Did nature also choose arsenic?

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Abstract: All known life requires phosphorus (P) in the form of inorganic phosphate (PO$_4^{3-}$) and phosphate-containing organic molecules. P$_i$ serves as the backbone of the nucleic acids that constitute genetic material and as the major repository of chemical energy for metabolism in polynucleotide bonds. Arsenic (As) lies directly below P on the periodic table and so the two elements share many chemical properties, although their chemistries are sufficiently dissimilar that As cannot directly replace P in modern biochemistry. Arsenic is toxic because As and P are similar enough that organisms attempt this substitution. We hypothesize that ancient biochemical systems, analogous to but distinct from those known today, could have utilized arsenate in the equivalent biological role as phosphate. Organisms utilizing such ‘weird life’ biochemical pathways may have supported a ‘shadow biosphere’ at the time of the origin and early evolution of life on Earth or on other planets. Such organisms may even persist on Earth today, undetected, in unusual niches.

Key words: Arsenic, phosphate, weird life, shadow biosphere, origins of life.

Phosphorus (P) ranks just behind hydrogen, oxygen, carbon and nitrogen (H, O, C and N) in a quantitative list of the most important elements in biology (Voet & Voet 1990). However, P is usually less available to life than these other elements, particularly in the oceans. H and O are available in any aqueous solution, while C and N can be found in gaseous compounds that are readily distributed through the atmosphere and that can be converted into highly soluble chemical forms. Although there is some speculation about extraterrestrial input of P to Earth, early life may have been mainly dependent on crustal elements (Pasek 2008). In contrast, while P is a relatively common element in the Earth’s crust (0.1% by weight) (Winter 2007), there is no gas phase P compound analogous to CO$_2$, CH$_4$, N$_2$ or NH$_3$, and common phosphate minerals such as apatite (Ca$_5$(PO$_4$)$_3$(OH, F, Cl)) are only sparingly soluble (Stumm & Morgan 1996). The distribution of bioavailable P at the Earth’s surface is therefore extremely heterogeneous. Although there is some speculation about extraterrestrial input of P to Earth, early life may have been mainly dependent on crustal elemental sources (Pasek 2008). In this way, P is similar to many of the so-called ‘micronutrient’ elements that are required in biology in trace amounts (e.g. Fe, Cu, Mn and Zn). As a result, the distribution of life at the Earth’s surface is often determined by the distribution of P, which is why phosphate (PO$_4^{3-}$) fertilizers are commonly used to compensate for low P concentrations.

Twenty years ago, Westheimer explained why life as we know it is based on P (Westheimer 1987). A critical feature is the acid–base chemistry of P in the 5+ oxidation state (P(V)) in the form of phosphoric acid (H$_3$PO$_4$), which dictates that the dominant soluble forms of P at biological pH (~7–8) are the charged species H$_3$PO$_4^{2-}$, HPO$_4^{3-}$ and PO$_4^{4-}$ (collectively, these species and H$_3$PO$_4$ are referred to as ‘inorganic phosphorus’ or P$_i$). Charged molecules are more easily contained within lipid membranes than are uncharged molecules, and hence evolution selected for biomolecules that include functional groups derived from P$_i$ and other weak acids such as carboxylic acids and amino acids (Davis 1958). However, P$_i$ is unique even among these weak acids because it can maintain a negative charge at physiological pH even when bonded to two other molecular units. Hence, as the building block for adenosine triphosphate (ATP) and adenosine diphosphate (ADP), P$_i$ prevents chemically stored energy from escaping the cell. Similarly, the repeating phosphodiester linkages in deoxyribonucleic acid (DNA) effectively make DNA a polyanion, so that P$_i$ helps cells retain the genetic material. The negative repeating charge of DNA is also a key factor in its physical stability in the way it prevents folding of the linear strand, thereby protecting template-like behaviour (Benner & Hutter 2002). Hence, P$_i$ is well suited as a component of both metabolic and genetic molecules.

