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Review Article

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Possible Role of Non-coding DNAs in the Cambrian Explosion

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Abstract

The "Cambrian explosion" (CE) refers to a sharp increase in the number of fossils of living beings in the sediments of the Cambrian period (CP), which began 538.8 ± 0.2 million years ago and ended 485.4 ± 1.9 million years ago. It was in the CP that drastic changes took place in the biosphere: if before that almost all life was simple and unicellular, then after the CE there was a sharp increase in the number of complex multicellular organisms. However, the reason(s) for these drastic changes remains unknown. Various hypotheses were put forward: a sharp change in climate; the appearance of sexual reproduction; bilaterality or an increase in oxygen concentration that allowed the development of multicellularity. Apparently, the essence of the problem is to clarify the mechanisms and material basis of fundamental changes in the biosphere. For such an explosion, radical changes in the genome are necessary. It is suggested that the CE is associated with the evolution of the most mobile part of the eukaryotic DNA genome, rather than an increase in the number of previously existing or newly emerged genes. From our point of view, the evolution of non-coding DNAs, which make up the vast majority of DNA in the eukaryotic genome, could play an important role in the emergence of CE.

Keywords: Cambrian explosion, Non-coding DNAs, cell thermoregulation, Chromosomal heterochromatin regions, Condensed chromatin

The "Cambrian explosion" (CE) means a sharp increase in the number of fossils of living beings in the sediments of the early Cambrian period (CP), since in the sediments of previous times (Precambrian) traces of the existence of animals are much less common. This period began 538.8 ± 0.2 million years ago, ended 485.4 ± 1.9 million years ago [1]. It is in the Cambrian period (CP) of the paleontological chronicle that the remains of animals of many types appear. In particular, all modern types of the animal kingdom appeared on the Cambrian border almost suddenly, without being descendants of a previously existing fauna.

In the CP, drastic changes took place in the biosphere: if before that almost all life was simple and unicellular, then at the beginning of this period there was a sharp increase in the number of complex multicellular organisms, many of which had either exo- or endo skeletons [2]. As a result, many modern types of organisms have appeared, such as chordates, arthropods, mollusks and many others. Thus, in the era of the CE, life on Earth acquired its familiar outlines. However, the cause(s) of these cardiac changes in the biosphere remains unknown.

Many attempts have been made to explain the reasons for such an "explosive" development. At the same time, it should be noted that quite complex three-layered animals existed before the Cambrian. However, it is in the Cambrian that the remains of many types of animals appear in the paleontological chronicle, in particular, chordates, arthropods, mollusks and many others [3]. Therefore, the evolutionary development in the early Cambrian appears to be exceptionally rapid.

The reasons for the CE of biodiversity remain unclear, and varieties of hypotheses are put forward to explain it: a sharp climate change; the appearance of sexual reproduction; bilaterality; the development of predator-prey relationships or the accumulation of such oxygen concentration in the atmosphere that allowed for the rapid development of multicellularity and specialization.

The main cause of the CE is considered to be environmental changes. At the same time, the main role is assigned to the increase in the concentration of oxygen in the water, since in the CP life was concentrated in the seas. As is known, the earliest atmosphere of the Earth did not contain free oxygen at all. Approximately 2.5 billion years ago, the concentration of oxygen in the atmosphere increased dramatically. Up to this time, all the oxygen produced by microorganisms was completely spent on the oxidation of elements with a high affinity for oxygen, such as iron [4].

It is generally believed that lack of oxygen could hinder the development of large complex organisms for a long time. The fact is that the amount of oxygen required for vital activity is determined by the mass and volume of the organism, which, as the size increases, grow faster than the area. An increase in the concentration of oxygen in the air and in the water could weaken or eliminate this restriction altogether. Therefore, a further increase in oxygen concentration (between the Ediacaran and Cambrian periods) could provide organisms with additional energy for the production of substances (such as collagen) necessary for the development of fundamentally more complex body structures, including those used for predation and protection from it [5].

The increase in oxygen concentration in water is associated with the role of environmental changes: in particular, with the factor of global glaciation of the Earth, during which most of it was covered with ice and the surface temperature was close to the freezing point even at the equator. Indeed, low temperatures increased the concentration of oxygen in the ocean – its solubility in seawater almost doubles when the temperature drops from +30°C to 0°C [6]. The climate on Earth during the CP differed from both the modern and the preceding Neoproterozoic epoch. If at present the average annual planetary temperature is about 14°C, and in the Neoproterozoic it was even lower-about 12°C, then during the Cambrian it was 22°C. Therefore, some researchers point out that this circumstance may be closely related to the CE, since the earliest known fossils belong to the period shortly after the end of the last complete glaciation [7].

