

# The Toxic Mechanism of Heavy Metals and Their Effects on Human Health

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**Abstract.** Heavy metals show significant risks to both human health and the environment. The analysis of the toxic mechanisms of heavy metals and their toxic effects on humans has received increasing attention. For this reason, this comprehensive research explores the toxicology effects of heavy metals, delving into their common sources, mechanisms of toxicity, specific health effects, routes of human exposure, regulation and prevention strategies, and notable case studies. Each section provides in-depth insights, from the neurological impacts of lead to the potential link between lead exposure and Alzheimer's disease. The research underscores the importance of understanding heavy metal toxicity, its regulatory framework, and preventive measures. Ultimately, addressing heavy metal contamination requires global cooperation, stringent regulations, and ongoing research to protect individuals and ecosystems from the adverse effects of these toxic elements. In addition, this study also provides a new approach for the study of the impact of heavy metals on human health.

**Keywords:** Heavy metals, human health, relationship.

## 1. Introduction

Heavy metals, ubiquitous in our environment, pose substantial risks to human health and the ecosystem. This essay explores the multifaceted dimensions of heavy metal toxicity. It begins by examining the common sources of heavy metal contamination, including natural geological processes and anthropogenic activities. Moving deeper, it unravels the intricate mechanisms through which heavy metals exert their toxic effects, encompassing cellular disruptions, oxidative stress, and interference with essential metals. The subsequent sections delve into the specific health effects of prominent heavy metals like lead, mercury, cadmium, arsenic, and chromium, shedding light on their neurological, renal, and carcinogenic impacts. The discussion extends to the various routes through which humans are exposed to heavy metals, spanning occupational, environmental, and consumer product-related pathways. Regulation and prevention efforts play a crucial role in mitigating heavy metal risks. Regulatory agencies, safety standards, and pollution control technologies are examined in detail, along with strategies for reducing exposure, environmental monitoring, and public awareness campaigns. Notable case studies illustrate real-world consequences and challenges related to heavy metal contamination.

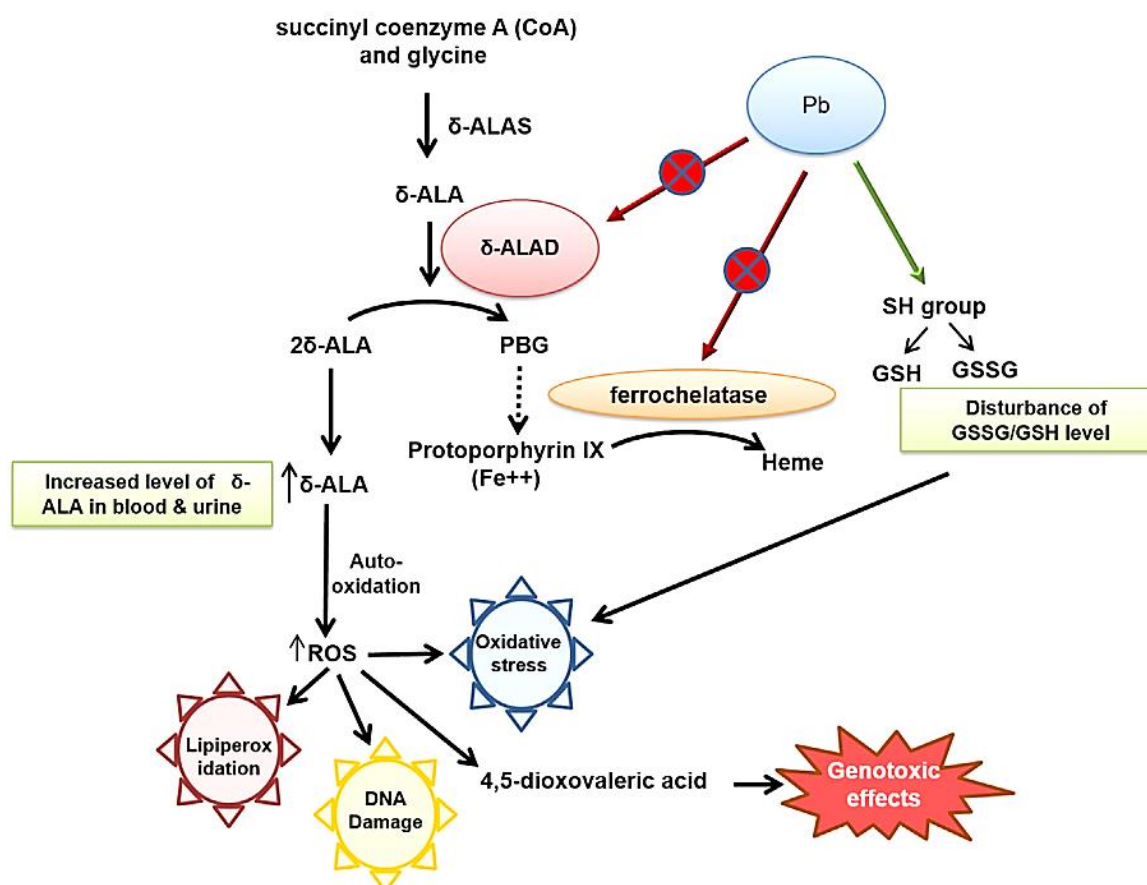
Heavy metals are ubiquitous in our environment and can be found in various sources, both natural and anthropogenic. Lead has a long history of use in various applications, from plumbing to paints. However, its toxicity has been recognized for centuries. Historically, lead poisoning was common among the Roman aristocracy due to their extensive use of lead-lined vessels and lead acetate in wines. In modern times, lead exposure has significantly decreased due to regulations and bans on lead-based products. Still, lead contamination can occur from deteriorating lead-based paint in older homes, contaminated soil, and drinking water transported through lead pipes [1]. Mercury exists in several forms, with methylmercury being the most toxic and commonly encountered in the environment [2]. Natural sources of mercury include volcanic eruptions, while human activities, such as coal combustion and gold mining, release mercury into the atmosphere. Once released, mercury settles into aquatic ecosystems, where it can be transformed into methylmercury by bacteria. This toxic compound bioaccumulates in fish and seafood, posing a risk to those who consume contaminated seafood. Cadmium is primarily a byproduct of zinc production, but it is also released into the environment through the burning of fossil fuels and the disposal of cadmium-containing products,