However, other elements share key chemical properties with P. Of these arsenic (As) in the (V) oxidation state warrants closer inspection. Inorganic As(V), like P(V), is negatively charged over a range of physiological pH conditions, as H$_2$AsO$_4^{2-}$, HAsO$_4^{3-}$, or AsO$_4^{5-}$ (i.e. arsenate or As$_i$). In fact,
the dissociation constants for \( \text{H}_3\text{AsO}_4 \) are so similar to those of \( \text{H}_3\text{PO}_4 \) that \( \text{As}^3 \) and \( \text{P}^5 \) follow strikingly similar speciation patterns (Figure 1A and B). Also, like \( \text{P}^5 \), \( \text{As}^3 \) is capable of retaining a negative charge even when it bonds to two other molecules. Owing to these similarities, known life cannot easily distinguish between \( \text{As}^3 \) and \( \text{P}^5 \). Thus, arsenate is taken up by cells via phosphate transporters and can substitute for \( \text{P}^5 \) in the early steps of many \( \text{P}^5 \)-based metabolic pathways (Braunstein 1931; see Table 1). For example, As is generally thought to decouple oxidative phosphorylation, the production of ATP using energy released by oxygen-consuming redox reactions, because no ATP is produced in phosphate-depleted, arsenate-rich mitochondrial particles even though oxygen uptake continues. This observation suggests that arsenate substitutes for phosphate in the early steps of this process (Crane & Lipmann 1953). These similarities account in large measure for the biological toxicity of \( \text{As}^3 \).

Why, despite these similarities, has the possibility of \( \text{As}^3 \)-based life been discounted? The primary chemical objection is that \( \text{As}^3 \)-based compounds hydrolyse much more rapidly than their \( \text{P}^5 \) counterparts (Westheimer 1987). In particular, polyarsenates hydrolyse orders of magnitude faster than do polyphosphates. However, this objection is not decisive. For example, the same type of problem exists for nucleic acids. As we shall argue, chemically exceptional aquatic environments and natural selection both offer solutions, particularly when considered in the context of prebiotic chemistry and the evolution of early life (Levy & Miller 1998). Similar logic could apply here.

The relative instability of polyarsenates does not rule out a role for \( \text{As}^3 \) in environments in which it is present at much higher concentrations than \( \text{P}^5 \). Such settings could sustain elevated steady-state concentrations of polyarsenates and other \( \text{As}^3 \)-based biomolecules versus \( \text{P}^5 \)-based analogues despite the faster reaction rates of the former. Intriguingly, such environments include both terrestrial and deep-sea hydrothermal systems (Von Damm 1990; Wilkie & Hering 1998; Langner et al. 2001) where life is conjectured to have originated (Corliss et al. 1979; Martin & Russell 2003) and where the last common ancestor may have avoided surface-sterilizing meteor impacts of the Late Heavy Bombardment (Maher & Stevenson 1988; Miller & Bada 1988; Sleep & Zahnle 1998). In these systems, As and many other elements react with hydrogen sulphide to precipitate as sulphide minerals, forming the famous ‘chimneys’ of undersea ‘black smoker’ volcanoes. The surfaces of these minerals, rich in bioessential arsenic species (C) in the systems \( \text{P}_2\text{O}_5 \cdot \text{H}_2\text{O} \) and \( \text{As}_2\text{O}_3 \cdot \text{H}_2\text{O} \) at 25 °C and 1 bar total pressure. Arsenic (solid lines) and phosphorus (dashed line) species have been overlaid within the bounds of the \( \text{O}_2 \cdot \text{H}_2\text{O} \) redox couple (dotted lines). On such a diagram, phase boundaries represent the conditions at which the activities of the species on each side of the boundary are equal (Morel & Hering 1993; Smedley & Kinniburgh 2002). Under dysoxic conditions (pe = 0) and at neutral to mildly alkaline pH, the dominant As species is \( \text{HAsO}_4^{2-} \) suggesting that it would be present under conditions possibly relevant to the early evolution of life on Earth.

