Harmful Interactions of Non-Essential Heavy Metals with Cells of the Innate Immune System

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Abstract

In trace amounts, some heavy metals are essential for optimum health, while exposure to others, which are non-essential, presents the potential hazard of acute or chronic organ toxicity. Cadmium, mercury, lead, vanadium, platinum and palladium are commonly encountered, non-essential heavy metals which mediate their toxic activities by various mechanisms. All have the potential to interact with extracellular and intracellular protein sulfhydryls, rendering them not only potentially allergenic, but also predisposing to oxidative stress, while displacement of essential elements from their protein carriers may result in deficiency disorders. In addition, several of these metals, especially cadmium, palladium, platinum, and vanadium interact pro-oxidatively with the phagocytic cells of the innate immune system, potentiating the reactivity and toxicity of phagocyte-derived reactive oxygen species. This review is focused on the pro-oxidative/pro-inflammatory interactions of non-essential heavy metals with the cells of the innate immune system, a somewhat under-appreciated mechanism of metal induced toxicity.

Keywords: Cadmium; Lead; Macrophages; Mercury; Neutrophils; Palladium; Reactive oxygen species; Vanadium

Introduction

Heavy metals comprise a heterogeneous group of elements, some of which are essential cofactors for various enzymes, while others are non-essential. The former group includes the trace elements cobalt, copper, iron, manganese, molybdenum, selenium and zinc. Because excessive concentrations of the free metals pose potential health risks, their circulating and tissue concentrations are tightly regulated through interactions with binding proteins. The latter group includes metals such as arsenic, cadmium, lead, mercury, plutonium, tungsten and vanadium [1]. These non-essential metals are potent toxins and gain access to organisms by virtue of physico-chemical properties, such as ionic charge, shared with their essential counterparts [2]. They may enter the body through food, water, air, or by absorption through the skin following inadvertent occupational exposure in the agricultural, manufacturing/industrial settings, or through environmental exposure. The manufacturing/industrial setting is the most significant source of exposure in adults [3].

Notwithstanding their direct cytotoxic effects on eukaryotic cells at high concentrations, interactions of non-essential heavy metals at lower non-cytotoxic levels with cells of the innate immune system, which abound in the airways, skin, gastrointestinal tract, liver, spleen, kidneys and circulatory system, may initiate harmful inflammatory responses with accompanying organ dysfunction and disease. These potentially harmful pro-inflammatory interactions of non-essential heavy metals (toxicants), specifically cadmium, lead, mercury, platinum, palladium and vanadium, with the cells of the innate immune system, and their adverse effects on health, are the topic of this review, which also includes cigarette smoking as a cause of exposure to heavy metals [4]. Of necessity, a consideration of the pro-inflammatory activities of these metals is preceded by a brief consideration of innate cellular defence mechanisms.

Innate Immunity

Innate immunity encompasses effector cells and proteins that serve as a first line of defence against infectious agents, restraining or, in some cases eliminating, microbial or viral pathogens while the host develops an adaptive, antigen-specific immune response [5]. Key cellular components of innate immunity include phagocytes such as neutrophils and monocytes/macrophages, as well as dendritic cells, mast cells, eosinophils, basophils and natural killer cells. Innate defenses also encompass physical barriers such as the epithelial and endothelial cell linings. Although not strictly classified as being cellular elements of the innate immune system, epithelial cells and endothelial cells are key orchestrators of both innate and adaptive immune responses.

Phagocytes accomplish their task at sites of infection by phagocytosing and killing bacteria and fungi, utilizing an arsenal of toxic molecules such as proteolytic enzymes and reactive oxygen species (ROS) (Table 1), as well as bacteriocidal proteins, which synergize/harmonize to eliminate these pathogens [6-7]. Although effective, these antimicrobial systems are indiscriminate and may cause significant inflammation-mediated damage to bystander host tissues if inappropriately and/or excessively activated. Excessive production of ROS may result in damage to lipids, proteins, or DNA, compromising cellular function, with resultant cytotoxicity. Because of this, chronic oxidative stress has been implicated in a number of human degenerative diseases, including cancer, cardiovascular disease, chronic obstructive pulmonary disease, atherosclerosis, neurodegenerative diseases (Alzheimer’s disease and Parkinson’s disease), rheumatoid arthritis, renal diseases, and ageing [8-9].