There are also suggestions that the CE is somehow connected with a change in the isotopic composition of carbon. It is known that a very sharp decrease is observed in sediments at the Precambrian-Cambrian boundary, followed by unusually strong fluctuations in the ratio of carbon isotopes $^{13}C/^{12}C$ throughout the Early Cambrian [8,9]. Some paleogeologists associate the CE with increased activity of the Earth's global magnetic field, which involved both the mantle and the plates lying on it in motion [10].
There are also biological explanations for the causes of the CE, when questions about the origin of bilateral symmetry are discussed. At the same time, they mean homeotic genes (Hox-genes)-groups of regulatory genes that turn on and off "working" genes in various parts of the body, and thereby control the formation of the anatomical structure of the organism. Indeed, very similar Hox-genes are found in the genome of all animals-from for example, jellyfish to humans [11]. Therefore, the emergence of such a system could lead to a sharp increase in diversity-both morphological and taxonomic.

Possible biological factors of the CE include the role of sexual reproduction. As is known, organisms that do not use sexual reproduction change very little. In most organisms that have sexual reproduction, the offspring receives about 50% of their genes from each parent. This means that even a small increase in the complexity of the genome can give rise to many variations in the structure and shape of the body [12]. The possible appearance of sexual reproduction or its significant development during the CE for very simple and similar creatures may mean a sharp increase in hereditary variability. Indeed, with the development of sexual reproduction, truly isolated biological species that do not interbreed with others appear.

There are also ecological explanations for the cause of the CE, which focus on the interaction between different species of organisms. Some of these hypotheses deal with changes in food chains; others consider an “arms race” between predators and prey, which could have caused the evolution of rigid body parts in the early Cambrian.

From our point of view, for biologists, the problem of the CE is mainly focused on the question: what is the mechanism and material basis of cardinal changes in the biosphere, because of which almost all life, represented as simple unicellular creatures, has become a complex and multicellular organization?

It seems highly probable that all of the above factors individually or even collectively could not by themselves cause an "explosion" in the biosphere. For such an explosion, radical changes in the genome of simple unicellular organisms that existed before the beginning of the CP are necessary. However, what radical changes could have occurred in the genome of the Cambrian fauna can only be guessed. For example, the composition of the genome of Precambrian organisms can be judged based on data obtained on the DNA of existing unicellular organisms. As is known, the genome of modern unicellular organisms consists of coding (genes) and non-coding DNA (ncDNAs). If, at the same time, the share of the genic part of DNA in simple unicellular organisms is the overwhelming majority, then the genome of higher eukaryotes consists mainly of ncDNAs.

Since all modern types of the animal kingdom appeared almost suddenly on the Cambrian border, not being descendants of pre-existing faunas, it can be assumed that the Cambrian explosion is somehow connected with the evolution of the most mobile part of the DNA genome, and not an increase in the number of previously existing or newly emerged genes. From our point of view, ncDNAs could play an important role in the origin of the CE. In this regard, it is necessary to emphasize once again the long-established pattern in the distribution of ncDNAs in the eukaryotic genome: the more complex the organism, the more non-coding sequences in its genome. For example, the share of ncDNAs in the human genome is more than 98%.

We have repeatedly discussed the possible role of ncDNAs in the evolution of eukaryotes, in particular, in the emergence of the eukaryotic nucleus, biological sex, multicellular organisms, cell thermoregulation, circulation system, homoeothermic animals, including modern humans [13-22].

In our opinion, ncDNAs could become the most suitable genetic material capable of responding to the challenges of the CP for a number of reasons: a) they consist of short repetitive sequences of nitrogenous bases; b) they are capable of forming higher forms of DNA organization as chromosomal heterochromatin regions; c) quantitative and qualitative changes in the composition of ncDNAs have no visible phenotypic manifestations; d) individuals in a population may differ significantly from each other in quantitative and qualitative composition of ncDNAs, remaining at the same time, a single biological species.

