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Prebiotic Chemistry

Histidine as an origin of life possible precursor

La histidina como un posible precursor en el origen de la vida

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Abstract

The chemical processes occurred during the first years of the evolution of the planet Earth, before the presence of cellular forms, have been continuous reason of studies at experimental level in many laboratories. Considering some possible prebiotic environments, the presence of materials such as clays-type minerals, which could provide chemical and structural elements such as their surfaces, have been given importance and validity to give protection and reactivity to the organic molecules existing in the surrounding environment. These catalytic processes, mediated by mineral surfaces, could give rise in the interstellar medium to a whole range of organic molecules. Many of these are low molecular weights, such as amino acids and carboxylic acids and sometimes molecular weights are much higher. Providing elements that help us to give new evidence about the origin of some molecules of biological importance in the interstellar medium, always enrich the scientific field related to the origin of life, and in particular open new horizons to understand the relevance of physicochemical processes that Could give rise to living organisms on primitive Earth. The present work discusses the possible abiotic synthesis of the amino acid histidine and its importance as an organic catalyst in the formation of oligopeptides in simulations of reactions at the origin of life. In this paper, we discuss the relevance of having histidine monocrystals, simulating a process of hydration-dehydration in shallow pools on the primitive Earth; A phenomenon that is essential for the formation of oligopeptides and, in turn, generate supramolecular assemblies before the appearance of life on our planet.
Keywords: histidine, prebiotic chemistry, molecular evolution, molecular complexity, catalyst.

Resumen

Los procesos químicos que se dieron durante los primeros años de la evolución del planeta Tierra, -antes de la presencia de formas celulares-, han sido motivo continuo de estudios a nivel experimental en muchos laboratorios. Considerando ambientes prebióticos plausibles, se ha dado importancia y validez a la presencia de materiales, tales como minerales y arcillas, que pudieron aportar elementos químicos necesarios para catalizar reacciones químicas y estabilizar otro tipo de compuestos orgánicos. La estructura cristalina de algunas biomoléculas de importancia biológica, así como su estereoquímica pueden llevarnos a comprender algunas de las formas de compuestos descritos en el espacio; en particular los compuestos orgánicos mencionados en algunas meteoritas. Finalmente, aportar elementos que nos ayuden a dar nuevas evidencias sobre el ¿cómo? y el ¿por qué? de la existencia de algunas moléculas de importancia biológica, siempre enriquecen el campo científico, y en particular abren nuevos horizontes para entender la relevancia en los procesos fisicoquímicos y más tardíamente, los procesos metabólicos, que pudieron dar lugar a organismos vivos de tipo unicelular en la Tierra primitiva. En el presente trabajo se discute la importancia de la histidina como catalizador orgánico en los estudios sobre el origen de la vida. Se presentan los resultados preliminares sobre la formación de monocristales de histidina en una disolución acuosa y sus posibles implicaciones como aminoácido esencial para la formación de oligopéptidos. Además se plantea la posibilidad de que este aminoácido haya actuado en un momento dado, como catalizador de ciertas reacciones químicas vitales en muchos seres vivos, apoyando su potencial actividad como catalizador orgánico.
Palabras claves: histidina, química prebiótica, complejidad molecular, catalizador.

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1 Introduction

One of the great questions of all time focuses on how life could be formed and give rise to the great biodiversity that planet Earth presents today. Beyond understanding the concept of life, which in many cases can be abstract by definition, this article seeks to clarify what could be the mechanisms that favored the primitive Earth prebiotic synthesis, which finally gave rise to life. Experiences in laboratories, based on reactions with inorganic compounds such as hydrocyanic acid, ammonia, water, and carbon dioxide, among others, plus the addition of a source of energy (e.g. electricity, ultraviolet light, radiation, etc.) propitiated the formation of certain biomolecules of the type of amino acids, sugars or molecules.

2 From simple molecules to genetic memory

Polymerization reactions of organic compounds with biological relevance and low molecular weight (no more than 10 kDa), have always kept the magnifying glass in the hands of scientists to find answers on the path followed by a synthesis and what products are formed . With this information, these reactions can be equated with those present in living systems. In the 1980s, researcher Stanley Miller (1986) assumed that some of the prebiotic syntheses of small inorganic molecules were carried out in the parental body of certain carbonaceous chondrites meteorites. These bodies could serve as reaction sites for the formation of some relevant molecules in biology.

