Bioinorganic Chemistry of Aluminium & Silicon

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An Introduction to our Research

In the natural selection of the elements (carbon, oxygen, calcium etc.) of life ubiquity is closely allied to essentiality. Thus, biota and biological processes are selected to accommodate the elements that are abundant in any particular environment. This general rule of thumb raises an intriguing paradox and it is this paradox, explained below, which underlies the raison d'être of our research.

Silicon and aluminium are respectively the second and third most abundant elements, behind oxygen, in the Earth's crust and yet, neither has any known biological function in higher animals. Silicon is required only as a structural element in a very few organisms, for example diatoms, whilst aluminium is inimical to all life forms. From an evolutionary perspective one might speculate that both of these elements have been selected out of biological processes. This is easier to accept for silicon, perhaps being replaced by calcium (or carbon!?), than for aluminium. The explanation for the latter may have much more to do with what we call biological availability. In our definition of this widely used term presence does not infer (though it may confer) biological availability and we have speculated that the apparent lack of beneficial aluminium biochemistry is the result of its low biological availability. In fact it has been one of the strengths of our work to link the biological availability of aluminium to silicon such that we have shown how apparent silicon essentiality can be explained as silicon acting as a geochemical control of the biological availability of aluminium. We have set ourselves the task of understanding the biological availability of both aluminium and silicon. Where the latter is concerned this is predominantly the bioinorganic chemistry of its weak acid, silicic acid ($Si(OH)_4$). There are no Si-C or Si-O-C bonds to explain apparent silicon essentiality. Our bioinorganic solution (the reaction of silicic acid with aluminium to form hydroxyaluminosilicates) is, as yet, the only proven mechanism of silicon essentiality in biota.

The biological availability of aluminium is, potentially at least, much more complicated due to the avidity with which oxygen (and fluorine) -based functional groups bind the free ion ($Al^{3+}_{(aq)}$). Aluminium is present in the environment, it may be a burgeoning presence, and it is found almost everywhere in the human body. The question arises as to the biological availability of this aluminium burden. It must participate in a number of chemical (biological?) reactions. However, it is unknown whether these reactions impact upon biological processes to alter their function and the function of the body (organism) as a whole. All of this raises the intriguing possibility that human activities, for example the extraction of aluminium from its erstwhile biologically-inert ores, have raised the biological availability of aluminium and that evolution is now proceeding in the presence of this biochemically reactive element. Considering the known ecotoxicity of aluminium this possibility may have (or may be having) important consequences for life on earth.

Human evolution is now proceeding in the presence of biologically available aluminium. No cell or compartment within the body is functioning in the absence of an aluminium burden, a proportion of which will be biologically active. Such activity includes substitution for essential metals in enzymes and other proteins, facilitation of redox reactions resulting often in greater oxidative potential, interactions with nucleic acids including genotoxicity and general disruption of the structure and functioning of membranes. The body has no inherent protection against aluminium. There is no specific response to its presence. Human life evolved in its absence and is now evolving in its presence and it the latter that must drive the need to understand all of the possible repercussions. One of the foci of such research is chronic disease and neurodegenerative disease in particular.

Concomitant with the emergence of higher forms of life are significant concentrations of environmental silicic acid and commensurate insignificant concentrations of biologically reactive aluminium. Silicic acid limits the biological availability of aluminium, and it is unable to compete with Mg(II), Ca(II), Fe(II/III) for binding by phosphate, carboxylate and hydroxyl functional groups. Aluminium is excluded from inorganic biochemistry. Subsequently over tens of millions of years and, recently concomitant with the activities of modern human beings, an increase in the concentration of biologically reactive aluminium occurs. This increase, coincident now and in the foreseeable future with evolutionarily-driven lower levels of environmental silicic acid, displaces essential metals from biomolecules which are integral to vital biochemical processes. Aluminium is now competitive and has become an active participant in biochemical evolution. What then are the implications of such for future biochemistry?

Key: Degree of shading indicates changes through evolutionary time in the environmental concentrations of biologically reactive (i) silicic acid ($[Si(OH)_4]_B$; blue) and (ii) aluminium ($[Al]_B$; red). The extent of coloured branches and their variously-shaped leaves estimates the major metal ion competitors for Al(III) and their preferred functional groups for binding respectively. mya: million years ago.

Aluminium is not the inert, safe, wonder metal that the aluminium industry would have us believe. Incidentally, the aluminium industry does not fund research either in house (at least not that is available for public scrutiny) or externally into the possible heath effects of aluminium. It is, of course, a wonder metal (element) but what we need to know is that we can continue to use it in the future without endangering life. The same concentration of aluminium that is allowed under EU legislation in our drinking water (200 μg/L) will kill a salmon in a mildly acidic river (pH 5.0-5.5) within 48 hours. But of course we are not fish, are we?

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