Cells of the innate immune system such as neutrophils and macrophages are also able to synthesize pro- and anti-inflammatory...
cytokines, growth factors and chemokines that mediate a wide range of physiological responses, primarily in host defence. In addition to their role in immunity and inflammation, however, overproduction of pro-inflammatory cytokines such as interleukin-1β (IL-1β), tumour necrosis factor (TNF) and interleukin-6 (IL-6), as well as chemokines such as interleukin-8 (IL-8, CXCL8), monococyte chemotactic protein-1 (MCP-1, CCL2) and macrophage inflammatory protein-1α (MIP-1α, CCL3) can trigger a variety of pathophysiological conditions [10].

The major mediators of inflammation released by cells of the innate immune system and their potential pathological effects are shown in Table 2.

Cadmium

Cadmium (Cd) is released into the environment through various industrial and domestic activities. Foremost amongst these are the combustion of fossil fuels (coal, diesel, gasoline etc.), incineration of industrial waste (especially Cd-containing batteries and plastics), metal alloy production, electroplating, and manufacture of phosphate fertilizers [11]. Cd is also present in tobacco, with each cigarette containing 1-3 µg of the metal, predisposing both active and passive smokers to the toxic effects of Cd inhalation [11]. In welders, acute exposure to Cd may lead to pneumonitis, pulmonary edema and death, with a Parkinsonism-like neurological disorder being a late effect of acute toxicity [1].

Notwithstanding predisposition to pulmonary disease, renal dysfunction is the most common adverse health effect of chronic exposure to Cd [12].

Cadmium toxicity may also result in osteoporosis by inducing renal tubular dysfunction with consequent increased urinary losses of calcium and phosphate as well as a direct effect on bone osteoblast and osteoclast activity [13-14]. Heavy metal toxicity in the setting of iron-deficiency anaemia may significantly increase the risk of infection as both iron-deficiency [15] and Cd-toxicity impair host responses to infection. Cadmium and zinc compete for carrier molecule binding sites on cell membranes and high Cd concentrations antagonize Zinc absorption and uptake by cells. Therefore, Cd toxicity may predispose affected individuals to zinc deficiency which can disrupt normal cellular and immunological functions [16-18].

In addition to direct cytotoxic effects of Cd at high concentrations on various cell types, including mononuclear cells and macrophages [19-20], a considerable body of evidence exists which implicates harmful