The nitrogenous bases we identify in DNA, RNA and some ribozymes are the same in all living beings present on the planet today. This is evidence supported by advances in molecular genetics, biochemistry and phylogeny, which supports the idea of the common origin of all living things. Beyond this assertion, the complexity and capacity to self-replicate and preserve a chemical memory is, perhaps, the key element in understanding, with the current biological components, the mechanisms that gave rise to life. This idea is not new. Charles Darwin mentioned in his work "The Origin of Species"that ...

The analogy would lead me to go one step further, or to believe that all animals and plants descend from a single prototype. But the analogy can be a misleading guide. However, all living beings have much in common in their chemical composition, their cellular structure, their growth laws, and in being susceptible to harmful influences ... (Chapter XIV Recapitulation and Conclusion, 1959). These characteristics determined by observation imply that we all descend from a common hypothetical ancestor, which has been called LUCA (Last Universal Common Ancestor). This organism should have the ability to reproduce itself using a metabolic machinery storing information through a chemical code, which would later be interpreted as the genetic code. Thus, chemistry provides an opportunity to clarify how organic compounds formed, which, after many processes, integrated this protobiont or primitive cell (Mosqueira, Negron-Mendoza, & Ramos-Bernal, 2015).

The organic molecules that make up all living things are structured mainly by carbon chains that are concatenated by covalent bonds. However, the presence of certain chemical groups, such as hydroxyl, amino and carboxyl, directly influence its three-dimensional arrangement, chemical reactivity and stability of macromolecules. The spatial distribution of each molecule determines the functionality and activity on a substrate or complex. Amino acids, for example, when bound, constitute proteins, huge molecules that perform different functions that range from being structural, enzymatic, and hormonal or oxygen carriers as the particular case of hemoglobin.

Amino acids by their chemical composition can act as charged or neutral molecules under certain conditions of pH and temperature, causing a reorientation of their charges. Some amino acids form crystals when they are exposed to changes in temperature, when their concentration in aqueous solutions increases, if the pH is modified, or if there are other salts, magnetic fields, which can activate catalyst-like actions by promoting oligomerization among other amino acids (Mosqueira, Negron-Mendoza, & Ramos-Bernal, 2015; Sugahara, H. & Mimura, K., 2014).

For example, crystalline glycine, obtained in hydration-dehydration cycles, promotes reactions, which increase the molecular weight of the other amino acids (RodrÃguez-GarcÃa, M. et al., 2015) and the orientation and elongation of other covalent bonds modify the geometry of the electrostatic forces forming the new peptide.

2.1 The importance of histidine in the origin of life

Histidine, by its catalytic and self-assembling capacity (called self-assembly to a process of spontaneous union of molecules, in which order and supramolecular properties are generated) plays a key role in chemical evolution and prebiotic chemistry. Histidine acquires its name from the Greek "ιστίον" (istosestion) which means mast and loom or tissue (Wikipedia, 2016). It is an essential amino acid characterized by the presence of the imidazole group (the resonant part in Fig. 1) which confers basic properties to it and its derivatives. Only plants and some microorganisms are able to synthesize it (Coordination of Biochemical Education, Faculty of Medicine UNAM, 2017). It is an amino acid linked to catalytic functions, in other words, histidine is present in the active site of several enzymes associated with electron transfer. Histidine not only has structural and catalytic versatility, but also has metabolic versatility, being a precursor of the derivatives of methylated amino acids such as alanine, lysine, methionine, asparagine, aspartic acid and arginine.

Life arose in the early Archean era, after the last intense bombardment (Gómez-Caballero, & Pantoja-Alor, 2003) approximately 3.7 billion years ago (Nutman et al., 2016). This means that by the time the first cell population originated, all amino acids should already have been formed and coupled in self-replicating machinery. Let us say that, in the study of the origin of life, the central discussion is how primitive organic compounds were formed and their subsequent organization in the first cell population (Lazcano, & National Association of Universities and Institutes of Higher Education, 1989 https://www.youtube.com/watch?v=Ewad09KhUKc).

Inorganic ions, including calcium, phosphates or silicates, present in some minerals, along with histidine, could help to form molecules of higher molecular weight (Plankensteiner, Reiner, & Rode, 2005). It is important to recognize that concentrations of organic compounds in the early Earth may have been low (Lazcano, & National Association of Universities and Higher Education Institutes, 1989), making it necessary to increase their concentration at the site where the chemichal reaction takes place (Fig. 2).

