system, being to a certain extent a closed system, exists due to a permanent connection with peripheral organs and, in particular, with permanent afferentation from these organs. We think that every functional system has a definite complex of afferent signals which directs and corrects the realization of that function.

Later on Anokhin defined the functional systems as dynamic, autoregulating organizations all components of which harmoniously interact and cooperate in achieving adaptive results, useful for the system itself and for the organism as a whole (Anokhin, 1974a). In functional systems Anokhin distinctly underlined a leading "creative" role of afferentation coming from peripheral organs — *an action result* — to relevant nerve centers. Anokhin called that afferentation "reverse afferentation." So the notion "reverse afferentation" was

Figure 2. N. Winner and P. Anokhin in Moscow (1961).

introduced into science 12 years before the Norbert Winner's idea of feedback (Fig. 2). In the structure of functional systems a leading role was attributed to afferentation from the peripheral organs. Anokhin's conception of functional systems furthered the study of brain functions from a new position.

Reflex Theory: Action and Result

For more than 300 years, from the times of René Descartes, physiology has based its theoretical conceptions on the widely spread reflex principle. The Russian scientists I.M. Sechenov and Pavlov were among the persons who disseminated the reflex principle in brain functions and in human and animal psychic activity. In his famous monograph *The Reflexes of the Brain* Ivan Sechenov wrote: "All acts of conscious and unconscious life by its origin are reflexes" (Sechenov, 1947). According to Sechenov the nature of even psychic reflexes begins with a sensory stimulation, continues with a definite psychic act and ends with a muscle contraction. The well-known theory of conditioned reflexes created by Ivan Pavlov became a new landmark in the objective investigation of the processes of higher nervous activity. However, in the formation and manifestation of conditioned reflexes the leading role as usual belonged to external stimuli.

In the framework of a reflex theory new conceptions about system organization of physiological functions have come to the fore. Pavlov's concept of the dynamic stereotype was the first step in the formation of a general system conception in brain activity (Pavlov, 1951). In the last years of his life, Pavlov was interested in the investigations of the higher nervous system of ape-anthropoids. He closely investigated the activity of such animals,

aimed at the active alteration of their environment and processes of mastering different instruments to satisfy their main needs. Pavlov was absolutely right to note that "this activity can not be called a conditioned reflex." He talked about the "catching of relations of things by animals" (Pavlov, 1949), however, the nature of these phenomena was not discovered in Pavlov's laboratory.

Problems that remained unsolved in Pavlov's laboratory have been elucidated from the point of view of the theory of functional systems. This theory, proposed by Anokhin, may be considered a historical continuation of scientific ideas in the Pavlov school, in particular, the ideas related to the studies of higher nervous system of humans and animals. According to Anokhin's concept, the result of action of any functional system is of vital importance for adaptation of the organism providing its normal biological functioning (Anokhin, 1935). Another source for the theory of functional systems was the Theory of Dominanta of A.A. Ukhtomsky 1925).[2] It postulates that the internal state of a man or an animal (a dominanta) can act as a basis of behavior that determines an active attitude of animals to external stimuli.

Brain as a System Organization

Most of all Anokhin was interested in the system organization of brain functions. The young Anokhin became attracted to the "synthetic" line in Pavlov's scientific work. This was Pavlov's striving in the last years of his life, i.e., to understand and to discover synthetic processes of higher nervous activity such as the dynamic stereotype mentioned above, types of higher nervous activity and its characteristics. While in Nizhny Novgorod, Anokhin proposed an original modification of the classic method of conditioned reflexes: in addition to a secretory, a motor component of a conditioned reflex was taken into consideration. Hereby, the animal was under the condition of active choice (method of active choice) on the side of reinforcement on the stand with two feeders on opposite sides. On the one hand the method allowed one to preserve the varied possibilities of analysis presented in Pavlov's method of conditioned reflexes, and on the other hand, made it possible to introduce elements of *a behavior as a whole* into the experiments so that the animal under the condition of active motor behavior had the choice of one or the other feeder (Anokhin, 1949a). These investigations underlined Anokhin's concept about afferent synthesis, as the initial stage of system organization of behavioral acts. The findings about cerebral systems architectonics of behavioral acts were fundamentally extended by Anokhin and his team of scientists at the Institute of Experimental Medicine in Moscow to which he moved in 1935.