such as batteries. The metal can accumulate in soil and water, making it accessible to plants. This bioaccumulation enters the food chain, with tobacco being a significant source of cadmium exposure for smokers.

Arsenic contamination has occurred due to both natural geologic processes and human activities [3]. Anthropogenic sources of arsenic include mining and processing of ores, as well as the smelting process, which can release arsenic into the air and soil. Geologic sources, such as arsenic minerals, and sedimentary bedrocks also contribute to groundwater contamination. Moreover, arsenic is present in various consumer products, such as dyes and certain pesticides. Chromium exists in different oxidation states, with hexavalent chromium (Cr (VI)) being highly toxic. It can be found in cement and leather tanning. Hexavalent chromium can contaminate groundwater and soil when not properly managed, leading to environmental hazards [4]. As a result, this research will discuss the mechanisms of heavy metal toxicity, specific health effects of heavy metals, routes of human exposure and regulation and prevention.

## 2. Mechanisms of heavy metal toxicity

The route of exposure significantly influences the extent of heavy metal toxicity. Heavy metals can enter the body through ingestion, inhalation, or dermal absorption. Each route has distinct implications for exposure and health outcomes [5], as shown in Fig. 1.



**Figure 1.** Anemia pathway caused by lead exposure [5].

Ingested heavy metals are absorbed through the gastrointestinal tract, and their absorption rates can vary depending on factors such as chemical form, food matrix, and individual physiology. For example, lead is absorbed more efficiently in an empty stomach, making fasting individuals more susceptible to lead poisoning. Inhalation is another common route for occupational exposure to heavy metals, especially in industries where airborne metal particles are prevalent. Metal particles inhaled into the lungs can directly enter the bloodstream, bypassing the digestive system. This route is

particularly relevant for metals like cadmium and hexavalent chromium. While dermal absorption is generally less significant than ingestion or inhalation, it can occur with prolonged skin contact with contaminated substances. Certain heavy metals, like mercury and lead, can penetrate the skin barrier and enter the bloodstream. Occupations involving contact with heavy metal-containing materials, such as paints or batteries, can pose a risk.

Once absorbed, heavy metals distribute throughout the body, with a predilection for certain organs and tissues. The distribution patterns are influenced by factors like the chemical properties of the metal, binding to proteins, and organ-specific transport mechanisms. Heavy metals have unique affinities for different organs and tissues [6]. For example, lead tends to accumulate in bones, where it can persist for years, posing long-term health risks. Mercury targets the central nervous system, including the brain, leading to neurological toxicity. When accumulating, heavy metals exert their toxic effects at the cellular and molecular levels, disrupting normal cellular functions and causing harm in various ways. Many heavy metals interfere with enzymes critical for cellular processes. For example, cadmium interferes with enzymes essential for DNA repair, contributing to DNA damage and mutagenesis. Hexavalent chromium disrupts enzymes involved in DNA replication and repair, increasing the risk of genetic mutations. Heavy metals have the potential to induce DNA damage. This can result in genetic mutations and chromosomal abnormalities, increasing the risk of cancer development.

