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Investigation on heavy metals toxicity

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Abstract

Heavy metals are naturally occurring elements characterized by high atomic weight and a density at least five times greater than that of water. Their extensive industrial, agricultural, domestic, medical, and technological applications have resulted in widespread environmental distribution, raising serious concerns regarding their impact on human health and ecosystems. Heavy metal toxicity poses a significant global public health challenge. Even metals without known biological roles can persist in the human body, interfere with metabolic pathways, and induce toxic effects. Some metals may act as pseudo-elements by substituting essential elements in biochemical processes, while others accumulate in tissues and biomagnify through the food chain, leading to chronic toxicity. The severity of toxicity depends on absorbed dose, route of exposure, chemical form (speciation), and duration of exposure (acute or chronic). Heavy metals induce cellular damage primarily through oxidative stress, free radical generation, enzyme inhibition, and interference with DNA repair mechanisms. Public health interventions have been implemented to reduce occupational, environmental, and accidental exposure. This review discusses the environmental occurrence, exposure pathways, molecular mechanisms of toxicity, and health effects of major heavy metals including arsenic, cadmium, chromium, lead, and mercury.

Keywords: *Heavy metals, oxidative stress, carcinogenicity, arsenic, cadmium, chromium, lead, mercury.*

Introduction

Heavy metals are metallic elements with relatively high density compared to water. Although the term "heavy metal" is often debated scientifically, it generally includes toxic metals and metalloids such as arsenic that can produce adverse health effects even at low exposure levels. Increasing industrialization, urbanization, and technological advancement have significantly elevated environmental contamination by heavy metals, making them a major ecological and global public health concern [1-3].

Heavy metals originate from both natural (geogenic) and anthropogenic sources. Natural sources include weathering of rocks, volcanic eruptions, and soil erosion. Anthropogenic sources include mining, smelting, fossil fuel combustion, industrial manufacturing, agricultural chemicals, pharmaceutical wastes, sewage discharge, and atmospheric deposition. Environmental contamination is particularly severe near mining sites, foundries, smelters, and industrial zones [4-7]

While certain metals such as cobalt (Co), copper (Cu), chromium (Cr III), iron (Fe), magnesium (Mg), manganese (Mn), molybdenum (Mo), nickel (Ni), selenium (Se), and zinc (Zn) are essential micronutrients required for enzymatic and metabolic functions, excessive exposure can result in toxicity. In contrast, non-essential metals such as arsenic (As), cadmium (Cd), lead (Pb), and mercury (Hg) have no known biological function and are toxic even at low concentrations [8-11]

Heavy metals enter biological systems through ingestion, inhalation, dermal contact, and, in some cases, parenteral exposure. Once absorbed, they can accumulate in tissues and affect critical cellular components including mitochondria, lysosomes, endoplasmic reticulum, and the nucleus. They interact with proteins, enzymes, and nucleic acids, leading to oxidative stress, DNA damage, disruption of cellular signalling pathways, apoptosis, and carcinogenesis [12-15].

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Metal-induced toxicity depends on several factors including oxidation state, solubility, bioavailability, exposure dose, duration, and individual susceptibility. Understanding the molecular mechanisms underlying heavy metal toxicity is essential for risk assessment, public health management, and preventive strategies [16-18].

Heavy metals: environmental occurrence, toxicity mechanisms and human health effects

Heavy metals are naturally occurring elements characterized by high atomic weight and density greater than 5 g/cm^3. Although some metals are essential micronutrients, excessive exposure leads to toxicity and severe health consequences. Rapid industrialization, mining, fossil fuel combustion, and agricultural activities have significantly increased environmental contamination. Heavy metals enter the human body through ingestion, inhalation, and dermal contact, accumulating in tissues and disrupting cellular functions. Toxicity mechanisms include oxidative stress, DNA damage, enzyme inhibition, altered signal transduction, and interference with essential metal homeostasis. This review discusses environmental occurrence, exposure pathways, molecular mechanisms, and health effects of major heavy metals including arsenic, cadmium, chromium, lead, and mercury. It also highlights public health implications and preventive strategies. Heavy metals are metallic elements with relatively high density and potential toxicity even at low concentrations [17-19]. Environmental contamination has increased globally due to anthropogenic activities such as mining, smelting, industrial manufacturing, fossil fuel combustion, and agricultural practices [20-22].