A multiple analysis of effector acts led Anokhin to the discovery of a very important new quality of brain functions, i.e., anticipation of future events. He demonstrated a very important characteristic of brain function, notably the ability to predict the main afferent features of the future action result. It allowed him to formulate the concept of a specific apparatus on which the properties of reinforcement are imprinted and that permanently estimates the parameters of practically achieved results by reverse afferentation. He called the apparatus acceptor of action results.

[2]A.A. Ukhtomsky (1875– 1942) — one of the most prominent Russian scientists and thinkers of the twentieth century. His theory of dominanta (as a universal biological principle that determines activity of all living systems) has influenced the whole range of modern studies and still attracts attention of specialists from different scientific disciplines. The theory of dominanta allows one to study physiological, as well as psychological and social processes. In general Ukhtomsky invented a concept of the human being at the crossover of different scientific disciplines — physiology, psychology, philosophy, sociology, and ethics.

The theory of functional systems regarding goal-directed behavior acts as a system dynamic organization. Therefore all functional systems, irrespective of the level of organization, have the same functional architectonics, where the result is a leading factor in a stable organization of systems. Operational architectonics of a functional system include the following mechanisms (Fig 3):

1. A stage of afferent synthesis.
2. A stage of "decision making."
3. The acceptor of action results.
4. The adaptive response of somatic functions and their autonomic provision.
5. The result of the system's activity is a starting point for all followed stages in the system's activity. The parameters of the result are constantly estimated by the acceptor of action results with the help of the reverse afferentation.

The principles of the theory of functional system, developed by Anokhin between 1932 and 1974, were published in *Biology and Neurophysiology of Conditioned Reflex* (1968), *Theory of Functional System* (1970), and *Fundamental Questions of the General Theory of Functional Systems* (1971). The theory made it possible to elevate the level of analytical research to a new grade and opened new perspectives of system analysis of the participation of different brain structures (up to its cell and molecular mechanisms) in the organization of various stages of human and animal goal-directed behavior.

At the time, Anokhin also formulated a conception of "systemogenesis" as a selective maturation of functional systems and their separate components in pre- and postnatal ontogenesis.[3]

During the World War II, Anokhin worked as a surgeon in Tomsk (Siberia), operating on the wounded suffering from peripheral nervous system injuries. Upon his return to Moscow in 1943, he continued his collaboration with N.N. Burdenko,[4] as a consultant and a surgeon at the Institute of Neurosurgery. At that time he was active in the organization of the USSR Academy of Medical Sciences. From 1943 until 1945, Anokhin was a professor at Lomonosov Moscow State University.

The 1950 Joint Scientific Session

The year 1950 was quite dramatic for physiology in the USSR, because of the differences in views of scientists on the role of external and internal factors in the processes of vital activity. It was time for a new comprehension of the rich heritage of Pavlov and his disciples. The problem needed to be solved by a joint session of two USSR academies, notably the USSR Academy of Sciences and the USSR Academy of Medical Sciences. The meeting was held in Moscow in the summer of 1950. Despite some positive moments, the session distorted the idea of scientific criticism in many respects, substituting a free exchange of opinions by an ungrounded condemnation of dissenters. The fundamental question of the session was "Who would develop Pavlov's doctrine and how?" The first meeting of the scientific session devoted to the problems of Pavlov's doctrine was held on June 25, 1950. Nine hundred and twenty-five scientists were invited. K.M. Bykov's

[3]The theory of systemogenesis was developed in details in the following papers: "Functional System as a Basis of Integration of Nervous Processes in Embryogenesis" (Anokhin, 1937), "Systemogenesis as a General Pattern of Evolution" (Anokhin, 1948), "Functional System as a Unit of Organism's Morphological Integration" (Anokhin, 1949b), and in the monograph "Biology and Neurophysiology of Conditioned Reflex" (Anokhin, 1968).