Heavy metals often promote the generation of reactive oxygen species (ROS). Excessive ROS production overwhelms the body's antioxidant defenses, which can disrupt cellular components. And heavy metals can disrupt cell signaling pathways as well, affecting cell growth, differentiation, and survival. For instance, arsenic can interfere with the mitogen-activated protein kinase (MAPK) signaling pathway, which can affect cellular responses to growth factors and stressors. Disruption of these signaling pathways can lead to abnormal cell behavior and contribute to the development of diseases. Except for generation of ROS and cell signal disruption, heavy metals can compete with essential metals for binding sites in enzymes and proteins. This competitive binding can lead to imbalances in essential metal homeostasis, further exacerbating toxicity.

Examples showing heavy metal toxicology mechanism are common [7]. Lead can displace calcium ions, interfering with neurotransmission and muscle function. This disruption of calcium-dependent signaling can lead to neurological symptoms and developmental deficits, particularly in children. Cadmium competes with zinc for binding to metallothionein, a protein responsible for regulating zinc homeostasis. This competition can result in decreased zinc availability for essential cellular functions, contributing to the toxic effects of cadmium.

### **3. Specific health effects of heavy metals**

#### **3.1. Lead toxicity**

Lead is notorious for its detrimental impact on the nervous system. It can lead to intellectual impairment, developmental delays, and learning disabilities in children. In adults, lead exposure can result in cognitive deficits, memory impairment, and mood disorders. Prolonged exposure can cause permanent neurological damage. Children are particularly vulnerable to the neurotoxic effects of lead. Their developing nervous systems are more sensitive to lead exposure. Even low levels of lead exposure during critical periods of brain development can result in long-term cognitive deficits and behavioral problems. Early-life lead exposure has been associated with an increased risk of cognitive decline in old age, which is relevant to Alzheimer's disease. While children are most vulnerable to the developmental effects of lead, older adults are also at risk. Lead accumulates in bones over time, and during periods of increased bone resorption, such as in old age, lead can be released back into the bloodstream, re-exposing individuals to its toxic effects. This re-exposure may contribute to cognitive decline, including the development or exacerbation of Alzheimer's disease in older adults.

Alzheimer's disease is characterized by the accumulation of beta-amyloid plaques in brain. It is suggested that lead exposure may enhance the production and accumulation of beta-amyloid. Lead-

induced oxidative stress and inflammation may contribute to the production of beta-amyloid and the progression of Alzheimer's pathology. In Alzheimer's, abnormal tau protein aggregation also leads to the formation of neurofibrillary tangles. Lead exposure has been associated with changes in tau phosphorylation, which is a key step in tau protein dysfunction. This may contribute to the tau pathology observed in Alzheimer's disease. Besides, lead-induced cognitive impairments, particularly in memory and executive function, share similarities with the cognitive deficits seen in Alzheimer's disease. The disruption of neuronal function and synaptic plasticity by lead may contribute to these cognitive impairments [8].

Lead interferes with heme synthesis and disrupts red blood cell production. This leads to anemia, characterized by fatigue, weakness, and pale skin. Lead poisoning can also lead to basophilic stippling, a distinctive feature seen in blood smears. And in males, lead exposure may reduce sperm quality and fertility [9].

### **3.2. Mercury toxicity**

Mercury primarily targets the central nervous system, especially in its organic form, methylmercury. Prenatal exposure to methylmercury can result in severe developmental delays, intellectual disabilities, and motor function impairments in children. In adults, mercury poisoning can cause tremors, muscle weakness, and sensory disturbances. And acute exposure to inorganic mercury can lead to severe abdominal pain, diarrhea, and tissue damage in the gastrointestinal tract. Mercury can accumulate in the kidneys, causing renal dysfunction and potentially leading to kidney disease [10].

### **3.3. Cadmium toxicity**

Cadmium has a strong affinity for the kidneys. Chronic exposure to cadmium can cause kidney damage, proteinuria, and even kidney failure. Except for kidney, Cadmium can replace calcium in bone tissue, weakening bones and increasing the risk of fractures. Cadmium is classified as a human carcinogen. Long-term exposure is associated with an increased risk of lung cancer, especially in individuals exposed to cadmium in occupational settings.

### **3.4. Arsenic toxicity**

Chronic exposure to arsenic can cause skin manifestations, known as arsenicosis. Specific skin lesions include hyperpigmentation, hypopigmentation, and keratosis. These changes are often localized to areas of high arsenic exposure. Arsenic is a well-established carcinogen. Direct use of arsenic contaminated water is closely related to the increased risk of lung cancer, liver cancer, bladder cancer and skin cancer. Emerging research suggests a link between chronic arsenic exposure and cardiovascular diseases, including hypertension and atherosclerosis.