### Table 1: List of abbreviations.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>Cd</td>
<td>Cadmium</td>
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<tr>
<td>CdCl₂</td>
<td>Cadmium chloride</td>
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<tr>
<td>CdS</td>
<td>Cadmium sulphide</td>
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<tr>
<td>Pb</td>
<td>Lead</td>
</tr>
<tr>
<td>Hg</td>
<td>Mercury</td>
</tr>
<tr>
<td>HgCl₂</td>
<td>Mercury chloride</td>
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<tr>
<td>MeHg</td>
<td>Methyl Mercury</td>
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<tr>
<td>MeHgCl</td>
<td>Methyl Mercury Chloride</td>
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<tr>
<td>V</td>
<td>Vanadium</td>
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<tr>
<td>Pt</td>
<td>Platinum</td>
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<tr>
<td>Pd</td>
<td>Palladium</td>
</tr>
<tr>
<td>ROS</td>
<td>Reactive Oxygen Species</td>
</tr>
<tr>
<td>O₂⁻</td>
<td>Superoxide anion</td>
</tr>
<tr>
<td>H₂O₂</td>
<td>Hydrogen Peroxide</td>
</tr>
<tr>
<td>HOCl</td>
<td>Hypochlorous Acid</td>
</tr>
<tr>
<td>OH'</td>
<td>Hydroxyl Radical</td>
</tr>
<tr>
<td>NO</td>
<td>Nitric Oxide</td>
</tr>
<tr>
<td>iNOS</td>
<td>Inducible Nitric Oxide Synthase</td>
</tr>
<tr>
<td>MMP</td>
<td>Matrix Metalloproteinases</td>
</tr>
<tr>
<td>LTB₄, LTC₄ and LTD₄</td>
<td>Leukotriene B4, Leukotriene C4 &amp; D4</td>
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<tr>
<td>IL (e.g IL-8)</td>
<td>Interleukin (e.g. interleukin-8)</td>
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<tr>
<td>TNF</td>
<td>Tumor necrosis factor</td>
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<tr>
<td>MCP-1</td>
<td>Monocyte chemotactic protein-1</td>
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<tr>
<td>MIP-1α</td>
<td>Macrophage inflammatory protein-1 alpha</td>
</tr>
<tr>
<td>NFκB</td>
<td>Nuclear factor kappa B</td>
</tr>
<tr>
<td>AP-1</td>
<td>Activation protein-1</td>
</tr>
<tr>
<td>JNK</td>
<td>c-Jun N-terminal kinase</td>
</tr>
<tr>
<td>MEK-1</td>
<td>MAP (Mitogen-Activated Protein) Kinase/ERK (Extracellular Signal-Regulated Kinase) Kinase 1</td>
</tr>
<tr>
<td>ERK-1</td>
<td>Extracellular Signal-Regulated Kinases 1</td>
</tr>
<tr>
<td>PI-3K</td>
<td>Phosphatidylinositol-3-Kinase</td>
</tr>
<tr>
<td>FMLP</td>
<td>N-formyl-methionyl-leucine-phenylalanine</td>
</tr>
<tr>
<td>PMA</td>
<td>Phorbol-12-myristate-13-acetate</td>
</tr>
<tr>
<td>PKC</td>
<td>Protein kinase C</td>
</tr>
<tr>
<td>PAF</td>
<td>Platelet Activating Factor</td>
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<tr>
<td>PGE₂</td>
<td>Prostaglandin E 2</td>
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pro-oxidative, pro-inflammatory interactions of Cd with neutrophils and macrophages in the adverse health effects of environmental and/or industrial exposure to this metal. With respect to pro-oxidative activity, Freitas et al. (2010) reported that exposure of isolated human neutrophils to CdCl \(_2\) caused increases in the production of ROS, specifically O\(_2^-\), H\(_2\)O\(_2\), and HOCI, both spontaneously and following activation of the cells with the phorbol ester, phorbol myristate acetate (PMA) [21]. The latter is a direct activator of protein kinase C (PKC), which in turn activates the superoxide-generating system of phagocytes, NADPH oxidase [21]. These findings were confirmed by others and were extended to include murine macrophages and macrophage cell lines in which exposure of these cells to Cd (10 \(\mu\)M) also resulted in increased production of nitric oxide (NO), an activity which was associated with both increased activity and synthesis of inducible NO synthase (iNOS) [22-24]. Although the exact molecular mechanisms which underpin the pro-oxidative interactions of Cd with neutrophils and macrophages remain to be conclusively established, it is noteworthy that exposure of murine macrophages to Cd at concentrations of 20–500 \(\mu\)M was found to increase cytosolic Ca\(^{2+}\) concentrations [25]. Ca\(^{2+}\) is a well-recognized second messenger, and increases in the cytosolic concentrations of this cation precede and are a prerequisite for receptor-mediated activation of NADPH oxidase [26].

Other mechanisms of Cd-mediated pro-oxidative activity include: i) inhibition of superoxide dismutase [27]; ii) bonding to sulfhydryl groups, depleting glutathione and protein sulfhydryls, thereby compromising intracellular anti-oxidative defences [28]; iii) activation of 5-lipoxygenase activity, leading to production of the neutrophil/monocyte chemoattractant, leukotriene B\(_4\) (LT\(_B\)\(_4\)), which also sensitizes these cells for increased activity of NADPH oxidase [29]; and iv) oxidative activation of redox-sensitive transcription factors such as nuclear factor kappa B (NFkB) and activator protein 1 (AP-1), which, in turn, activate the expression of genes encoding pro-inflammatory proteins, including iNOS [14,30-32].

The harmful pro-oxidative, pro-inflammatory activities of Cd have also been demonstrated in animal models of experimental pulmonary inflammation. Kataranovski et al. reported that intraperitoneal administration of CdCl\(_2\) (0.5 – 2 mg/kg body mass) resulted in a dose-related elevation in the number of circulating neutrophils, as well as those present in lung tissue, which was associated with increased: i) adhesive and pro-oxidative activities of these cells; and ii) circulating levels of the pro-inflammatory cytokines TNF and IL-6, the latter being significantly correlated with the numbers of blood and pulmonary neutrophils [33]. In addition, Kirschvink et al. [34] reported that repeated (x3 weekly for 3-5 weeks) CdCl\(_2\) (0.1%) nebulizations resulted in pulmonary inflammation in mice which was characterized by increased influx of neutrophils and macrophages in the setting of elevated levels of the matrix metalloproteinases-2 and -9. Histomorphometric analysis of the lung revealed changes compatible with emphysema, which correlated with the activities of the MMPs.