[4]N.N. Burdenko (1878–1946) — outstanding Russian neurosurgeon.

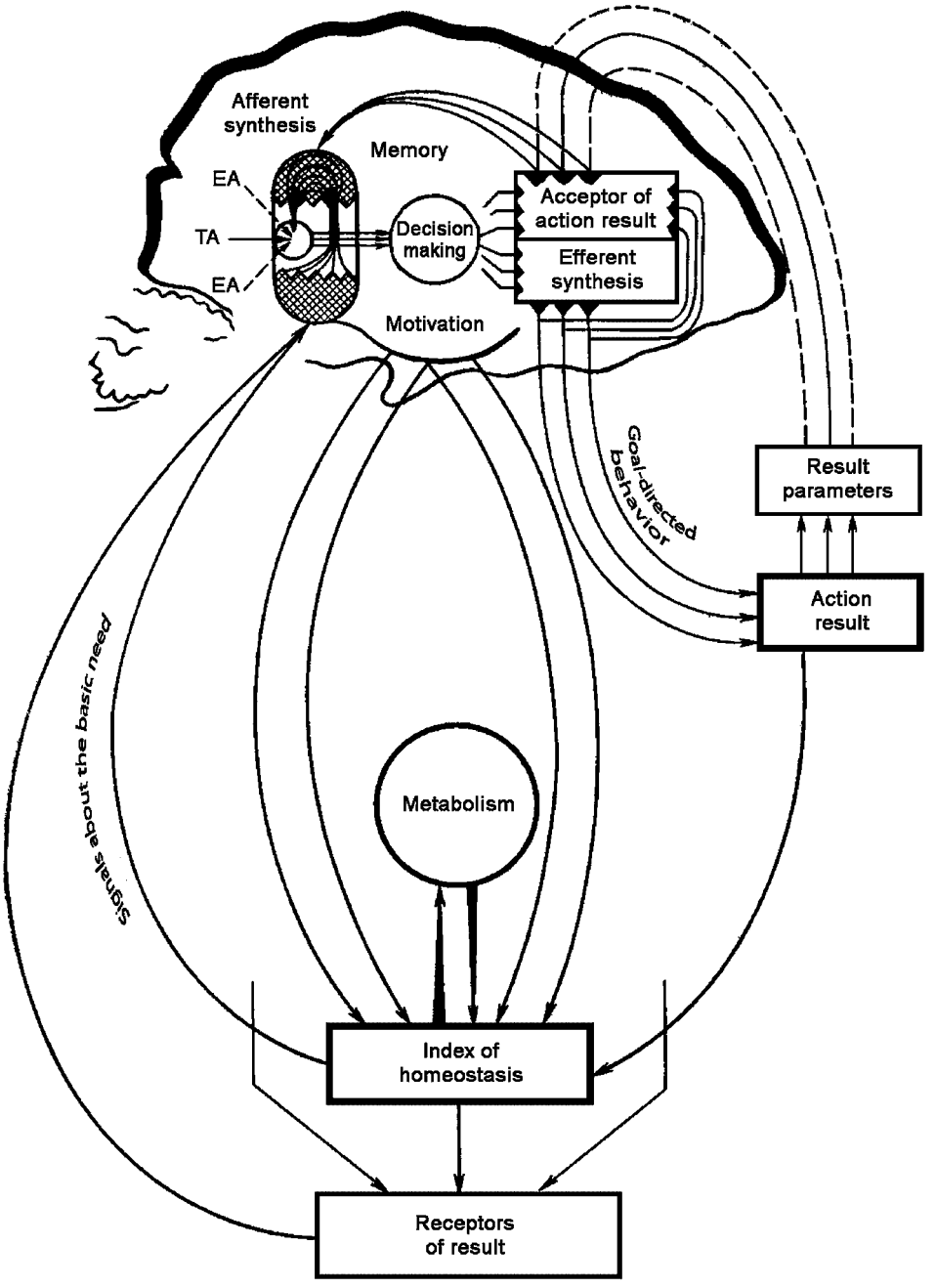

Figure 3. Central architectonics of a functional system of a behavioral level (by P.K. Anokhin). EA - environmental afferentation; TA - trigger afferentation.