In the laboratory of Radiation Chemistry and Radiochemistry attached to the Department of Chemical Evolution at the Institute of Nuclear Sciences of the Universidad Nacional Autónoma de México, stability tests of organic compounds such as nitrogen bases, carboxylic acids and amino acids are carried out mainly to corroborate the chemical behavior and the ability of protection that they present before the exposure to ionizing radiations under conditions of saline saturation in the presence of clays and silicates. From preliminary studies obtained so far, it has been shown that once these organic compounds are in contact with the crystalline network of a clay such as sodium montmorillonite, some physico-chemical properties of the organic compound can be changed, as in the case of guanine that increases its stability when exposed to gamma radiation (Meléndez-López, Ramos-Bernal, & Ramírez-Vázquez, 2014) and, in parallel, increases local concentration by promoting chemical reactions. At the same time, the common processes in natural environments such as hydration-dehydration are able to favor polymerization reactions, causing an increase of the molecular masses of the present compounds. That is, chemical evolution and prebiotic chemistry are strongly associated with aspects of the physical environment such as the presence of water and certain mineral phases.

3 Histidine and its possible prebiotic synthesis

In the prebiotic conditions, it is possible to obtain chemical precursors of histidine and to achieve the synthesis of the whole molecule (Shen, Shen and Oró) Fig. 3. The critical step is the preparation of the imidazole group, starting with an aldehyde, glyoxal and ammonia. The imidazole group is the key in the functioning of histidine as a catalyst. Formaldehyde and ammonia are organic compounds readily found in the universe, specifically in molecular clouds and meteorites (Miller, 1986; Ehrenfreund, & Charnley, 2000). If the synthesis of these compounds occurred spontaneously in the universe, then, it can be thought that the primitive Earth also had this type of compounds that in the end could form these biomolecules abiotically.

In amino acid formation some reactions are key, one of these reactions is the synthesis of Strecker. Imidazole-4-formaldehyde is converted to histidine through this reaction (Fig. 4)..

The Strecker reaction (1850) is actually a set

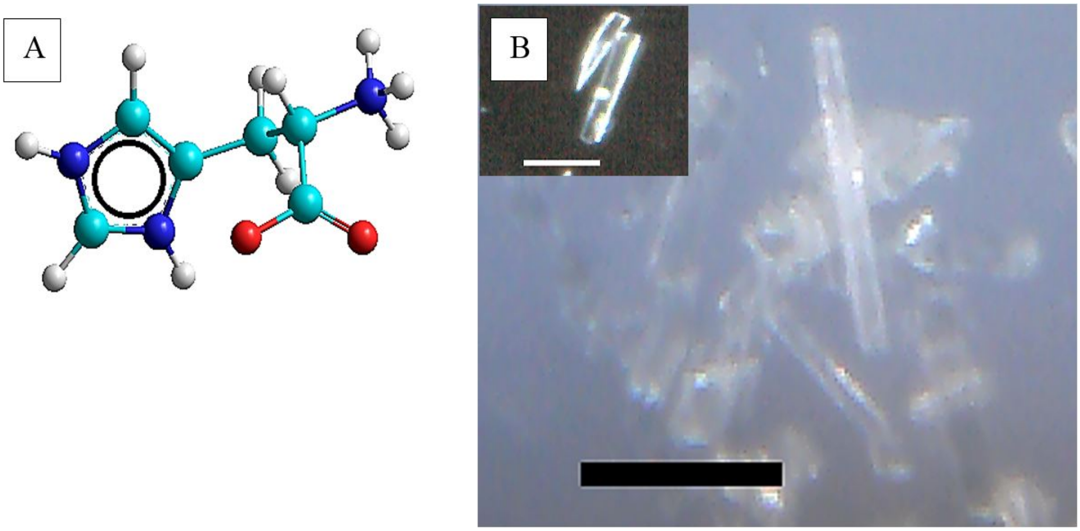

Figure 1. A. Structure of histidine, it has an imidazole group, the ring containing a circle, representing the resonance. B. Histidine crystal obtained in the laboratory (scale bars ca. 100 um) can serve as a catalyst