It is probable that Cd-mediated pulmonary inflammation and damage results from the pro-oxidative interactions of the metal with alveolar macrophages and other resident cells of the innate immune system, resulting in oxidative activation of NFκB and AP-1, leading to synthesis of IL-6, IL-8, and TNF [30,35-36]. In this respect it is also noteworthy that exposure of a murine macrophage cell line to Cd has been reported to activate a Ca\(^{2+}\)-ROS-JNK-caspase-3 intracellular signalling pathway which promotes phosphorylation/dephosphorylation of JNK and p38 MAPkinase, modulating cellular mitochondrial activity and proliferation, leading to apoptosis and necrosis [25]. The study by Kirschvink et al. [34] mentioned above is clearly compatible with a pathogenetic link between inhalation of Cd in cigarette smoke, chronic pulmonary inflammation, and development of emphysema. This contention is supported by the observation that relative to non-smokers, concentrations of Cd (and strontium) are elevated in the blood of cigarette smokers [37]. Furthermore, in a study to which 16024 adult humans were recruited, an increasing trend in urinary Cd\(^{2+}\) levels from never, through former, to current smokers was observed, which was negatively correlated with forced expiratory volume in 1 second (FEV\(_1\)) and the ratio of FEV\(_1\) to forced vital capacity (FVC), both indicative of airflow obstruction [38].

The pro-oxidative and pro-inflammatory effects of Cd on neutrophils and macrophages are depicted in Figure 1.

### Lead

According to Hu [39], the worldwide production of lead (Pb) is approximately 5.4 million tons and continues to rise. The major use of lead is in pb batteries, accounting for 78% of reported global consumption in 2003 [40]. This metal is also used in the production of pigments, glazes, solder, plastics, cable sheathing, ammunition, weights, fuel additives, and a variety of other products [39]. The predominant source of worldwide dispersion of pb into the environment for the past 50 years has been the use of pb organic compounds as anti-knock additives in motor vehicle fuels [39]. Emissions from this source have, however, declined with the phasing out of leaded petrol worldwide.
Cadmium

Increased cytosolic Ca2+ concentration

Increased ROS, MMPs, LTB4

(ROS)

Oxidative activation of NF-kB & AP-1

Synthesis of IL-6, IL-8, TNF

(Ca2+)i-ROS-JNK
-Caspase-3 signaling Pathway

Apoptosis

Pro-inflammatory effects including attraction of neutrophils to sites of inflammation:
-Activation of adhesion molecules on endothelial cells
-ROS may damage cellular lipid, proteins & DNA:
- MMPs cause matrix breakdown
- LTB4 associated with neutrophil recruitment

Figure 1: The pro-oxidative and pro-inflammatory effects of Cd on neutrophils and macrophages.

Lead is also present in tobacco, and Zielhuis et al. [41] demonstrated that blood lead levels in male and female students increased with the number of cigarettes smoked per day, although other sources of Pb such as exhaust fumes and food may also play a role. Lead levels among adults with high second-hand smoke exposure were found to be similar to those of smokers [42].

Depending on the dose, Pb exposure can cause a wide spectrum of health problems, including neurological, cardiovascular, renal, gastrointestinal, haematological and reproductive disorders. Pb accumulates in bone, which may serve as a reservoir for exposure in later life [40]. Children are particularly susceptible to lead intoxication, while at lower blood lead concentrations various neurological and behavioural problems may occur, ranging from a raised hearing threshold to a reduction in intelligence quotient (IQ) [43].

With respect to interactions with cells of the innate immune system, Pb has been reported to negatively affect the functions of both neutrophils and macrophages. In the case of neutrophils, chemotaxis, the generation of ROS, and the killing of Candida albicans were found to be decreased in workers occupationally exposed to Pb, even in those with blood levels below the currently acceptable biological lower limit [44-48]. On the basis of these observations, Quieroz et al. [46] suggested that immune dysfunction may be a sensitive indicator of exposure to Pb. More recently, Di Lorenzo et al. (2006) reported an association between Pb exposure and the numbers of circulating neutrophils, with the strongest association being observed in occupationally-exposed workers who smoked [49]. This latter observation is not surprising given the well-recognized association of smoking with i) neutropenia [50]; and ii) increased levels of Pb in the blood of smokers as described above. Although the authors speculate that increased numbers of circulating neutrophils may represent a mechanism to compensate for Pb-mediated immune dysfunction, they concede that it is more likely to reflect a neuroendocrine response to toxicity/stress. In this setting, increased production of endogenous glucocorticoids and catecholamines may contribute to both neutrophilia and neutrophil dysfunction possibly by interfering with the adhesion of these cells to vascular endothelium [49].

