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Hypothesized origin of microbial life in a prebiotic gel and the transition to a living biofilm and microbial mats

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ABSTRACT

This article hypothesizes that the origin of the first microbial cell(s) occurred as a series of increasing levels of organization within a prebiotic gel attached to a mineral surface, which made the transition to a biofilm composed of the first cell(s) capable of growth and division. A gel microenvironment attached to a surface for the origin of life, and subsequent living cells offers numerous advantages. These include acting as a water and nutrient trap on a surface, physical protection as well as protection from UV radiation. The prebiotic gel and the living biofilm contained the necessary water, does not impede diffusion of molecules including gases, provides a structured gel microscopic location for biochemical interactions and polymerisation reactions, where the necessary molecules for life need to be present and not limiting. The composition of the first gel environment may have been an oily-water mixture (or the interface between an oily-water mixture) of microscopic dimensions, but large enough for the organization of the first cell(s). The living biofilm then made the evolutionary transition to a microbial mat.

1. Introduction

The origin of life is elusive from an experimental perspective; however recent hypotheses and ideas have been proposed [1–12]. Plausible hypotheses as to where [13], time scales relevant in biology [14] and how life organized are under investigation especially in the initial absence of organic genetic instructions and enzyme controlled metabolism and replication. The origin of genetic instructions and the energetics of genome complexity [15] in an organic molecular communication system, where the message in the DNA is normally the correct one for each gene transcribed and translated are also not understood.

The origin of life is often placed in water. Scientists researching the origin of life are attempting to hypothesize and obtain evidence on plausible locations for the origin of life, and mechanisms which preceded the first cell(s) capable of growth and division. This involves an understanding of chemistry, physics, geology, biology, thermodynamics and prebiotic system(s) with increasing levels of organization. In addition, research is conducted on plausible locations for the origin of life, mechanisms for genetic instructions being embedded in DNA and RNA and the study of extreme environments to isolate and study unique life forms, such as the recent report on a bacterium capable of growth using arsenic instead of phosphorus [16]. The origin of life on the Earth occurred under anaerobic and extreme conditions by comparison to the biospheric conditions present today. In this article, it is hypothesized that a prebiotic gel that made the transition to a living biofilm and then a microbial mat may have been a plausible environment for the origin of life.

A biofilm is an aggregation of microorganisms attached/growing on a solid substrate. Today, biofilms are characterized by their colonization characteristics in the environment and in human health, numbers of viable and non-viable cells, species diversity, resistance to antibiotics, gene expression profiles, metabolism, a number of interactions such as sensing and gene transfer events (e.g., transformation, conjugation) and the presence of an

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extracellular matrix of biopolymer materials. The biofilm mode of growth as opposed to planktonic bacterial growth is very common [17–20].

The order of events in the origin of the first microbial cell(s) is hypothesized to be a prebiotic gel on a mineral surface making the transition to a living biofilm or biosystem of bacterial cells, capable of growth and division and subsequent Darwinian evolution via natural selection and genetic mutational events. Whether the microscopic gel and biofilm environment were on, or between mineral surfaces in the subsurface of the Earth, with abundant water and nutrients, or adjacent to a shallow or deep ocean vent, the gel to biofilm transition provides numerous advantages for the origin of life over a planktonic mode of organization, and then cell growth. The initial gel and biofilm would only need to be microns (or less) in dimensions as this would be sufficient for a cell to organize and undergo division. A gel or biofilm as small as 1 mL could contain millions of bacterial cells (or more) depending on the cell sizes and shapes, the packing of cells in the biofilm or biosystem and the nutrient availability. The origin of life would not have required an environment of macro-scale dimension if sufficient water, nutrients and environmental conditions were within the ranges suitable for the origin of life.

Recognized limitations and knowledge gaps in this hypothesis are the exact size, location and composition of the original gel. However, hypotheses can be formulated in the event that experimentation can be conducted. One possibility is that the composition could have been an aqueous-hydrocarbon mixture [6,21] with a size domain in the micron order of magnitude, attached or stabilized on or between mineral surfaces. It is also possible that the composition of the increasingly more organized prebiotic gel and the central role of water as a component of the gel are both crucial to the origin of life. During the formation of the initial gel and the subsequent transition to the living biofilm, the gel state would provide a protective environment, prevent UV radiation from damaging genetic information, permit diffusion of gases and nutrients, and prevent dehydration. Later, during Darwinian evolution in the biofilm, when cells die, they become available as a source of both nutrients and organic genetic instructions in the form of DNA. The presence of both viable and non-viable cells (lysed and providing a source of DNA) present in the same physical gel location may have had a role in early gene transfer events such as genetic transformation, with the outcome being more rapid evolution of the bacterial cells in the biofilm. An increasing number of viable cells in the biofilm would also be accompanied by an increasing amount of genetic instructions contained in the gel environment. If nucleases were not present, the genetic instructions may have persisted longer periods of time in the biofilm. An immense knowledge gap still exists because it is still not understood how the genetic instructions became embedded in DNA and RNA for the correct protein synthesis during the translation process at the ribosomes.

