Medical Hypotheses 76 (2011) 901–904

Contents lists available at ScienceDirect

Medical Hypotheses

journal homepage: www.elsevier.com/locate/mehy

Evolution and possible storage of information in a magnetite system of significance for brain development

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ARTICLE INFO

Article history:
Received 23 February 2011
Accepted 3 March 2011

ABSTRACT

The initial evolutionary electromagnetic steps in the history of brain development are still unknown, although such knowledge might be of high relevance in understanding human degenerative diseases. All prokaryote organisms, one-celled or multicellular, must have an inherited system to process and store information activating instincts and reflexes, in order to give a quick response to external stimuli. We argue that magnetite is an obvious compound to be evaluated as an initial precursor from prebiotic Earth history in the evolution of such a system. Magnetite is a stable ferrimagnetic compound, present in organisms ranging from bacteria to humans. It occurred naturally in the early Earth environment and was later synthesized *de novo* in biotic organisms. We suggest that the use of magnetite has evolved to represent the main storage system for learned memory in all organisms living today.

"*Not everything that counts can be measured. Not everything that can be measured counts*"

Albert Einstein.

Introduction

Degenerative diseases in the human brain, such as Alzheimer's disease [1,2], are of great relevance and a major challenge in medical research. Here we present a hypothesis for the initial start of the evolutionary process of a brain information storage system and memory development, a process which is still largely unknown. What is the details of processing and storing of information in the development of precell structures, prokaryotes and later eukaryote biological organisms? The question is pertinent because we are not aware of any report suggesting a mechanism for memory storage either in the prebiotic or biotic world. Instead, huge gaps in our knowledge are very evident [3]. We suggest that magnetite may give us a clue, because it is the Earth's most distributed and important magnetic mineral, and because it is found in living organisms but with no obvious, recognized function, except for being involved in navigation. Magnetite has been described in organisms like bacteria [4,5], butterflies, fish, turtles, birds and mammals [6]. In humans, it is present in the brain [7]. Magnetite is also present in other organs, as in heart, spleen and liver [8]. We have suggested that memory is stored in clusters of magnetite present on the inside of the membranes in the neurons of the brain [9], and that the dendrites might function as a reading frame. In accordance with the close connection between neurons and astrocytes we have suggested that also the astrocytes are involved in the magnetic-based storage of memory [10]. It has been proposed that any type of information could be stored in the form of "neuronal-associated magnetic fields" [11] and a possible role for magnetite nanoparticles in storage of information that arrives the neocortex [12]. The compound is a potential candidate for being a universal memory molecule [13]. It has also been suggested that biomagnetite must have a biological function in living cells in general [14,15]. The purpose of the present paper is to discuss an early existence of a possible magnetite memory system, and whether the prokaryotes have evolved such a system for storing information about instincts and reflexes, either separate from or in addition to DNA.

Abiotic formation of magnetite

When the temperature on Earth decreased for about four billion years ago, water vapour condensed and made it available for chemical reactions in liquid form. It also resulted in a clearer atmosphere which made the sunlight more available for photochemical reactions. In an aqueous environment, the UV oxidation of Fe^{2+} to Fe^{3+} was followed by coprecipitation of ferric and ferrous oxides, Fe_2O_3 and FeO, respectively. These oxides were formed from the irons and water molecules, releasing protons as byproducts, as well as the mineral magnetite:

$$2Fe_2^+ + Fe_2^+ + 4H_2O \rightarrow 6H^+ + H_2 + [Fe_2O_3][FeO]. \quad (1)$$

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0306-9877/$ - see front matter
doi:10.1016/j.mehy.2011.03.004

The released protons were available for the reduction of a large variety of substances and could have been responsible for the production of such species as H_2, CH_4, HCN, and NH_3 as long ago as 3.8 billion years [16]. These reduced species are otherwise not readily produced in other abiotic processes and are essential for the subsequent chemical evolution of amino acids and other compounds. It should be noted that UV energy was one of the most abundant forms of energy in the primitive Earth environment. The formidable amount of inorganic magnetite deposits that we find today, indicate that the oxidation of Fe^{2+} to Fe^{3+} to magnetic compounds must have been a dominant and important reaction before life had evolved.

