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A theoretical approach to the link between oxidoreductions and pyrite formation in the early stage of evolution

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Abstract

There are two fundamental axioms of surface metabolism theory: (i) pyrite formation from H_2S and FeS is proposed as a source of energy for life, and (ii) archaic reductive citric acid cycle is put into the center of a metabolic network. However, the concept fails to indicate how sulfide oxidation ought to be coupled to processes driven by free energy change occurring during pyrite production, and secondly, how reductive citric acid cycle ought to be supplied with row material(s). Recently, the non-enzymatic methylglyoxalase pathway has been recommended as the anaplerotic route for the reductive citric acid cycle. In this paper a mechanism is proposed by which the oxidation of lactate, the essential step of the anaplerotic path, becomes possible and a coupling system between sulfide oxidation and endergonic reaction(s) is also presented. Oxidoreduction for other redox pairs is discussed too. It is concluded that the S^o/H_2S system may have been the clue to energy production at the early stage of evolution, as hydrogen sulfide produced by the metabolic network may have functioned as a coupling molecule between endergonic and exergonic reactions.

Keywords: Surface metabolism; Pyrite; Oxidoreduction; Common intermediate; Methylglyoxalase pathway

1. Introduction

Prebiological evolution is the history of the origin of cell including the explanation of how primordial cell got separated from the surroundings, became metabolically active and developed genetic machinery. The first comprehensive hypothesis became known as primeval soup theory of Oparin. However, in 1988 a new chemoautotrophic scenario for the origin of life was presented by Wachtershauser [1]. It was postulated that the energy needed for endergonic reactions was provided by the formation of pyrite (FeS_2) from hydrogen sulfide (H_2S) and ferrous sulfide (FeS) [1]. Furthermore, the hypothesis supposed that the constituents of network were anchored to a charged surface of iron-sulfur layer [2].

In the literature, the FeS/H_2S system is referred to as a strong reducing agent ($\varepsilon'_o = -0.62$ Volt) and the reaction:

$$FeS + H_2S \rightarrow FeS_2 + H_2 \qquad \Delta G'_o = -38.58 \text{ kJ/mol} \tag{1}$$

is said more than favorable as having a standard free energy change of $\Delta G'_o = -9.23$ kcal/mol (-38.58 kJ/mol) [3–5]. This source of energy is thought to have simply been used for supplying appropriate driving force for primary reductions [3]. However, a mechanism for the oxidation of intermediates participating

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in metabolic pathways has not been presented yet. The question emerges, if pyrite formation was the reaction providing energy for prebiotic metabolic machinery, how it was fulfilled. Namely how endergonic and exergonic reactions were interconnected.

Nowadays some experimental data support the view that the FeS/H_2S system may effectively reduce various organic compounds under unaerobic experimental conditions [6,7]. Nevertheless, in underlying experiments external H_2S was added to the reaction mixtures in a final concentration of 2 mM [6–8]. This raises the problem whether under prebiotic conditions the concentration of H_2S had ever been as high as provided in the experiments.

As to the nature of the first chemical pathways, according to the theory of Wachtershauser, those were organized into interconnected cycles in such a manner that reductive citric acid cycle was put in the center of metabolic machinery [3]. Nonetheless, the anaplerotic reactions suggested for the reductive citric acid cycle were too complex and seemed unlikely to have operated at any time [9]. This has been the reason of why recently a more plausible way involving the non-enzymatic methylglyoxalase pathway and formose cycle has been proposed for the ignition of reductive citric acid cycle [9]. The critical point of this pathway has been the oxidation of lactate into pyruvate [9], since no mechanism for the oxidation of constituents has been suggested in the surface metabolism concept yet. To overcome this obstacle, a theorem has been raised in our previous paper, in which the biogenic formation of H_2S from elemental sulfur accompanying dehydrogenations has been supposed [9].

In this article the possible way of oxidoreductions and their thermodynamic background with special interest in the role of the S^o/H_2S system will be discussed. To make a closer look at these reactions, as an example, the oxidation of lactate to pyruvate will be analyzed in details as well as the metabolic source and fate of H_2S will also be shown.

2. Suggestion for the oxidation of lactate into pyruvate under prebiotic conditions, and the link between pyrite formation and lactate oxidation

The interconversion of pyruvate and lactate requires another redox pair functioning as hydrogen acceptor or donor. In the extant metabolism, $NADH+H^+/NAD^+$ or $FADH_2/FAD$ are usually the redox partners for lactate/pyruvate couple. Taking the lactate/pyruvate and $NADH+H^+/NAD^+$ redox systems, the standard reduction potentials for interacting redox pairs are $\varepsilon'_o = -0.19$ Volt and $\varepsilon'_o = -0.32$ Volt, respectively [10]. From the above values it follows that on its own, the equilibrium of the reaction between lactate and pyruvate is shifted towards lactate formation, that is lactate production would be preferred over pyruvate formation. Indeed, despite the facts mentioned above, under normal conditions there is no way for lactate accumulation in the cells, since both pyruvate and $NADH+H^+$ are used up in metabolism. However, the question emerges how this reaction might have been managed during prebiological evolution since it seems unlikely that in the course of early evolution NAD^+ or other hydrogen transporting compounds might have existed. But rather inorganic molecules might have been involved in this process.