In a recent review [9], Trevors discussed the organization of precytoplasm and in a book chapter Trevors et al., [10], examined possible environmental locations for the origin of life and discussed a cool origin of life on mineral surfaces in a hydrogel and then biofilm. In this article, the hypothesis is expanded from a prebiotic biogel to a living biofilm and then microbial mats. One type of microbial mat is preserved as laminated layers of successive deposits known as stromatolites, found on the Earth today [22], and may be some of the most ancient preserved biological communities. This transition hypothesis may bring forth new ideas and experimental evidence for the origin of microbial life on the Earth that can be testable via experimentation with existing and synthetic microbiological life.

2. The first prebiotic gel and the transition to a living biofilm

A prebiotic gel of microscopic dimensions with the chemical composition yet to be determined has been hypothesized as the microenvironment for the origin of life. A gel is composed of a polymer network permeated by water [17]. Consider if the polymer network was partly composed of non-biological in origin, hydrocarbons, present at the time the Earth was formed [23]. A warm ancient Earth with mineral surfaces and crevices, bathed in solutions of water and hydrocarbons mixing to form an emulsion may have provided the best of both the hydrophillic and hydrophobic worlds of prebiotic chemistry, for prebiotic cells to make the transition to living cells in an increasing organizing biosystem that was the precursor of what we designate today, a biofilm.

It is rational to hypothesize that an understanding of water, hydrocarbons and gels [11,24] as complex fluids may assist in discovering the origin of microbial life. Even the relative motions of the different component of the interacting fluids may have been central to the polymerisation reactions and macromolecular stability necessary for the origin of life. The prebiotic gel would be an asset in the organization of a gel-like or structured cytoplasm, and at the same time, assist with the organization of a continuous semi-permeable membrane as the precursor of the hydrophilic-hydrophobic characteristics of the precursor to the cytoplasmic membrane (CM). A gel environment containing necessary molecules and elements for the origin of life may have been easier to enclose in a semi-permeable, continuous membrane. The gel is cohesive and provided a stable microenvironment for eventual encapsulation by a membrane.

It could be counter argued that the prebiotic gel and then living biofilm would restrict nutrient availability by its slower diffusion through the prebiotic gel and then the biofilm. However, a microscopic sized gel and hundreds of millions of years of time eliminates the diffusion problem. Possibly, the gel acted as a nutrient trap maintaining the necessary concentrations of molecules and elements required for the organization of life, as heterogeneous fluids bathed the prebiotic gel. From heterogeneous mixtures, the necessary molecules and concentrations became available at a singular microscopic location such a gel, in the microscopic crevices of geological surfaces protected from intense solar radiation by being in a subsurface location, but still receiving some solar radiation that was not harmful.

The prebiotic gel does not cause a diffusion problem but provides a solution to the origin of life – a stable environment, protection, prevents dehydration, protects against extreme pH changes, permits some solar radiation to enter, buffers against decomposition reactions and yet provides a sufficient aqueous environment for polymerisation reactions. The gel structure also keeps the molecules in a somewhat confined environment and prevents their dilution and escape. This type of prebiotic biosystem offers many advantages without the initial presence of an energy source, defined continuous membrane, or the presence of organic genetic instructions. The transition to a living biofilm would require the metabolism, growth and reproduction all dependent on organic, genetic instructions. The gel assists in this by containing the molecules and organizing cellular components in a singular location, which explains in part the rapid emergence of life on Earth. The mechanisms for the organization are still unknown, however, the gel hypothesis solves many challenges for the origin of life as opposed to a harsh, purely aqueous, turbulent environment which has less organization and is more random with higher entropy and polymerisation reactions obeying thermodynamic laws would be more difficult [8], as well as having the correct concentrations of reactants never limiting.