The possible presence of magnetite in early forms of life

Several known light sensitive compounds and pigment structures were present very early in Earth history. Probably, such early photochemical formations were a necessity in the evolution of life because they would adsorb solar energy and convert it into chemical energy through some sort of a primitive "photosynthesis". The earliest organism must have been chemo-autotrophs followed by photo-autotrophs; they were anaerobic, and did not produce O_2 as a byproduct during photosynthesis, because they did not use water as a reagent. The first aerobic photo-autrotrophs had evolved 3.3–3.5 billion years ago. They were like present day cyanobacteria and could release O_2 into the atmosphere because they used water as the reagent.

We suggest that the inorganic formed magnetite was incorporated in an organic precell structure, or later in the evolution of a cell sticking to a mineral surface containing magnetite. Mineral surfaces have been suggested, and also demonstrated by experiment, to adsorb organic molecules and thus promote polymerization [3]. A subsequent step may have been a selective evolutionary process forming biogenic magnetite, making the organisms independent on the external magnetite sources. Hence, two alternatives exist for the occurrence of magnetite in bacteria, namely by uptake of Fe^{2+} and the formation of magnetite, and by adsorbtion of magnetite from the early Earth environment.

The magnetic crystals formed by a biological controlled process (biogenic) have features different from magnetites formed through geological processes. We suggest that biogenic magnetite has been caused by natural selection to have suitable properties for serving as a memory molecule (see below), and that it explains how instincts and reflexes in the early biotic world would work. In contrast to learned memory, the ability to perform an instinct or reflex reaction is likely to be inherited and based on electromagnetism, as indicated by the speed that an organism responds to a peculiar instinct-based situation. The informational basis of instincts must be stored somewhere and we suggest that magnetite serves the purpose. Such information stored, of learned memory and instinct, must also have the ability to be activated by external signals.

Magnetite as a memory molecule

Magnetite (Fe_3O_4) is ferrimagnetic, i.e. it exhibits permanent magnetization in the absence of an external magnetic field. It is ferromagnetic at room temperature. Magnetite belongs to the spinel group which are any class of minerals of general formulation A^{2+}+$B_2{}^{3+}O_4{}^{2-}$, where A and B can be the same metal under different charges. It is the only stable iron oxide that contains Fe^{2+}. There is an intimate link between magnetic and electric fields that form the foundation of electromagnetism. An electric current generates a magnetic field and a magnetic field can generate an electric current.

Electromagnetic properties are characteristic for all forms for life. All magnetite crystals described from organisms are synthesized *de novo* and they display cubo-octahedral shapes. They are usually elongated in the [1 1 1] direction [17]. The elongation of biogenic crystals in the [1 1 1] direction serves to maximize the net magnetic moment of the particle. For obtaining maximal magnetic moment, it is important that the crystals are perfectly organized and without impurities which must affect inorganic magnetite crystals. The magnetic state of a crystal is strongly dependent on both size and shape.

In the most primitive organisms a single magnetic crystal could serve according to the principle of a data chip. Single atoms are able to store information by changing the orientation of their individual spins. Thus extreme amounts of information can be stored into tiny devices [18], meaning that a biogenic memory system based on magnetite would not depend on its size in order to store information important for survival of the organism.

We suggest that biogenic magnetite can store large amounts of information. This is based on the knowledge that quantum computers are using magnets, each made out of a single molecule. They are not limited to two states, like 0 or 1; they encode information as quantum bits, or qbits. Qbits represent atoms, ions, photons or electrons, and their respective control devices, and they are working together to serve the function as computer memory and a processor. Because a quantum computer can contain these multiple states simultaneously, it has the potential to be millions of time more powerful than today's most powerful supercomputers. Thus, if our hypothesis is not falsified, more information about quantum computers and quantum coherence in biological systems may contribute to the understanding of memory storage in living organisms.