report on the "Development of I.P. Pavlov's Ideas (Tasks and Perspectives)" presented an obvious criticism of fundamental trends in national physiology, developed by L.A. Orbeli, Anokhin, I.S. Beritashvili, N.A. Bernstein, N.S. Kupalov, A.D. Speransky, and others. Anokhin was criticized for "the swerve from Pavlov's study." The main blow was delivered to the concept of a functional system and methodology in Anokhin's studies of brain activity. He was accused in prejudicing "the ABC of Pavlov's doctrine — a reflex theory."

From the point of view of the orthodox supporters of Pavlov's study, Anokhin's conception undermined the basis of reflex theory, denied the principle of determinism and led to vitalism. However, the concept of a functional system only shows that the notion of causality is wider and deeper, as besides external stimulation, at least two additional factors should be taken into consideration: the inner state of the animal and the character of the feedback. Modern investigations completely confirm these ideas. Another position of Anokhin, notably the problem of analysis and synthesis, was also under fire. Anokhin was not satisfied with a pure descriptive side of a very complex process such as "excitation" and "inhibition," neither was he with Pavlov's approach to the study of nervous processes such as observation and registration of external manifestations of behavior — salivation and movements.

At the subsequent meeting, on June 3 1950, Anokhin spoke in defense of his conceptions and, in particular, on his brainchild, the concept of the functional system. He said:

> "The concept of functional system is defensible as it at least allowed, reasoning from Pavlov's ideas about self-regulation, to make some generalizations in different fields of biology and physiology. It permitted to suggest a view about mechanisms of embryonic evolution and mechanisms of inheritance of acquired features. In pathology the concept of functional system allowed to come closer to the understanding of the pathogenesis of hypertension and so on."

And he continued to say that:

> . . . in view of censorious remarks to my address I intend to make a series of reports at the Physiological Society on questions of fundamental mechanisms of higher nervous activity. I invite my colleagues of the Pavlov school to take part in the discussion.

However, Anokhin was not heard. Very soon after the session he was deprived of all his scientific positions and "was exiled" to Ryazan, where he headed the Department of Normal Physiology at Ryazan Medical Institute. At that time one part of his followers stayed in Moscow, working at the A.V. Vishnevsky Institute of Surgery, where Anokhin headed a physiological laboratory, the others became his associates in Ryazan. Some of his disciples worked in other institutes. But the unity of the Anokhin Scientific School remained. Anokhin had to guide the research in Moscow, to create anew an experimental base in Ryazan, and had to deliver lectures on physiology for students. The reorganization of the work, the tiring journeys for lectures to Ryazan and back to Moscow, and the divergence of opinions in biological science — that "indelible scar" of the 1950s — undoubtedly slowed down the pace of scientific investigations. During the period 1950–1951, none of Anokhin's scientific papers appeared in press. Only in 1955, when Anokhin was elected head of the Department of normal physiology at the I.M. Sechenov First Moscow Medical

Institute (now Moscow Medical Academy), the scope of scientific investigations under Anokhin's guidance was significantly enlarged.

The Period 1955 –1974

Just in that period the fundamental principles of the theory of functional systems reached an advanced stage of development: an original interpretation of studies of the brainstem

Figure 4. P.K. Anokhin in 1968.

reticular formation was proposed, a convergent theory of conditioned reflex was experimentally substantiated, an integrative theory of neuron was put forward, and the main principles of the theory of systemogenesis were specified (Anokhin, 1974a, 1974b).

In his last years Anokhin created a new direction in physiology, notably functional neurochemistry aimed at the investigation of brain chemical processes in the dynamics of developing central architectonics of functional systems. He disclosed the mechanisms of adaptation and resistance of functional systems in extreme situations. The application of the system approach to the analysis of mechanisms of autoregulation in pathology made it possible for Anokhin to formulate a number of notions about the pathogenesis of some diseases. He developed clinically important ideas about the mechanism of the selective effect of narcosis, psychotropic agents on cortico-subcortical interactions, and he formulated an original theory of narcosis and integrative theory of sleep and wake.

