BACTERIAL TRANSFORMATIONS OF AND RESISTANCES TO HEAVY METALS

Simon Silver and Tapan K. Misra
Biology Department
Washington University
St. Louis, Missouri 63130

ABSTRACT

Bacteria carry out chemical transformations of heavy metals. These transformations (including oxidation, reduction, methylation, and demethylation) are sometimes byproducts of normal metabolism and confer no known advantage upon the organism responsible. Sometimes, however, the transformations constitute a mechanism of resistance. Many species of bacteria have genes that control resistances to specific toxic heavy metals. These resistances often are determined by extrachromosomal DNA molecules (plasmids). The same mechanisms of resistance occur in bacteria from soil, water, industrial waste, and clinical sources. The mechanism of mercury and organomercurial resistance is the enzymatic detoxification of the mercurials into volatile species (methane, ethane, metallic Hg) which are rapidly lost from the environment. Cadmium and arsenate resistances are due to reduced net accumulation of these toxic materials. Efficient efflux pumps cause the rapid excretion of Cd\(^{2+}\) and AsO\(_4^{3-}\). The mechanisms of arsenite and of antimony resistance, usually found associated with arsenate resistance, are not known. Silver resistance is due to lowered affinity of the cells for Ag\(^+\), which can be complexed with extracellular halides, thiols, or organic compounds. Sensitivity is due to binding of Ag\(^+\) more effectively to cells than to Cl\(^-\).

INTRODUCTION

Bacterial cells divide the Periodic Table into three classes. Some elements are necessary for intracellular metabolism (67); some elements are not used generally within the cell, but abound in natural environments and can be coupled to extracellular structural or...
regulatory functions; finally, some elements have no useful biological function (69,79). Potassium and phosphorus are examples of the first class; calcium and chlorine are not needed at all for most bacteria; and arsenic, mercury, and cadmium are examples of toxic elements without biological utility. This report will deal with toxic elements and their compounds. In some cases, such as mercury and arsenic, microbes can transform elements from relatively less toxic inorganic ions into relatively more toxic methylated forms. The same or other microbes can degrade organometallic compounds (15,79); oxidation and reduction by microbial enzymes also affect the bioavailability and toxicity of heavy metals. It is crucial to understand the interactions of microbes with heavy metals in order to follow the pathways and transformations of heavy metals in the environment, and to design interventions that will reduce pollution.

Free-living bacterial cells have evolved resistance mechanisms to cope with heavy metal pollution. These resistance mechanisms are highly specific. The genes determining the resistance mechanisms occur on small nonchromosomal DNA molecules called plasmids. These resistance plasmids also have genes controlling resistance to most known antibiotics. We have reviewed this subject periodically (e.g., 68-70, 79) most recently in Ref. 70.

MERCURY AND MERCURIAL TRANSFORMATIONS AND RESISTANCES

The mercury cycle (Fig. 1) is the best known case of microbial metabolism affecting the chemical form of a heavy metal. Microbial activity is associated with mercury methylation, demethylation (15), and oxidation and reduction of inorganic mercury. I will deal first with the transformations from highly toxic methylmercury (found in fish) to less toxic ionic Hg\(^{2+}\) (the predominant form in seawater) to least toxic Hg\(^0\). Both of these transformations are carried out by enzymes governed by bacterial resistance plasmids and transposons (moveable DNA sequences) and not by the more usual (chromosomal) genes. Without the plasmid genes, the cells remain mercury sensitive. Then we will address microbial oxidation and methylation of mercury.

The earliest studies of enzymatic detoxification of Hg\(^{2+}\) were with a multiply drug-resistant *Escherichia coli* (37) and with a soil pseudomonad (21,84). The frequency of Hg\(^{2+}\) resistance among clinical isolates can be over 50% (44,45,92). Recently, mercuric- and organomercurial-resistant strains with very similar properties have been found in a wide variety of bacterial species from soil, water,

\[
\text{CH}_3\text{Hg}^+ \rightleftharpoons \text{Hg}^{2+} \rightleftharpoons \text{Hg}^0
\]

*Fig. 1. Environmental transformations of mercury.*