In the case of macrophages, Pb, at non-cytotoxic concentrations of 0.1-10 µg/ml, has been reported to inhibit the production of NO by cytokine-induced cell lines by interfering with induction of iNOS at the level of gene transcription [51,52]. Moreover, exposure to Pb, at a concentration of 1300 ppm, was found to inhibit the adherence of murine peritoneal macrophages to plastic tissue culture dishes, which may underpin the inhibitory effects of the metal on the migratory responsiveness of these cells [53,54]. These effects of Pb on the induction of iNOS and spreading of macrophages are opposite to the effects on cytokine production. Flohé et al. [55] observed that exposure of murine bone marrow-derived macrophages to Pb (0.2-20 µM), prior to activation with bacterial lipopolysaccharide, resulted in augmentation of production of TNF, IL-6 and IL-12, as well as prostaglandin E2, while production of anti-inflammatory IL-10 was decreased. More recently, Valentino et al. [56], in a study designed to measure the circulating levels of pro- and anti-inflammatory cytokines in workers exposed to very low levels of Pb, found significant increases in the plasma concentrations of TNF and IL-10 relative to those of non-exposed control subjects. They reasoned that the Pb-mediated increase in IL-10 was a biological, anti-inflammatory strategy to counteract the increase in the production of pro-inflammatory TNF [56].

Several mechanisms, including pro-oxidative properties and antagonism of the second messenger function of Ca2+ have been proposed to explain the modulatory effects of Pb on the function of cells of the innate immune system. With respect to pro-oxidative activity, the chemical properties of Pb favour interactions with diverse bio-lipids, particularly protein sulphydryls [57]. Increases in Pb-binding proteins, as well as in glutathione (GSH), occur soon after metal exposure and are believed to protect against Pb toxicity [57]. However, by depleting glutathione and protein sulphydryls, Pb can compromise host anti-oxidant defences, creating an intracellular environment conducive to the oxidative activation of transcription factors such as NFκB, while promoting oxidant-mediated inhibition of the protective functions of neutrophils and macrophages.

However, the prevailing theory of Pb-mediated modulation of the functions of neutrophils and macrophages is that the metal may affect intracellular Ca2+ homeostasis, either by mimicking Ca2+ action and/or antagonizing Ca2+-dependent cellular functions. Given the critical second messenger role of Ca2+, exposure to Pb may affect several intracellular signalling pathways, including those involving activation of protein kinase C possibly underpinning interference with neutrophil and macrophage functions as described above [58].

Mercury

Elemental mercury (Hg) is liquid at room temperature, and in this form is less toxic than inorganic or organic bound Hg. Methylmercury (MeHg), the most predominant form of organic Hg, is the form that most commonly poses a health risk, mainly through fish consumption [59]. Between 2700 and 6000 tons of elemental Hg are released into the biosphere annually through degassing from the earth’s crust and oceans [60,61]. Occupational (chloralkali plants, production of lamps and batteries, gold mining, dentistry) and environmental (dental amalgams, food) exposures to Hg also occur frequently [62]. According to reports "a single dental amalgam filling with a surface area of only 0.4 cm² is estimated to release as much as 15 micrograms of Hg per day primarily through mechanical wear and evaporation.” It is also stated that “the average individual has eight amalgam fillings and could absorb to
120 micrograms of Hg per day from their amalgams" [63,64].

Hg has been found to cause various health problems, including neurological, renal, immunological, cardiac, motor, reproductive and even genetic disorders [65]. Pre- or post-natal exposure to high levels of MeHg causes mental retardation, cerebral palsy, seizures and ultimately death [66], while inorganic Hg is known to induce autoimmune disease in susceptible rodent strains. Additionally, in inbred strains of mice prone to autoimmune disease, Hg can accelerate and exacerbate disease manifestations [67]. Metals such as Hg may also contribute to the pathogenesis of autoimmune diseases by modulating mast cell activity [68].