One candidate system is the S^o/H_2S system having a standard reduction potential of $\varepsilon'_o = -0.24$ Volt [11]. The oxidation of lactate to pyruvate with the parallel reduction of sulfur to H_2S in a way shown in the equation:

$$\begin{aligned} & H_3C-CH(OH)-COOH+S^o_{(rhomb)} \\ & \quad \rightarrow H_3C-CO-COOH+H_2S \\ & \quad \Delta G'_o = +9.62\ \mathrm{kJ/mol} \end{aligned} \tag{2}$$

is an endergonic process as the standard free energy change calculated on the basis of standard reduction potentials presented, comes $\Delta G'_o = +9.62$ kJ/mol [9]. This corresponds to an equilibrium constant of 0.02 for the reaction [9]. Although the free energy change in this reaction is smaller than the free energy change ($\Delta G'_o = +25.2$ kJ/mol) determined for the interconversion of lactate into pyruvate when nicotinamide dinucleotide is used as hydrogen acceptor [10], on its own this reaction also favors lactate formation over pyruvate production. Though the above reaction is correct in thermodynamical terms, its link to the general way of energy production being suggested during pyrite formation is still unknown.

Eq. 2 shows that in the reaction between lactate/pyruvate and S^o/H_2S redox pairs lactate formation by the dehydrogenation of H_2S is preferred over the opposite reaction. Consider the mechanism shown in Eqs. 1 and 2), and summarized in the equation:

$$\begin{aligned} &H_3C-CH(OH)-COOH+S^{o}_{(\mathrm{rhomb})}+FeS \\ &\rightarrow H_3C-CO-COOH+FeS_2+H_2 \\ &\Delta G'_{o}=-28.96\ \mathrm{kJ/mol} \end{aligned} \tag{3}$$

In this case the produced H_2S is stoichiometrically consumed in the reaction in Eq. 1, pyrite is formed and the reaction goes forward to pyruvate formation. The overall free energy change in the series of reactions makes the whole process exergonic and H_2S is the clue to the link between the reactions in Eqs. 1 and 2. In this manner one of the most foremost problems of surface metabolism theory, the missing coupling system having been criticized by de Duve and Miller [12], is solved. Furthermore, if we add that pyruvate may enter reductive citric acid cycle and hydrogen may diffuse away, thus decreasing the concentration of products, it is clear that the reaction is thermodynamically favorable. Since H_2S formation takes part in the above reactions its in situ prebiogenic production is guaranteed.

All of these assumptions seem to give support for the point that FeS/H_2S may play a role in the above oxidoreduction as driving force. However, a central point in surface metabolism theory is that chemical reactions go forward on a charged ore surface to which they are anchored. In watery organic electrolyte the corrosion of pyrite occurs according to the reaction:

$$\begin{aligned} &FeS_2+2H_2O\rightarrow Fe(OH)_2S_2+2H^{+}+2e^{-} \\ &\rightarrow Fe^{2+}+2S^{i}+2H_2O \end{aligned} \tag{4}$$

This reaction not only liberates Fe^{2+}, but also creates pyrite lattice bound sulfur (S^{i}) [13]. The electromotive force for S^{i}/H_2S redox pair is $\varepsilon'_{o}=-0.142$ Volt [13]. On the basis of the above redox potential the availability of chemical energy, the standard free energy change for the reaction:

$$\begin{aligned} &H_3C-CH(OH)-COOH+S^{i} \\ &\rightarrow H_3C-CO-COOH+H_2S \\ &\Delta G'_{o}=-9.23\ \mathrm{kJ/mol} \end{aligned} \tag{5}$$

has been calculated from the standard redox potential difference ($\Delta\varepsilon'_{o}=0.048$ Volt). The value of calculated free energy change ($\Delta G'_{o}=-9.23$ kJ/mol) corresponds to an equilibrium constant of 42 for the reaction. This means that theoretically the whole redox process, in contrast to the reaction in Eq. 2, is sufficiently exergonic to allow pyruvate formation. Nevertheless, it should be noted that its relevance in biooxidation has to be questioned for the reason of strong acidity needed for the reaction in Eq. 4 to proceed. This note is meaningful since it is doubtful whether there had been any part of primeval terrestrial sea where the milieu would have been as acidic as pH 1.7 [13]. It is rather suggested that the prevailing conditions in the aqueous environment were mildly basic or neutral [14,15]. And further, the conversion of methylglyoxal into lactate, a reaction pathway that was suggested to be fundamental for the ignition of reductive citric acid cycle [9], would not proceed in strongly acidic environment [16]. So whatever else it is or whatever scientific merit the reaction in Eq. 4 otherwise might have, now it seems that it cannot be central to chemical evolution implying lactate/pyruvate interconversion.