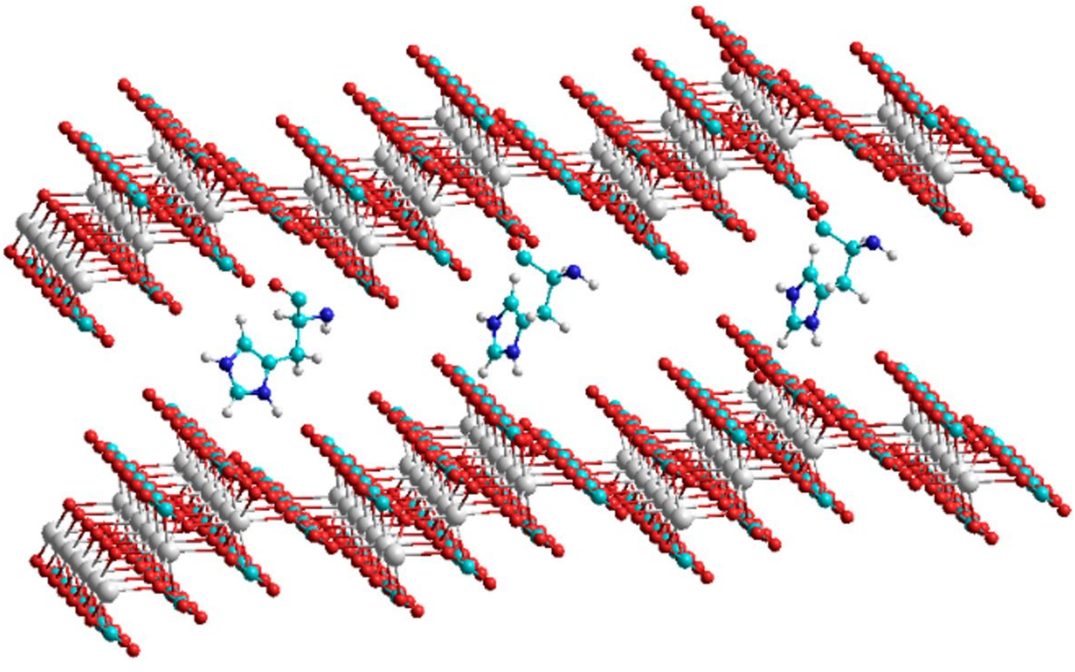

Figure 2. The mineral surfaces could be a center of concentration of organic compounds. In these, the electrostatic interactions and those of the type of hydrogen bridge could be of great relevance. The figure shows the interaction between histidine molecules and a computationally simulated montmorillonite.

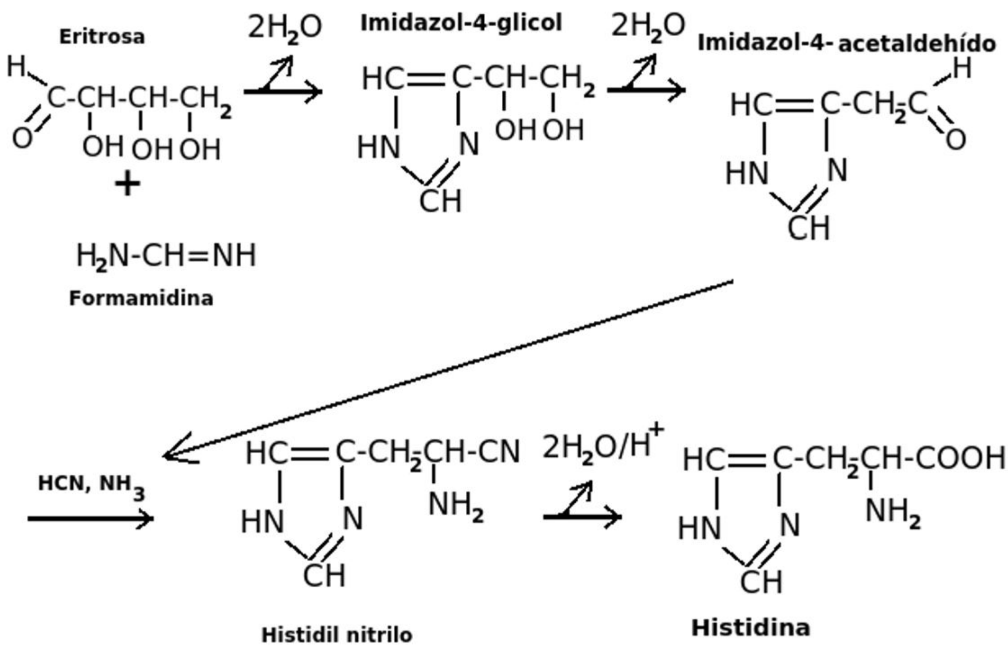

Figure 3. Formation of histidine from erythrosa (a sugar). It can be seen that the synthesis of this amino acid involves the loss of several molecules of water, to achieve the formation of the imidazole ring.