Behavior of bacteria and biofilm

Bacterial chemotaxis represents the simplest and best studied example of unicellular behavior. Chemotaxis allows swimming bacterial cells to follow chemical gradients in the environment by performing temporal comparisons of concentrations of the appropriate compounds. Molecular memory is assumed to be an essential component of the chemotaxis [19,20].

Biofilm is a highly structured living arrangement of bacteria. It develops on any surface that bacteria can attach to with a protective matrix. Biofilm research may provide a glimpse of the evolutionary path from single cells to communicating "tissue" structures. Species of single bacteria may work as a team and employ chemical communication to form highly complex colonies, 10^9–10^{12} bacteria in each. Communication also seems to occur among different species of bacteria, with their joint behavior resembling that of a multi cellular organism with cell differentiation. Apparently, the single bacteria uses internally stored information as well as novel information from the environment. For a recent example on the behaviour of a bacterial colony [21].

The precise mechanism determining how a biofilm functions, is not known, although some insights have been gained. Many of the cooperative behaviors are regulated by a process known as quorum sensing. It enables bacteria to coordinate and respond quickly to environmental change, such as availability of nutrients, and the presence of other microbes, or toxin, in the environment. The signals used in the biofilm include small organic molecules or peptides. It has been suggested that microbial colonies may survive, communicate and share energy in part through electrically conducting hairs known as bacterial nanowires [22,23]. Such structures are widespread in the microbial world and may help bacteria to communicate as well as respire. The cells must react in response to environmental change, in addition to the communication with other cells. This means that a mechanism for storage of information must exist in every cell on how to react to the various stimuli, to provide a rapid and relevant response. We suggest that magnetite has a key role.

A nonmagnetic mutant of *Magnetospirillum*

Magnetotactic bacteria are capable of forming magnetosomes, which are specific intracellular structures enabling the cell to orient along magnetic field lines. The biomineralization of magnetosome particles is achieved by a complex mechanism that controls the uptake, accumulation and precipitation of iron. The system produces up to 60 cubo-octahedral magnetosomes in bacteria that are approximately 45 nm in size and consist of membrane-bounded crystals of magnetite. A nonmagnetic mutant has been isolated and it lacked any structures resembling magnetosome crystals as well as internal membrane vesicles [24].

Like other organisms, the mutant of the bacteria *Magnetospirillum gryphiswaldence* might still contain magnetite, despite the lack of magnetosome crystals. If so, the memo-magnetite must be synthesized by another pathway than the formation of the magnetosome particles, a pathway controlled by other genes. According to our hypothesis, the magnetosomes for navigational purposes must have evolved later than the postulated magnetite involved in memory.

Ferritin in magnetite formation and storage

A candidate for the storage of magnetite in prokaryotes is ferritin. In plants, magnetite has been described in phytoferritin [25], and it may participate in plant information storage and transfer [26]. Bacteria have evolved multiple systems for iron uptake. Under oxygen-poor conditions, iron mainly occurs as binary iron which is water soluble. The Fe^{2+} form of iron is acquired by a specific type of transporter, whereas Fe^{3+} is taken up by another. The reduced molecule enters the ferritin cavity where it is rapidly oxidized to Fe^{3+} and H_2O_2 by ferrioxidase. The net result is ferrihydrite that could be the precursor for magnetite [27]. It has been demonstrated that the core in horse spleen ferritin consists of ferrihydrite, magnetite and hematite [28]. Magnetite is present in the ferritin core in small amounts and less than 1% compared to ferrihydrite. If magnetite is involved in memory, it is either located in the ferritin cavity or it is transported to some other place in the cell. When pumpkin plants (*Cucurbita maxima)* are grown in an aqueous medium containing magnetite nanoparticles, they can absorb, translocate and accumulate the particles in the plant tissue [29]. A similar mechanism may be present in prokaryotes.