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**Fig. 1.** pH and redox potential (pe) are the most important factors controlling arsenic speciation. Phosphate (A) and arsenate (B) speciation are shown as a function of pH for the (V) oxidation states. \( \text{H}_3\text{PO}_4 \) or \( \text{H}_2\text{AsO}_4^- \) (dashed and dotted line), \( \text{H}_2\text{PO}_4^- \) or \( \text{H}_2\text{AsO}_4^- \) (dashed line), \( \text{HPO}_4^{2-} \) or \( \text{HAsO}_4^{2-} \) (dotted line) and \( \text{PO}_4^{3-} \) or \( \text{AsO}_4^{3-} \) (solid line) are all indicated as a percentage of total \( \text{P} \) or \( \text{As} \). The distribution curves in (A) and (B) show that \( \text{As}^3 \) and \( \text{P}^5 \) have similar charge and speciation under biologically relevant pH (Westall et al. 1976; Allison et al. 1991; Serkiz et al. 1996). Redox speciation is shown on a pe-pH diagram for aqueous
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Table 1. Evidence of arsenate substitution for phosphate by modern, extant biochemical processes

| Reaction or enzyme | Arseno-analogue | Phosphate compound | Reference |
|--------------------|----------------|-------------------|-----------|
| Adenylate deaminase | 5’AMAs | 5’AMP | Lagunas et al. (1984) |
| Adenylate kinase | 5’AMI(CH$_2$)As | AMP | Adams et al. (1984) |
| Aspartate aminotransferase | Pyridoxal arsenate | Pyridoxal phosphate | Ali & Dixon (1992) |
| Chloroplastic electron transport | ADP-As | ATP | Avron & Jagendorf (1959) |
| Glucose-6-phosphate dehydrogenase | Glucose-6-arsenate | Glucose-6-phosphate | Gresser (1981) |
| Hexitolase | ADP-As | ATP | Gresser (1981), Moore et al. (1983) |
| Human red blood cell sodium pump | As$_i$ | P$_i$ | Kenney & Kaplan (1988) |
| Mitochondrial O$_2$ consumption | As$_i$ | P$_i$ | Crane & Lipmann (1953) |
| Myokinase | AMAs | AMP | Lagunas et al. (1984) |
| RNA polymerase | Pyroarsenate | Pyrophosphate | Rozovskaya et al. (1984) |
| R. rubrum light induced phosphorylation | ADP + As$_i$ | ADP + P$_i$ | Slooten & Nuysen (1983) |
| Phosphoenolpyruvate mutase | Arsenopyruvate | Phosphonopyruvate | Chawla et al. (1995) |
| Phosphotransacetylase | As$_i$ | P$_i$ | Kyrtopoulos & Satchel (1972) |
| Protein synthesis | ADP-As hydrolysis | ATP hydrolysis | Ozawa et al. (1970) |
| Purine nucleoside phosphorylase | As$_i$ | P$_i$ | Kline & Schramm (1993) |

trace metals and S, and bathed in fluids containing dissolved volatiles such as CO$_2$ and N$_2$ (Forrest et al. 2005), are widely recognized as a promising environment for prebiotic catalytic chemistry and early life (Schoonen & Xu 2001; Brandes & Devol 2002). Importantly, As, unlike P, forms sulphide minerals, rendering it far more accessible than P for (bio)-chemical reactions occurring on hydrothermal sulphide mineral surfaces. Although present in these minerals in a highly reduced form, arsenic (AsO$_3^{3-}$) and arsenate are thermodynamically and kinetically stable even in anoxic waters at pH $>$ 7, as long as the concentration of sulphide is low (Berner 1981; Smedley & Kinniburgh 2002; Oremland et al. 2004). Such chemical conditions probably typified the Archean oceans (Canfield 2005), so that As$_i$ could have been available near the surfaces of As-rich sulphide minerals where As sulphides dissolved in seawater.

If arsenate is present then, in striking contrast to their P$_i$ analogues, As$_i$ biomolecules indeed form spontaneously. For example, in vitro mixtures of adenosine (or a deoxy analogue) and As$_i$ readily form As-nucleosides and As-nucleotides (Lagunas et al. 1984) (Figure 2). Furthermore, these synthetic 5’AMAs can substitute for 5’AMP in reactions catalysed by the enzymes myokinase and adenylyl deaminase (Lagunas et al. 1984). Thus, rapid hydrolysis per se may be unproblematic in environments rich in As$_i$, as key molecules can be quickly replenished.