A gel biosystem also offers advantages to organizing the first cell shape as the container for the cytoplasm, core genome, ribosomes and the metabolic pathways. A spherical shaped prebiotic cell (and then living cell) is the worst possible shape for nutrient uptake by diffusion [25]. However, if the surrounding gel traps and supplies the required nutrients, and the spherical cell was very small, which is highly plausible, then the pre-cell and the first living cell(s) are not at a disadvantage. The rod-shaped cells may have a better surface to volume ratio, but they arrived later as a product of evolutionary change. The small, less than micron-sized coccoid bacterial cell in a gel transitioning to a living biofilm is a plausible hypothesis. The need to rely on diffusion process into the gel and the organizing prebiotic cells is not an obstacle. Diffusion meets the needs over small distances and for small pre-cells (the smaller the spherical cells; increases the surface to volume ratio) and then living cells, where the initial amount of cytoplasm present was small in the small spherical cell. Transporter processes would organize later when genetic instructions were present. Moreover, small spherical cells would be surrounded by a diffusion sphere, that is a thin layer of external fluid attached to and surrounding the cells [25]. Such a diffusion sphere may have been more stable in a gel and biofilm and contain the trapped nutrients, molecules and elements required for the prebiotic cells and then the living cells. A diffusion sphere in a turbulent aqueous environment may have not trapped the required molecular building blocks of life as easily.

It has been hypothesized that a hydrophobic medium (HM) of hydrocarbons was the location for the origin of life on Earth [21]. The origin of the hydrocarbons in the hydrophobic medium was polymerization of methane in the atmosphere catalysed by ultraviolet irradiation [21,26] which fell as precipitation to the Earth producing a hydrophobic hydrocarbon layer.

This hydrophobic medium would be conducive to polymerisation reactions as opposed to hydrolysis reactions in water that would favour decomposition, not polymerisation and molecular assembly and cellular organization. A second piece in the puzzle is the eventual need for an energy source at the site of the origin of life, and more ubiquitous as primitive bacterial cells dispersed and colonized the Earth.

The colloidal state that resembles the gel state has been recently discussed by Pollock et al. [27]. Moreover, they hypothesized that the sun's radiant energy separates charges in water capable of inducing condensation mechanisms. This provides supporting evidence as to why water is central to the origin of life as dispersed molecules organized into a more condensed state would have been necessary for the origin of life.

The hypothesized surface biofilm mode of growth is somewhat supported by the microfossil morphology record of coccoid, rod and vibroid shapes) and stromatolites. Biofilms that eventually expanded and became macroscopic mats [22] would be the next postulated stage in evolution. Hansma [28] hypothesized that the voids between mica sheets may have been a possible location for the origin of life where potassium ions were present, polymer entropy was low, and cyclic wetting and drying occurred.

3. Summary

The evidence for early life on the Earth is linked to the geochemistry of the Earth that includes radiation, anaerobic conditions and elevated temperatures that present obstacles to cellular organization.

It is recognized that the hypothesized origin of life proceeding from a prebiotic gel to a living biofilm is a hypothesis and supporting observations and experimentation are required. It is also recognized that the types of experiments that need to be complete are not easy to carry out. This hypothesis should be viewed as speculative but with the potential to stimulate new research directions that may bring forth new knowledge relevant to the origin of life research. One immense difficulty is not knowing the exact composition of the original gel and if was similar to a water-oil emulsion stabilized in some manner on surfaces and in crevices of minerals where all the necessary elements and molecules for a prebiotic biogel were present in sufficient concentrations to not be limiting, so the transition could occur to living cells capable of growth and division in a microscopic scale biofilm. From that time forward, Darwinian evolution would be possible. The prebiotic gel could have provided an environment conducive to polymerisation reactions as supposed to decomposition reactions in a harsher, radiation impacted environment and where nutrients and molecules may have been too dilute for the biological organization of life.

It is well established in the scientific literature that the microbial biofilm mode of growth is very common in our present biosphere. Given the sensitivity of many proteins and nucleic acids to harsh environmental conditions, it is not unreasonable to hypothesize a more stable gel environment for prebiotic life making the transition to living cells and establishing a biofilm biosystem. In addition, the biofilm may have provided the balance between protection from damaging UV radiation while allowing sufficient light to enter the biofilm when the evolutionary transition occurred from anaerobic to aerobic oxygen producing microorganisms.

The warm little pond may have been a microscopic gel, and the gel and biofilm may have been central to the transition from unicellular prokaryotes to higher multicellularity. Microbial biofilms acting as a biosystem and making the transition to microbial mats and preserved as stromatolites have characteristics of a structural unit such as stability, mechanical integrity and cohesiveness; all properties useful in the evolution of microbial cells to multicellular organisms with increasing genome sizes and diversity. However, actual experiments will present challenges to obtaining supportive and non-supportive evidence. If the initial microscopic gel sites were numerous in the millions to billions or even more, then unknown and uncountable failed attempts at the origin of life may have occurred. Also, microscopic gels may have acted in an interactive manner by combining their contents and providing the necessary molecules and concentrations required for the relatively rapid emergence of life on Earth. It is also significant that as the biofilm(s) and mats increased in physical dimensions, diversity and cell numbers, that increases in the organic, genetic information content would also occur.

Disclosure of interest

The author declares that he has no conflicts of interest concerning this article.

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