### **3.5. Chromium toxicity**

Hexavalent chromium (Cr (VI)) is a known human carcinogen. Inhalation of Cr (VI) compounds can increase the risk of lung cancer, and contact with Cr (VI) can lead to allergic skin reactions, including dermatitis and skin ulcers. This is commonly observed in workers exposed to chromate compounds. Inhalation of Cr (VI) has different effects on the human body, such as respiratory irritation.

## **4. Routes of human exposure**

There are some ways human exposed to heavy metals: Workers in mining and smelting industries face significant risks of heavy metal exposure. They may inhale metal dust, handle contaminated materials, or work in environments with airborne metal particles. Industries involved in manufacturing and recycling of products containing heavy metals, such as batteries, electronics, and paints, expose workers to these toxic elements. Proper safety measures and personal protective

equipment are crucial in minimizing exposure. Construction workers may encounter heavy metals in materials like lead-based paints or in the demolition of older structures. Dust and debris generated during these activities can pose inhalation risks. Agricultural workers may be exposed to heavy metals through the use of contaminated fertilizers, pesticides, and irrigation water. Crop uptake of metals from contaminated soil can further contribute to exposure.

There are some ways environment exposed to heavy metals Heavy metals can leach into groundwater and soil from various sources, including industrial runoff, waste disposal, and natural mineral deposits. This contamination can affect drinking water sources and agricultural lands, posing risks to both human health and ecosystems. Industrial emissions and combustion processes release heavy metal particles into the air. These particles can be inhaled by nearby residents, leading to respiratory and systemic health effects. For example, heavy metals can be enriched in crops, and animals that graze on these crops or prey on contaminated wildlife can also bioaccumulate heavy metals. This process can result in human exposure through the consumption of contaminated food products.

There are some other products contain heavy metals: Although lead-based paints have been banned in many countries, older homes may still have led-based paint on walls and surfaces. Ingesting or inhaling lead dust or paint chips can lead to lead poisoning, especially in children. Certain types of seafood, especially large predatory fish like swordfish and shark, can contain elevated levels of methylmercury. Regular consumption of contaminated seafood can lead to mercury exposure. Cadmium is used in rechargeable batteries and electronic components. Improper disposal of these products can release cadmium into the environment, potentially contaminating soil and water.

## 5. Regulation and prevention

Heavy metal contamination poses significant risks to public health and the environment. Therefore, comprehensive regulatory frameworks and preventive measures are essential to minimize exposure and mitigate the adverse effects of heavy metals. In this section, we will delve into the regulatory aspects and strategies for prevention. Regulatory agencies establish permissible levels of heavy metals in ambient air to protect public health. Emissions from industrial facilities, vehicles, and other sources are subject to strict controls. To ensure the safety of drinking water, regulatory agencies set maximum allowable levels for heavy metals like lead, mercury, and arsenic. Water treatment and monitoring are essential to meet these standards. In areas with soil contamination, remediation efforts may be required to reduce heavy metal levels. Remediation techniques include soil removal, soil washing, and in situ immobilization.

It also needs to prevent heavy metal exposure. Industries must adopt pollution control technologies to reduce heavy metal emissions into the environment. These technologies include air and water pollution control systems, such as scrubbers and filtration systems. Proper disposal of heavy metal-containing waste is crucial to prevent contamination. Hazardous waste should be stored and disposed of in accordance with regulatory guidelines. Continuous monitoring of air, water, and soil quality is essential to detect and respond to heavy metal contamination promptly. Monitoring allows authorities to identify pollution sources and assess the effectiveness of pollution control measures. Raising public awareness about the risks of heavy metal exposure is vital. Educational campaigns can inform individuals about potential sources of exposure, safe practices, and the importance of complying with regulations.

## 6. Conclusion

In a world where heavy metals continue to permeate our environment; this comprehensive exploration has underscored the profound implications of heavy metal toxicity. From their common sources to the intricacies of their mechanisms of toxicity, we have delved into the depths of this multifaceted issue. The specific health effects of heavy metals, from lead's neurological impacts to

arsenic's role in skin manifestations and cancer, have illuminated the broad spectrum of risks these elements pose to human well-being. Understanding the routes of exposure, be it through occupational hazards, environmental contamination, or consumer products, has emphasized the pervasive nature of this threat. Regulation and prevention strategies, backed by regulatory agencies and global guidelines, provide a framework for mitigating these risks. Pollution control technologies, public education, and vigilant monitoring efforts represent essential tools in our arsenal against heavy metal contamination. Notable case studies, from Minamata to Flint, serve as stark reminders of the real-world consequences and challenges associated with heavy metal exposure.

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