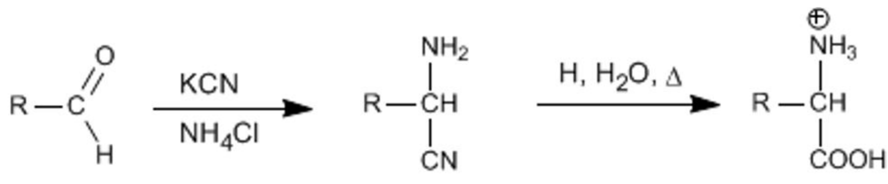

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Figure 4. Mediante la reacción de Strecker se sintetizan aminoácidos de forma abiótica.

of chemical reactions, which generate amino acids from aldehydes or ketones. In addition, histidine was able to contribute to the formation of other compounds of great biological relevance such as the so-called .^{en}ergy currencies"(Shen, et al., 1990, 2016) as a catalyst. In current organisms, the formation of these çoinsïs mediated by histidine. This makes us suppose that histidine could generate chemical reactions similar to those that we see in the laboratory at the moment, reason why its synthesis was crucial for the prebiotic chemistry.

4 The imidazole group traveling in the interstellar medium

There is not much information about the presence of histidine in extraterrestrial bodies. On the other hand, the presence of the imidazole group has been confirmed in different carbonaceous meteorites (Ehrenfreund, & Charnley, 2000) as Murchison (Oba, & Naraoka, 2006). This makes us assume that the synthesis of this compound could occur during space travel. An alternative is that the impact chemistry could offer additional ways for the molecule to be synthesized in its fall to the Earth, although other possibilities exist, such as being formed by surface reactions on the minerals irradiated by the emissions of a young Star (Gaustad, & Vogel, 1982). On the other hand, the complex molecules found in the Murchison meteorite are already complex molecules (Figs 3 and 4). In our studies, we considered it important to simulate computationally molecular physicochemical environments to form molecules of the histidine type, which as mentioned above, has only been found on Earth as a product of biological activity. Using these types of tools could determine what pressures; temperatures and which of the imidazole derivatives could react more easily to give rise to this important amino acid.

Molecular evolution is a further step in the complication of organic matter. For example, it can be said that a linear molecule is of less complexity to a branched molecule, even if it has the same molecular mass. This is an example of molecular evolution (Fig. 6).

In the case of amino acids, an increase in molecular mass may lead to the formation of peptides, and again, impact chemistry, could be the promoter of these polymerization reactions.

In this overview of chemical evolution to form the amino acid histidine, we have some relevant observations to consider. For example, the precursors of histidine and those of nucleotide bases are similar. The fact is that histidine behaves chemically in a very versatile way, which could bring answers to the synthesis routes of both groups of compounds. In these cases the computational models are necessary to obtain additional data to the studied phenomenon.

5 Conclusions

Here we review the current outlook of the studies that link the structure of histidine and its chemical capacity to have different physicochemical properties. These data help us understand that this relatively simple molecule could have a relevant role in local chemical transformation before the onset of life.

Currently, our interest is directed to investigate the consequences of the interaction of histidine and imidazole with other amino acids, with inorganic ions and minerals rich in phosphates. In our preliminary results, we are able to form histidine crystals and they are subjected to irradiation experiments with gamma radiation and hydration-dehydration processes, which will lead us to understand the molecular pathway by which histidine behaves as a catalyst. We want to understand how these chemical compounds were able to transform into other biomolecules of higher molecular weights and if we can place this chemical transformation in a punctual phenomenon that helps to know more about the prebiotic history on Earth and the universe. In general, our projects want to transfer data from chemical evolution to phenomena of molecular evolution to explain, as far as possible, the origin of life.

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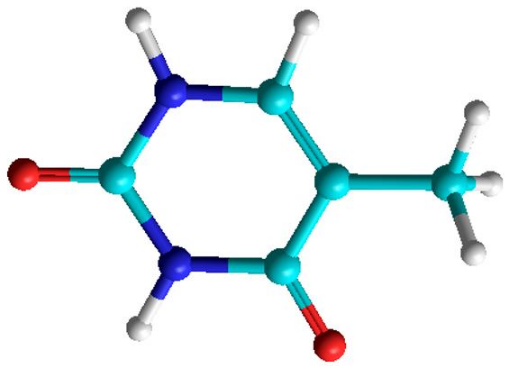

Figure 5. Thymine, found in the Murchison meteorite.

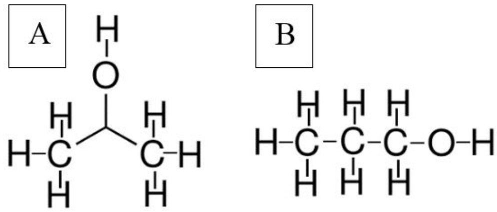

Figure 6. The same molecular mass can give rise to several geometries and this is an example of molecular evolution. Isopropanol (A) and propanol (B) are an example of geometric variation of the molecule without varying the molecular mass (molecular mass of both is 60 g/mol).

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