What’s Current with Electric Microbes?

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Microbes capable of interacting with insoluble electron acceptors and/or donors have broad implications, ranging from geomicrobiological processes, alternative energy production, bioproduction of commodity chemicals, and an understanding energy flow in anaerobic environments. Electromicrobiologists investigate bacteria capable of transferring electrons extracellularly to and/or from insoluble surfaces, driving internal metabolic processes. Electromicrobiology is a cross-disciplinary field that covers the processes, mechanisms and applications of electric bacteria.

A wide range of microbes have been discovered that are capable of electrically interacting with their environment. Dissimilatory metal reducing bacteria are among the most studied, being capable of "breathing metals" in anaerobic environments. Derek Lovley isolated the first dissimilatory metal reducing microbe, Geobacter metallireducens, from sediment in the Potomac River in 1987 [1]. This microbe is capable of the complete oxidation of organic carbon to carbon dioxide, while utilising an insoluble electron acceptor to support growth. Geobacter species are able to reduce a wide range of mineral and metalloids, including iron, manganese and uranium. Utilising metal oxides in anaerobic environments for respiration; dissimilatory metal reduction plays an important role in carbon and geochemical cycles. An understanding of their function can be applied to the bioremediation of organic pollutants, heavy metals and radionuclides in anaerobic environments [2].

An interesting aspect of the Geobacter species was the discovery, that they do not produce any electron shuttles, but directly transfer electrons extra cellularly to iron oxide [3]. Subsequent studies have demonstrated electrically conductive pili and the outer membrane c-type cytochrome OmcS, as the route of extracellular electron flow between the microbes and the iron oxides [4,5]. Iron oxide particles are normally much smaller than the bacterial cells, leading to the microbes being planktonic in the environment, expressing flagella too in the search for oxidised electron acceptor [6]. During this time, Geobacter species are capable of utilising the extensive heme containing c-type cytochromes as capacitors to hold excess electrons, until a suitable electron acceptor can be found to allow the cytochromes to be discharged [7].

The electricity breathing ability of these microbes can be collected from the environment as an electrical current, using a device called a Microbial Fuel Cell (MFC) [8-10]. Microbes utilise an electrode as an electron acceptor for anaerobic respiration. Initially designed for the harvesting of electrical current from organic compounds, difficulties in scalability above pilot scale has seen their application in power production, focused towards the powering of low power devices in aquatic environments [11-13]. Some of the more interesting current applications of MFC include applications where the harvesting of electrical current is not the primary focus, these include: acting as sensors for microbial metabolism in subsurface environments [14]; stimulating bioremediation of organic environments by providing an electrode as an electron acceptor [15]; and providing a means for balancing electron flow during the production of the microbial production of commodity chemicals [16].

Compared to metal reduction in the environment, an electrode can act as an infinite electron sink. This leads to both similarities and differences in the microbial behaviours utilising these insoluble electron acceptors. Geobacter species are extensively enriched within the electrode-associated communities of MFC, when a diverse range of environmental inoculum and organic carbon source are used [11]. Geobacter species seem to be the most adapted in utilising an electrode as an electron acceptor. They produce the highest current density of both pure and mixed cultures in a MFC; are able to directly interact with an electrode without the use of an electrode shuttle, and produce relatively thick biofilms (>60 µm) [17]. This biofilm has the unusual property of being electrically conductive, allowing all cells within the biofilm to be metabolically active and capable of transferring electrons to the electrode, across distances greater than 50 cell lengths [18,19]. Geobacter species on the electrode surface utilise a network of pili and the outer membrane cytochromes, more specifically OmcZ, to electrically connect to the electrode [20-22]. The ability to produce a conductive biofilm and act as a capacitor has seen an interest in utilizing these microbes in bioelectronics applications [23].

The range of applications has been further broadened with the discovery that microbes can also utilize an electrode as an electron donor. The molecular method for electron transfer from an electrode does not appear to share any molecular similarities with the electron transfer to an electrode or iron oxide. The electrically conductive pili, the outer membrane cytochromes, OmcS and OmcZ, are not essential for the microbes to accept electrons from the electrode. The only protein current found to be essential is a separate outer membrane c-type cytochrome, whose current roll is unknown [24]. Being able to provide energy to microbes, directly utilizing an electrode, has significant potential in the bioremediation of a number of recalcitrant contaminants, such as chlorinated compounds [15,25], toxic and radioactive metals [26], and nitrate [27,28]. Microbes may also act as catalysts on an electrode, for the conversion of an electrical current to hydrogen and methane [29-31]. Electrons may also be utilised as a reductant for the reduction of organic compounds to commodity chemicals [32,33].

Some microbes can even utilise the reducing power of an electrode to fix carbon dioxide for the production of organic chemicals. Due to the similarities to photosynthesis, the microbial fixation of carbon dioxide utilising an electrode as a reduction process has been termed electrosynthesis [32]. Electrosynthesis has the potential to produce liquid transportation fuels and other useful organic commodities in...
a more efficient and environmentally sustainable manner, than other biomass based biofuel production strategies.

While it may be thought that the ability to interact with insoluble minerals, metals and metalloids in the environment gives the Geobacter species an advantage on an electrode, recent findings suggest the evolution of conductive biofilms may have evolved from syntrophic interactions with methanogenic microbes. Previously, it has been considered that syntrophic interactions in methane producing communities occurred mainly through hydrogen transfer between the partners, where by the electron-donating partner would produce hydrogen and the electron-accepting methanogen would utilise hydrogen as an electron source. Studies of electric bacteria have demonstrated that microbes in methanogenic communities are capable of directly transferring electrons through large aggregates to each other. Direct interspecies electron transfer can be the primary mechanism for electron transfer in methanogenic aggregates [34,35], although this is not always the case [36].

During direct interspecies electron transfer, Geobacter species produce an electrically conductive network capable of long-range transfer, more resembling the biofilm produced on an electrode, rather than when grown on iron oxides. These microbes within conductive anaerobic syntrophic networks are a new potential source of electric bacteria with beneficial characteristics. While great inroads have been made, our understanding of electric bacteria is still limited. Evaluation of the full potential of electric microbes in industrial, biomaterial and environmental applications is reliant on the growing field of electro microbiology.

References

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