3. Possible oxidation of carboxylic acids other than lactate

The redox potentials for some redox couples connected to normal hydrogen electrode are listed in Table 1. The corresponding free energy changes are also shown (Table 1). As seen, the lactate/pyruvate couple is the most favorable to take place in such reaction providing support for their involvement in an anaplerotic route for reductive citric acid cycle. Nevertheless, other reactions are also likely to occur. As shown in a generalized form in the equation:

$$\begin{aligned} &R-CH(OH)-COOH+S^{o}_{(\mathrm{rhomb})}+FeS \\ &\rightarrow R-CO-COOH+FeS_2+H_2 \end{aligned} \tag{6}$$

the mechanism of coupling reactions remains hidden, but in effect they use elemental sulfur and via H_2S formation they produce pyrite at a pH being almost physiological in the extant metabolism.

Table 1

Redox potentials of electron donors and acceptors, and free energy changes and equilibrium constants for their redox reactions coupled to S^o/SH_2

Redox pair	Redox potential[a] (mVolt)	$\Delta G'_o$ (kJ/mol)[c]	Equilibrium constant (K)[d]
Lactate/pyruvate	−190	9.62	2×10^{-2}
Oxaloacetate/malate	−172	13.08	5×10^{-3}
Acetoacetate/β-hydroxy-butyrate	−152[b]	16.92	1.1×10^{-3}
Acrylyl-CoA/proprionyl-CoA	−15	21.63	1.6×10^{-4}
Fumarate/succinate	33	26.25	2.4×10^{-5}

[a] Data have been taken from [20] with the exception of b.

[b] This redox potential has been calculated from the $\Delta G'_o$ value for acetoacetate+$H_2 \Rightarrow$ β-hydroxy-butyrate reaction [20].

[c] $\Delta G'_o$ values for the reactions between given redox pairs and S^o/SH_2 have been calculated on the basis of the following equation: $\Delta G'_o = -nF\Delta\varepsilon'_o$, where n = number of electrons transferred in the reaction, F [Faraday constant] = 23 kcal/Volt equivalent, $\Delta\varepsilon'_o = \varepsilon'_o(S^o/SH_2) - \varepsilon'_o$(for the given redox pair). Data have been given to the second decimal after correction.

[d] Calculation has been made by using the equation of $\Delta G'_o = -1.36 \log K$, where the unit for $\Delta G'_o$ is given as kcal/mol.

4. Discussion and conclusions

The only way for the transfer of chemical energy from one chemical reaction to another is to have a common intermediate [17]. The nature of such an intermediate has not been elucidated in the surface metabolism theory, yet [1,3,12]. In this paper a set of simple reactions is shown under conditions which might have been present in the prebiotic Earth and which may be relevant to extant metabolism, as well (Table 1). All the reactions considered in this report proceed under very primitive conditions. Eq. 6, the sum of individual reactions, does not show how H_2S serves as a link between oxidoreductions and pyrite formation. However, these unusual oxidations, e.g. that of lactate into pyruvate, form H_2S being consumed in pyrite formation, thus providing a direct linkage between exergonic and endergonic reactions (Eqs. 1, 2 and 3). In contrast to surface metabolism theory, in the above scenario, H_2S is produced as an intermediate of network and therefore the system is not dependent on the concentration of H_2S in the surroundings. Furthermore, H_2S can diffuse away from the space of its generation and thus it provides substrate for pyrite formation in other places of mineral surface. And in this way H_2S transfers hydrogen and electrons as a special, mobile carrier, and also prevents its own accumulation.

An important factor in determining which reaction may be of evolutionary significance, is the pH. It is likely that the pH in the aqueous environment at the early stage of evolution was basic or neutral [14,15]. And this is in accordance with the pH requirements for the reactions presented here and this is the fact that makes the use of standard values for calculations possible.

Theoretically the surface bound sulfur might have served as an alternative being produced during the corrosion of pyrite shown in Eq. 4. Even though, on the basis of thermodynamical calculations, its participation in lactate/pyruvate conversion would make the reaction exergonic, the strong acidic milieu required for the reaction impedes any biological relevance.

Iron-sulfur proteins are very common in all forms of cells and are inserted into energy producing processes [18,19]. Their use in such reactions is to be a fundamental mode of how life operates. Probably, their origin has to be traced back to the advent of life when iron-sulfur minerals might have participated in reactions providing driving force for endergonic reactions.

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