It is interesting to speculate that the reactivity of polyarsenates versus polyphosphates might have actually been a virtue in prebiotic chemical systems or ancestral organisms. Owing to the stability of P$_i$ compounds, all known organisms require sophisticated enzymes to catalyse the removal or addition of P$_i$ (phosphatases and kinases, respectively). As$_i$ compounds might have needed less sophisticated molecular machinery to fulfill their biochemical roles in ancient systems, facilitating the development of P$_i$-like metabolism. It is perhaps no coincidence that it is relatively simple, through site-directed mutagenesis, to change an arsenate reductase to a phosphatase (Rosen 2002). One interpretation of this similarity is that reductases derive from phosphatases. However, an equally plausible interpretation is that the fundamental biochemistry of P$_i$-based life emerged in an As-rich environment.

Natural selection could have stabilized As$_i$ biomolecules, analogous to the ways that P$_i$-bearing biomolecules have evolved stability against hydrolysis. The phosphodiester bonds of ribonucleic acid (RNA), for example, are stabilized in vivo by 5’ and 3’ end modifications as well as by numerous protein interactions (Deana & Belasco 2005; Slomovic et al. 2005; Petrillo et al. 2006). Without these mechanisms, the phosphodiester linkages to ribose hydrolyse within seconds under biological conditions (Lindahl 1993; Selinger et al. 2003). Moreover, in vitro studies replicating thermophilic environments where early life may have resided show the rate of RNA hydrolysis steadily increases as temperature rises from 65 to 100 °C (Eigner et al. 1961), approaching reaction rates which are comparable to those for short strands of polyarsenates (Kawamura 1999, 2001a,b; Nagahama & Kawamura 2002; Kawamura et al. 2005). It is therefore plausible that As-based life emerged in As-rich environments and, once established, evolved strategies that would enable it to persist.

A second objection to As raised by Westheimer is that it is easily reduced from As(V) to As(III), whereas P is rarely reduced from P(V) at the Earth’s surface (Westheimer 1987). Although this difference poses some challenges to As-based metabolism, it also implies some benefits because the redox properties of As provide possible bioenergetic pathways. Indeed, some extant microorganisms exploit this metabolic opportunity (Stolz & Oremland 1999; Rosen 2002; Bhattacharjee & Rosen 2007). As$_i$ can serve as an electron acceptor by anaerobic heterotrophic bacteria that oxidize reduced carbon and produce arsenite (Dowdle et al. 1996; Stolz & Oremland 1999; Oremland et al. 2002; Oremland & Stolz 2003), in chemolithohautotrophic arsenite oxidizers that fix inorganic carbon and produce arsenate (Ehrlich 2002) or in cyanobacteria and purple bacteria that use arsenite as an electron donor in anaerobic photosynthesis (Kulp et al. 2008). Therefore, far from being a liability, the redox
character of As potentially makes it more biochemically versatile than P.

Once life ventured forth from its As-rich primordial home, the balance of advantage probably tipped in favour of P because P is typically 10,000 times more abundant than As at the Earth’s surface. However, As-based life could even survive today in restricted pockets where As is present in abundance, such as shallow and deep-sea hydrothermal systems or at Mono Lake (Von Damm 1990; Pilcher et al. 1999; Oremland et al. 2002, 2004; Roesler et al. 2002).

In conclusion, there seems to be no knockout argument against As-based life, and considerable circumstantial evidence to suggest its plausibility. In recent years, astrobiologists have devoted considerable attention to exploring the possibility of alternative forms of extraterrestrial life (dubbed ‘weird life’) (Baross 2007). Curiously, little thought has been devoted to the possibility that the Earth may have once also harboured weird life. It is a tantalizing prospect that an ancestral, alternative form of life might even continue to lurk in modern As-rich Earth habitats forming an extant ‘shadow biosphere’ (Cleland & Copley 2006; Davies et al. 2009). A search of such environments would seem to be a promising initial step to test this hypothesis. In view of the extensive consideration given to the possibility of emergent life on other planets, it would be ironic if we overlooked a candidate right here on Earth.

Fig. 2. Examples of both described and yet undetected arsenate containing biological molecules (at pH 7): (A) As-deoxyribonucleic acid (As-DNA); (B) As-ribonucleic acid (As-RNA); (C) adenosine diphosphate arsenate (ADP-As); and (D) adenosine monoarsenate (AMAs).
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