Anokhin was not only a talented scientist-experimentalist but a clever organizer of science able to carry his ideas and developments to their practical application. The theory of functional systems has its multiple applications not only in medicine but in some other fields of science as well. The most fruitful turned to be its application in cybernetics, bionics in the modeling of automatic machines and complex systems (Anokhin, 1978, 1998). He was a person of amazing virtue to attract young people and to excite interest in physiology without moral teaching by his personal love of science, his inexhaustible diligence, and his aspiration.

His pedagogical activities were not limited to teaching students. He permanently took care of the future of science, devoting a lot of time and energy to training and to educating young scientists. Scientists from many republics of the former USSR and from abroad, including Bulgaria, German Democratic Republic, Poland, Czechoslovakia, Yugoslavia, Argentine, Brazil, Egypt, China, Salvador, and the United States. Anokhin educated a galaxy of talented scientists and researchers, who now represent independent physiological schools. The atmosphere in his laboratories was always inspired with spirit of benevolence, friendship, and creative striving. His brilliant lectures and eloquence, personal charm, and great authority did not only attract physiologists but also specialists from other fields of science. That is why many people, even those who did not belong to the Anokhin school, regard him as a teacher. Many of his disciples and followers are now leaders of scientific teams in Russia as well as abroad.

Anokhin lived a remarkable life and contributed much to the evolution of soviet and international physiology and trained a whole generation of practical physicians. He died in Moscow in March, 1974, and he was buried at the famous Novodevichy Cemetery.

In October 1974, the Institute of Normal Physiology of the Russian Academy of Medical Sciences was founded in Moscow and named after P.K. Anokhin. The USSR Academy of Medical Sciences instituted the Anokhin Prize for the best work on normal physiology. In 1976 a scientific arrangement “The Anokhin Readings” was instituted, with the purpose of further development of the scientific heritage of this outstanding physiologist.

Anokhin memorial boards were placed in Moscow at the building of the Department of Normal physiology of I.M. Sechenov Moscow Medical Institute, in Nizhny Novgorod at the building of Novgorog Medical Institute, and in Ryazan at the building of the Department of Physiology in Ryazan Medical University. One of the streets in the South-West of Moscow was named after Anokhin. During the years after Anokhin’s death, a great number of All-Union and International conferences and symposia have been held in his memory, in particular on his development of the theory of functional systems. A traditional

International Anokhin Seminar "Development of the Theory of Functional Systems" continues to function.

Anokhin Scientific School

After Anokhin's death, the theory of functional systems was successfully developed by his disciples. However, the basic principles of the theory remain unchanged. Questions that have not been addressed by Anokhin are being investigated, and some general points of the theory are being experimentally proved. The findings of the Anokhin Scientific School show that the whole organism presents a harmonic interaction of a number of functional systems at molecular, homeostatic, behavioral, and population levels. The principle of interaction of functional systems of the organism is a multiparametric coordination. This means that any change of parameters in one functional system immediately reorganizes the state in other functional systems connected with it.

A new principle of interaction of functional systems in the organism as a whole, discovered in Anokhin Scientific School, is the principle of successive cooperation when the result of action of one functional system stimulates the activity of the other functional system. Dynamics of the formation in time of functional systems follow a principle of system quantization of vital processes — "systemoquanta" (Sudakov et al., 1997).

A series of special experiments showed that dominant motivations are closely connected with another leading stage of system architectonics of behavioral acts — an acceptor of action result, which constitutes a directing component of behavior (Sudakov, 2004). The ideas about a structural organization of the acceptor of action results have been further developed.

Many other aspects of systems activity in organisms are under research in the laboratories of the Anokhin Institute of Normal Physiology, indicating that his scientific ideas are widely used in basic scientific researches as well as in the practice of public health service. And with respect to the evolution of science, Anokhin expressed his view in the following words: "We are ready to agree with any new concept about the subject matter if it is proved that a new concept can better resolve the existing contradictions and give more reasonable interpretation to so far inexplicable facts."

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