Hg has been reported to affect the functions of the cells of the innate immune system, including neutrophils, monocytes/macrophages, natural killer cells and dendritic cells as well as epithelial cells. In the case of neutrophils, Jansson et al. [69] reported that exposure of these cells to low micromolar (≤5 µM) concentrations of HgCl₂ in vitro resulted in significant, albeit variable, increases in the production of superoxide activated by the chemoattractant, N-formyl-L-methionyl-L-leucyl-L-phenylalanine, but not with other activators such as PMA or opsonized zymosan. At approximately the same concentrations, HgCl₂ and MeHgCl were found to inhibit spontaneous apoptosis of human peripheral blood mononuclear leukocytes to HgCl₂, as well as NFκB, which was actually decreased [76]; and iii) decreased production of IL-6 and TNF by human monocyte-derived dendritic cells in vitro [70]. These effects persisted following reductions in the ROS, superoxide, H₂O₂ and hydroxyl radical [82]. Oxidative stress resulted from metal-mediated depletion of intracellular sulphydryls, resulting in cytotoxicity.

In contrast to the aforementioned studies which addressed the effects of short-term exposure to Hg on neutrophil function and viability in vitro, prolonged exposure to the metal in the workplace was reported to be associated with impairment of neutrophil chemotaxis and generation of ROS [71]. These effects persisted following reductions in exposure due to improvements in factory hygiene practices, prompting the authors to propose that exposure to Hg, even at levels considered to be "safe", may lead to impairment of neutrophil function.

With regard to monocytes/macrophages, electron microscopic analysis of cells exposed to MeHg clearly revealed uptake of the metal with deposition in lysosomes and dispersal in the cytoplasm and nuclei [72]. Functional analysis of macrophages exposed to Hg (1-5 µM) demonstrated: i) impairment of their phagocytic and migratory activities, possibly as a consequence of increased production of ROS by metal-exposed cells [72,73]; ii) increased production of LTB₄ [74], possibly resulting from increased activity of the cytokines IL-6 and TNF, which was associated with increased activity of p38 MAPK [75], but not NFKB, which was actually decreased [76]; and iii) decreased production of NO in the setting of increased synthesis of the cytokines IL-6 and TNF, which was associated with increased activity of p38 MAPK, but not NFKB [76].

The stimulatory effects of Hg on the production of IL-6 and TNF by macrophages are essentially in agreement with the findings of an earlier study by Villanueva et al. [36]. These authors reported that exposure of human peripheral blood mononuclear leukocytes to HgCl₂, as well as to CdCl₂, as mentioned earlier, resulted in increased production of both IL-1β and TNF in the setting of decreased production of anti-inflammatory IL-10 and IL-1 receptor antagonist. The cytokines interferon-γ, IL-4 and IL-17 which typify activation of the Th1, Th2 and Th17 sub-populations of CD4+ T-cells of the adaptive immune system respectively, were also increased following exposure of mononuclear leukocytes to HgCl₂ [77].

In addition to its effects on neutrophils and monocytes/macrophages, Hg, as mentioned above, has been reported to modulate the functions of natural killer cells, and epithelial cells. In the case of the former, dietary intake of MeHg (3.9 µg/gram diet) by mice and rats resulted in suppression (42-44%) of the tumoricidal activity of blood and splenic natural killer cells, as well as proliferation of the T-cells and B-cells of the adaptive immune system [78,79]. More recently, Migdal et al. [80] investigated the effects of thimerosal and other Hg-containing compounds on the spontaneous expression of surface markers of cell activation, as well as on the production of the pro-inflammatory cytokine TNF, and the chemokine IL-8 by human monocyte-derived dendritic cells in vitro. The authors observed that exposure of the cells to all of these compounds was associated with over-expression of CD86 and HLA-DR, both of which mediate T-cell activation, as well as increased production of TNF and IL-8. From a mechanistic perspective, these pro-inflammatory interactions of Hg with dendritic cells were associated with increased intracellular oxidative stress, presumably as a consequence of the interaction of the metal with glutathione and protein sulphydryls, and delayed, oxidant-mediated influx of extracellular Ca²⁺ [80,81]. Both of these events (increased intracellular levels of ROS and associated Ca²⁺ influx) result in activation of transcription factors and expression of genes encoding pro-inflammatory proteins.