When the organism *Shewanella oneidensis* was grown anaerobically in the presence of lactate as the electron donor and silica ferrihydrite as the sole electron acceptor, nanocrystalline magnetite was formed along the length of the bacterial nanowires [22]. Could this biogenic magnetite be transferred to other growing bacteria and subsequently be incorporated into a memory site? So far there has been no report of magnetite in prokaryotes, except for the magnetotactic bacteria. Hence, the possible magnetite involved in memory may be present in very low quantities only. Consequently, large amounts of crushed material will be needed for a study, possibly causing undesired, misleading magnetic signals owing to the low concentration.

Information storage systems

Instincts and reflexes are fundamental properties of all forms of life. During the evolution of such traits, the organisms needed a mechanism to store information, a mechanism that later may have been extended to learned memory. In higher forms of life, it has been suggested that the relevant information is stored in the neurons [30]. Neurological reactions in organisms have to respond rapidly to environmental changes, like changes in temperature, light, and salinity. One advanced possibility for the storage of such information is the DNA/RNA system, where RNA serves to transfer information from the DNA to the protein synthesis machinery, or to some other place(s) in the cell. We assume that such information sites for storage of instincts and reflexes must consist of stable molecules. One such molecule is DNA. The weight of the smallest animal genome, belonging to the plant parasite nematode *Pratylenchus coffeae,* is about 0,02 pg, while the largest animal genome, from the marble lung fish *Protopterus aethiopicus,* is approximately 143 pg. This represents more than a 7000 fold difference in DNA content. To compare, the weight of the human genome is about 3 pg [31]. This demonstrates that minute amounts of biological materials can store tremendous amounts of information. However, storing large amounts of information in RNA is not easy, because their chemical properties make large RNA molecules inherently fragile and sensitive to hydrolysis. The instability of RNA has made it unlikely to have functioned in the storage of information in the early stages of life (1). If DNA is involved, the signals have to be decoded and initiate the protein synthesis, and the resulting proteins will take the proper responses.

We suggest an alternative information storage system where magnetite is involved. DNA could be decoded and the information transported to other areas in the cell where they can be stored and go into action by activating the cell machinery when triggered. Such a mechanism would be more convenient because several steps would be avoided, like decoding and protein synthesis, and definitely faster. It has been suggested that bacterial chemotaxis is analogous to sensory reception in higher forms of life. This is seen from the specificity of the response of bacteria to attractants, an indication that the receptor molecules are located in the outer membrane, and the sensitivity to ratios of concentrations rather than to absolute, linear differences [19]. We suggest that the magnetite could be stored in a membrane envelope, like the magnetosomes, that could be linked to a matrix, or to the outer membrane, to improve stability. Magnetite could in some way be involved in the response to the electron flow. The current could trigger the memo-site system that leads to the release of enzyme induction, and/or production of low molecular weight compounds.

Obviously, our idea has to be critically tested because many questions remain, e.g. on how information from DNA is transported to the possible information storage sites. We do not know how the external signals enter the cells and how they are translated into an instinct reaction, nor how specific this event is. Furthermore, we do not know when in the cell division cycle the instincts are translated and transported to the storage sites, nor how mechanisms, like quantum computing and quantum coherence, are involved in memory.

Conclusion

An understanding of the basic steps in early evolutionary history of brain development is urgently needed as a prerequisite in medical research for understanding the nature of human degenerative diseases. All cells must have a system to process and store information needed to produce instincts and reflexes, and to store information from the biotic and abiotic environment. Biogenic magnetite is inorganic, ferromagnetic and stable and it occurs in a crystalline form. It seems to occur in every living organism, but with no recognized and obvious function. We suggest that magnetite has functioned as a universal, biological memory molecule from the very beginning of life on Earth, and thus that it has been an essential component for life to evolve, along with the DNA memory system. However, our idea has to be critically tested because several questions remain unanswered.

Conflict of interest statement

No Conflict of interest.

Acknowledgement

We thank Dag Klaveness, Department of Biology, University of Oslo for valuable comments on the manuscript.

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