While essential trace metals such as iron, zinc, copper, manganese, and selenium play vital biochemical roles [23-25], non-essential metals like arsenic, cadmium, lead, and mercury have no known biological function and are toxic even at minimal exposure levels [26-27]. Chronic exposure has been associated with neurological disorders, renal dysfunction, cardiovascular diseases, reproductive toxicity, and cancer [28-30].

Classification of heavy metals

- **Essential Heavy Metals**
  These are required in small amounts for physiological functions but become toxic at high concentrations: Iron (Fe), Zinc (Zn), Copper (Cu), Chromium (Cr III), Cobalt (Co).
- **Non-Essential Heavy Metals**
  These metals have no known biological role and are toxic even at low levels:

Arsenic (As), Cadmium (Cd), Lead (Pb), Mercury (Hg).

Sources of heavy metal contamination

Heavy metals originate from both natural and anthropogenic sources.

- **Natural Sources**
  Weathering of rocks, volcanic eruptions, Soil erosion, and Forest fires.
- **Anthropogenic Sources**
  Mining and smelting, Fossil fuel combustion, Industrial effluents, Agricultural pesticides and fertilizers, Battery production, Paints and pigments.

General mechanisms of toxicity

Heavy metals induce toxicity through: Generation of reactive oxygen species (ROS), Lipid peroxidation, DNA strand breaks, Inhibition of DNA repair, Binding to sulfhydryl groups of proteins, Disruption of calcium homeostasis, Mitochondrial dysfunction, Oxidative stress plays a central role in metal-induced cytotoxicity and carcinogenesis.

Major heavy metals and their toxicity

1. **Arsenic (As)**
   Arsenic is a metalloid found in inorganic (As III, As V) and organic forms. Inorganic arsenic is highly toxic and carcinogenic [20]. The sources are contaminated groundwater, Pesticides, Mining, Industrial emissions. This metal effects the human Health, and create a diseases like Skin lesions, cardiovascular diseases, Neurological disorders, Lung, bladder, kidney cancers etc.
2. **Cadmium (Cd)**
   Cadmium is widely used in batteries, pigments, and electroplating.
   The Sources are Cigarette smoke, Contaminated food, Industrial emissions. This metal effect the human Health, Renal dysfunction, Osteoporosis, Pulmonary damage, Lung cancer etc.
3. **Chromium (Cr)**
   Chromium exists mainly in Cr III (essential) and Cr VI (toxic) forms.
   The Sources are Electroplating, Stainless steel welding, Leather tanning. This metal effect the human Health, and create a problems like Respiratory cancers, Dermatitis, Renal toxicity etc.
4. **Lead (Pb)**
   Lead exposure remains a major public health concern.
   The Sources are Lead-based paints, Batteries, Contaminated water, Industrial dust. This metal effect the human health and born a Neurodevelopmental disorders in children.

5. **Mercury (Hg)**
   Mercury exists in elemental, inorganic, and organic (methylmercury) forms.
   The Sources are Fish consumption, Dental amalgams, Industrial discharge, Health Effects Neurotoxicity, Renal toxicity, Developmental abnormalities etc.

Public health implications

Chronic exposure to heavy metals leads to long-term morbidity and mortality. Mixed metal exposure may produce additive or synergistic effects. Preventive strategies include: Safe drinking water systems, Industrial emission control, Occupational safety measures Lead-free paints, Antioxidant-rich diet, Regular biomonitoring etc.

Conclusion

Heavy metals are significant environmental pollutants with profound impacts on human health. While some metals are essential in trace amounts, excessive exposure causes systemic toxicity, oxidative stress, genotoxicity, and carcinogenesis. Continued research is necessary to better understand mixture toxicity and molecular mechanisms. Effective legislation, monitoring, and public awareness are crucial for reducing exposure and protecting future generations.

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Conflicts of interest
The authors declare that there are no conflicts of interest regarding the publication of this paper

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