Epithelial cells are also prone to metal-mediated oxidative stress as described by Han et al. [82]. These authors reported that exposure of the bronchial epithelial cell line (BEAS-2B) to Hg or, as mentioned earlier to Cd in particular, at concentrations of 0-50 µM, resulted in dose-related oxidative stress due to increased intracellular generation of the ROS, superoxide, H₂O₂ and hydroxyl radical [82]. Oxidative stress resulted from metal-mediated depletion of intracellular sulphydryls, resulting in cytotoxicity.

The pro-oxidative, pro-inflammatory and cytotoxic properties of Hg are clearly similar to those of Cd and Pb, resulting from the interactions of the metal with, and depletion, of intracellular sulphydryl groups [83]. Oxidative stress, in turn, leads to influx of Ca²⁺ and activation of p38 MAPK, resulting in production of pro-inflammatory cytokines by cells of the innate immune system [25]. Excessive and prolonged oxidative stress, however, results in oxidative inactivation of protective functions such as adherence, migration and phagocytosis in the case of neutrophils and monocytes/macrophages, and ultimately to cell death by apoptosis due to p38 MAPK-mediated activation of caspase 3 and oxidant-mediated necrosis [25].

**Vanadium**

Metallic vanadium (V) does not exist in nature; rather, V compounds exist in oxidation states ranging from -1 to +5, the most common valences being +3, +4, and +5, with quadrivalent salts being the most stable. Occupational exposure to V is common in the petrochemical, mining, steel, and utilities industries; fossil fuels and some ores contain significant amounts of this metal [84]. Inhalation is the most prevalent route of human exposure to insoluble pentavalent V oxides and soluble salts in urban/occupational settings. Workers exposed to V-bearing dusts or fumes display an increased incidence of several lung diseases (e.g., asthma, bronchitis, pneumonia) [85]. Exposure to V can also take place through the smoking of cigarettes. The concentration of V in cigarettes ranges between 0.49 – 5.33 mg/g (average: 1.11 mg/cigarette). About 60% of the vanadium remains in the ash, 8.3% in the cigarette filter and 31.3% in the smoke [4,86].

Like the other metals, V has been found to interact pro-oxidatively with cells of the innate immune system, including neutrophils, macrophages, basophils, as well as epithelial cells. In the case of neutrophils, Fickl et al. [87] reported that exposure of activated human
Platinum Group Metals: Platinum and Palladium

Heavy Metals and Predisposition to Infection

Cigarette smoking is a well-documented cause of exposure to metals such as Pt and Pd, and its effects are widely recognized. Exposure to these metals may compromise innate host defenses and inflame the airway. A summary of the macrophage- and neutrophil-derived inflammatory mechanisms that are increased following exposure to heavy metals is presented in Table 3.

Exposure to Pd may also compromise innate host defenses, albeit by a different mechanism. As mentioned earlier, heavy metals such as Pt and Pd may cause oxidative stress and inflammation. The protective function of macrophages and neutrophils against oxidative stress can be compromised by exposure to Pd. Exposure to Pd may also alter the expression of pro-inflammatory cytokines, such as interleukin-1, tumor necrosis factor-alpha, and interferon-gamma. These cytokines are crucial for the activation of macrophages and neutrophils, and their expression is modulated by oxidative stress.

Exposure to Pt may also affect immune function. Pt exposure can alter the function of dendritic cells, which are crucial for the presentation of antigens to T cells. Pt exposure can also alter the function of T lymphocytes, which are important for the immune response. Pt exposure can alter the balance of pro-inflammatory and anti-inflammatory cytokines, which can affect immune function.

Platinum (Pt) and palladium (Pd) have been reported to affect the immune system. A study in which Pt and Pd were administered to mice demonstrated that exposure to these metals significantly increased the magnitude of oxidative interactions of the metals with neutrophils. The authors proposed that these pro-oxidative interactions of Pt and Pd with neutrophils may result in the activation of NF-kappa B, which may increase the production of pro-inflammatory cytokines.

In conclusion, exposure to Pt and Pd may alter the function of immune cells, which may increase the risk of infection. These metals may also alter the expression of cytokines, which may affect immune function. Further studies are needed to fully understand the mechanisms by which Pt and Pd affect the immune system.
an unusual mechanism involving the inactivation of the neutrophil/monocyte chemotactants, IL8 and the complement cleavage product, C5a. Brief exposure to the metal (25 μM) resulted in either partial (IL-8) or complete attenuation (C5a) of both the Ca2+-mobilizing and chemotactic activities of the chemotactants for neutrophils [113].