Why could ncDNAs be the most in demand in the CE? We believe that, unlike unicellular creatures, for the normal functioning of complex macroscopic organisms in the conditions of the CP, the problem of maintaining temperature homeostasis could become a task of paramount importance. Indeed, during this geological period, there were: a) an increase in oxygen concentration; b) an increase in ambient temperature; c) the problem, determined by the mass and volume of the organism, became extremely acute; d) there was a need for the production of complex structures (solid mineralized exo- and endo skeletons); e) complex interactions between different species of organisms such as an 'arms race' between predators and victims; (i) changes in food chains; (k) the evolution of rigid body parts requiring the production of collagen necessary for the development of fundamentally more complex body structures, including those used for predation and protection against it. All of them, taken together, could become triggers of evolution, leading to a sharp acceleration of cellular metabolism, since these processes are usually accompanied by the release of a large amount of thermal energy, which must be removed outside the body in a timely manner.

If the events developed in this way, then it is necessary to find an answer to the question: how was the task of maintaining temperature homeostasis solved, more precisely, how was excess heat removed outside the whole organism and especially from individual cells? From our point of view, the problem was not solved here only by involving well-known mechanisms of physiological organ-based thermoregulation, which dissipated excess heat from the bodies of macroscopic organisms. The problem lies in the fact that physiological thermoregulation based on the circulation system removes excess heat contained mainly in the intercellular spaces, and not from individual cells, since, with rare exceptions (e.g.: endothelium, lining vessels) the fluid circulating in the body (blood, lymph) do not come into direct contact with the cells. Moreover, it is not known whether the organ-bass system of physiological thermoregulation even existed in the CP.

We believe that the problem of temperature homeostasis at the initial stages of the development (evolution) of complex macro organisms was solved mainly at the level of individual cells using special mechanisms of cellular thermoregulation, and physiological organ-based thermoregulation arose later on its basis (for details see, [14,15,19,20]).

Here, without going into details, we will note only some features of cellular thermoregulation. 20 years ago, based on a study of the distribution of one of the forms of ncDNAs, the so-called chromosomal heterochromatin regions (HRs), the hypothesis of cell thermoregulation was put forward in norm and pathology [13]. The essence of cell thermoregulation (CT) hypothesis is elimination of the temperature difference between the nucleus and cytoplasm when the nucleus temperature becomes higher than in the cytoplasm. The nucleus, in contrast to the cytoplasm, cannot conduct heat directly in the extracellular space, from where the heat is taken by the circulating flow of blood and lymph. Thus, the nucleus can transfer surplus heat only in the cytoplasm. With this, the nucleus has two options: either by increasing its volume or increasing the heat conductivity of the nuclear envelope. As the first option is limited, and the second one is hampered because of the vulnerability of the cell membranes to temperature changes, apparently the higher eukaryotes took advantage of the opportunity of a dense layer of peripheral condensed chromatin (CC) as heat conductor for a more efficient elimination of the temperature difference between the nucleus and cytoplasm. The CC localized between a nucleus and cytoplasm is made of chromosomal HRs, which are one of the forms of higher organization of ncDNAs. The higher eukaryotes use a dense layer of peripheral CC as heat conductor for a more efficient elimination of the temperature difference between the nucleus and cytoplasm. Thus, CT is a product of the evolution of a part of ncDNAs that formed the highest form of organization of highly repetitive sequences of nitrogenous bases in the form of chromosomal HRs [13-20].

Perhaps in the CP of the development of life, a biological sex also arose, which, as we believe, is also a product of the evolution of ncDNAs with all the consequences that follow from this (for details see, [15-19]).

Finally, let us summarize the consequences of the evolution of ncDNAs for organisms, survivors of the CP:
1) Cell thermoregulation has emerged, which is able to remove excess thermal energy from individual cells;
2) Thanks to cell thermoregulation, organisms that are able to effectively remove excess heat from cells, and subsequently outside the whole body, have gained advantages;
3) With the advent of mechanisms for removing excess heat from deep parts of the body, it became possible for complex macroscopic organisms to arise;
4) On the basis of cell thermoregulation, physiological organ-based thermoregulation has emerged, capable of removing excess heat outside the body;
5) On the basis of the evolution of ncDNAs, mitotic chromosomes, mitosis and meiosis arose, which eventually led to the development of biological sex and sexual reproduction, without which it would have been impossible to create a variety of complex life forms characteristic of the CE;
6) Due to cell thermoregulation, mechanisms of sex determination and differentiation have emerged [21,22].

Thus, ncDNAs could play an important role in the evolution of the biosphere in the CP, a vivid witness of which is the undeniable fact that the genome of modern higher eukaryotes consists mainly of short, repetitive sequences of nitrogenous bases.

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Conflicts of Interest

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Statement of Consent/Ethical Approval

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