

The energy metabolism of microorganisms

Friday, 23 January 2009

If bacteria want to survive, grow or become dominant within a microbial community, they do not only require substrate and nutrients but they also need the presence of an appropriate electron acceptor. Based on the usage of a final electron acceptor, there are two main modes of microbial energy conservation: respiration and fermentation. These processes are ubiquitous in various natural environments.

Recently, they have been accompanied by a new exciting respiration process occurring in bioelectrochemical systems (BESs): electrogenesis.

The working principles of these three processes are covered in this item.

Respiring
bacteria gain energy by the
transfer of electrons to external acceptors

Microorganisms survive and grow due to the energy they generate by transferring electrons. During respiration, microorganisms liberate electrons from an electron rich substrate at a low redoxpotential and transfer these electrons through a number of electron transport complexes through the cell membrane where a final electron acceptor is reduced (Figure I)(Schlegel, 1992). Microorganisms do not use the energy produced by the flow of electrons in a direct way, instead, the flow of electrons is used to create a proton gradient across the cell membrane as described by Mitchell (1961). The energy released by the inward flux of the protons through a membrane complex (ATP synthase) is used to regenerate energy carrier molecules, such as adenosine triphosphate (ATP) (Figure I-5). By creating this proton gradient, the potential difference between the electron donor (i.e. the substrate at low potential) and the electron acceptor is translated into a process for the generation of energy. The higher the potential difference between the electron

donor and electron acceptor, the higher the proton driven potential difference and the higher the potential amount of ATP which can be refuelled. Respiring microorganisms can use a large variety of different electron acceptors, ranging from oxygen, nitrate, iron and manganese oxides to sulfate, but their ability to use the acceptor with the highest redox potential will increase their energy for growth (Madigan et al., 2000) and is their incentive to explore alternative electron acceptors.

Figure I: The left figure shows the orientation of the electron carriers (electron transfer chain) and the electron transport in the membrane of a model prokaryote. Whereas: FMN: flavoprotein, FAD: flavin adenine dinucleotide, Q: quinone, Fe/S: iron sulfur protein; cyt a, b, c: cytochrome, + and - charges represent respectively H⁺ and OH⁻. The right figure shows the structure and function of ATP synthase (ATPase, Complex V). As protons enter, the dissipation of the proton motive force drives the ATP synthesis which is catalyzed by complex F₁. (after Madigan et al., 2000)

Fermenting bacteria generate energy by the internal recirculation of electrons

In many environments, the availability of electron acceptors is limited, which impedes microorganisms from using the respiratory pathway. In these cases, which are abundant in many environmental conditions, fermenting organisms are likely to establish themselves. Fermentation is an ATP-regenerating metabolic process in which degradation products or organic substrates serve as electron donor as well as electron acceptor (Schlegel, 1992). The advantage of this pathway is that fermenting organisms are able to grow in numerous environments which are non supportive for organisms that only use the respiratory pathway because suitable electron acceptors are lacking. Fermenting organisms are important within the overall microbial processes in nature for their ability to degrade polymeric compounds into readily degradable monomers. However, fermentation is energetically far less efficient compared to respiration as only 1 to 4 moles of ATP are formed during the fermentation of glucose where 26 to 38 moles of

ATP are formed during the aerobic degradation of glucose (Schlegel, 1992). This is also reflected in the Gibbs free energy value, which is a factor 7 lower for the fermentation of glucose compared to the aerobic respiration. The remainder of the Gibbs free energy is not lost but is conserved within the excreted fermentation products such as volatile fatty acids, hydrogen, alcohols and many more. The trade off between their low energetic yield, and their ability to colonize niches devoid of readily available electron donors and acceptors, determines the success of fermenting organisms in many ecosystems.

Electrogenesis:

the biocatalyzed transfer of electrons to an electrode

Unlike natural environmental systems, the anode compartment of a BES is an engineered environment in which the availability of soluble electron acceptors is limited. The microbial electricity generation in a BES relies on the drive of bacteria to acquire maximum energy. The main electron acceptor present in a BES, enabling bacteria to use respiratory processes, is a solid conductive electrode. The higher amount of metabolic energy released by transferring electrons to the electrode compared to the use of other electron acceptors, is their drive to colonize the electrode and develop electron transfer strategies. The complete web of electron transfer mechanisms is not fully understood yet, probably a complementary range of processes such as direct electron transfer and mediated electron transfer are used. The result is a process in which bacteria serve as a biocatalyst to transform an electron rich substrate i) into electrons, which are transferred to the electrode, ii) into protons which migrate to the cathode and iii) into oxidized products which leave the reactor. The electrons flow through an external electrical circuit towards the cathode electrode where a final electron acceptor is reduced by a chemical (Zhao et al., 2006) or microbial catalyst (Clauwaert et al., 2007a, Clauwaert et al., 2007b).

Redrafted after:

Aelterman, P. (2009) Microbial fuel cells for the treatment of waste streams with energy recovery. PhD Thesis, Gent University, Belgium

References
cited:

Clauwaert, P., K. Rabaey, P. Aelterman, L. De Schamphelaire, H. T. Pham, P. Boeckx, N. Boon, and W. Verstraete. 2007a. Biological denitrification in microbial fuel cells. *Environmental Science & Technology* 41:3354-3360.

Clauwaert, P., D. Van der Ha, N. Boon, K. Verbeken, M. Verhaege, K. Rabaey, and W. Verstraete. 2007b. Open air biocathode enables effective electricity generation

with microbial fuel cells. *Environmental Science & Technology* 41:7564-7569.

Madigan, M.

T., J. M. Martinko, and J. Parker. 2000. *Brock Biology of Microorganisms*, vol. Prentice-Hall, Upper Saddle River, N. J.

Mitchell,

P. 1961. Coupling of phosphorylation to electron and hydrogen transfer by a chemiosmotic type of mechanism. *Nature (London)* 191:144-148.

Schlegel,

H. 1992. *General microbiology* 7th ed., vol. Cambridge University Press, Cambridge.

Zhao, F.,

F. Harnisch, U. Schörder, F. Scholz, P. Bogdanoff, and I. Herrmann. 2006. Challenges and constraints of using oxygen cathodes in microbial fuel cells. *Environmental Science & Technology* 40:5193-5199.