### Heavy Metals and Respiratory Disease

Exposure to numerous metals may injure the lung directly or via interaction with cells of the innate immune system. Metal-induced injury may involve the airways, alveoli or interstitial tissues of the lung or predispose subjects to bronchial carcinomas. Airway diseases such as bronchitis and bronchiolitis may occur following exposure to metal oxides such as cadmium oxide. Welders are at increased risk and are limited over 48 hours [116].

Metal fume fever is an acute inflammatory response triggered by pulmonary macrophages following exposure to fumes containing metal oxides such as cadmium oxide. Welders are at increased risk and symptoms such as fever, malaise, myalgia, dyspnea and cough begin about 4 – 8 hours after exposure. Bronchial lavage fluid contains high concentrations of tumour necrosis factor-alpha, interleukin-6 and interleukin-8 as well as neutrophils. The course of the illness is self-limiting over 48 hours [116].

A severe form of acute lung injury manifesting as pneumonitis or the acute respiratory distress syndrome (ARDS) known as acute metal fume toxicity may occur following heavy exposure to Cd[117,118] and Hg [114]. These metals are cytotoxic and alveolar damage results in acute lung injury which may progress to respiratory distress.

Mercury in its metallic form may reach the lungs via embolization from the venous system and has been reported in intravenous drug users and in some cases of attempted suicide [119]. An acute inflammatory reaction is elicited in the lung in the form of a foreign body giant cell reaction. Interstitial lung fibrosis may follow the inflammatory response [120].

The carcinogenic potential of metals such as Cd [121] and arsenic [122] may increase the risk of bronchus carcinoma. Smelter workers exposed to these agents were more likely to develop lung cancer. Concomitant exposure to tobacco smoke may accentuate the risk of a pulmonary malignancy.

### Conclusion

To minimize the risk of inflammation-mediated tissue damage to bystander tissues, activation of the cells of the innate immune system should be efficient and transient. Occupational and environmental exposure to heavy metals, especially Cd, Pt and V is, however, an important cause of inappropriate activation of these cells, predisposing to oxidant- and protease-mediated tissue damage. Cigarette smoking is a major, albeit eminently avoidable risk, which results in simultaneous exposure to multiple heavy metal toxins and may be compounded both by occupation and proximity to combustion of fossil fuels in the environmental setting. In these latter settings, in which avoidance may be difficult, frequent monitoring and early recognition of symptoms of metal- associated toxicity is recommended, with consideration given to the implementation of anti-inflammatory/anti-oxidative therapy where necessary.

### References


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**Mediator** | **Effect** | **References**
---|---|---
ROS | Increased generation in CdCl2/CdS (0.5μM-1nM) treated neutrophils & macrophages. | [21-23]
| Increased generation in MeHgCl(1.25-5μM)-treated monocytes, activated with PMA. | [30,36]
| Pt & Pd (0.025-25μM) potentiates reactivity of neutrophil derived ROS. | [74]
| Vanadium 2+, 3+, 4+ (25μM) mediate hydroxyl radical production from FMLP- & PMA- activated neutrophils. | [87]
| Increased generation by rat alveolar macrophages treated with sodium metavanadate (50-1000μM). | [88]

**NO** | 0.6-10μM CdCl2 cause increased NO production by macrophages. | [23-24]

**LTB4** | <30μM CdCl2 augments LTB4 secretion by rabbit alveolar macrophages. | [29]
| Production increased in neutrophils from lead exposed workers. | [45]
| Increased generation by rabbit alveolar macrophages exposed to HgCl2. | [74]

**Cytokines** | Increased production(or expression of mRNA) of IL-1, TNF, IL-6 by PBMC exposed to CdCl2/CdSO4 (1-10μM). | [30,36]
| Increased production of TNF, IL-6, IL-12, PGE2 and decreased production of IL-10 by Pb treated macrophages. | [55]
| HgCl2 (200nm-5μM) increases the production of IL-1β, TNF, IL-6 and downregulates production of IL-Ra & IL-10. | [36,77]

**Table 3:** Macrophage- and neutrophil-derived inflammatory mediators which are increased following exposure to heavy metals.

**Abbreviations:** CdCl2, cadmium chloride; CdS, cadmium sulphide; MeHgCl, methyl mercury chloride; Pt, Platinum; Pd, palladium; FMLP, N-formyl-methionyl-leucine-phenylalanine); PMA, phorbol-12-myristate-13-acetate


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