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Review

Fate of manganese associated with the inhalation of welding fumes: Potential neurological effects☆

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Abstract

Welding fumes are a complex mixture composed of different metals. Most welding fumes contain a small percentage of manganese. There is an emerging concern among occupational health officials about the potential neurological effects associated with the exposure to manganese in welding fumes. Little is known about the fate of manganese that is complexed with other metals in the welding particles after inhalation. Depending on the welding process and the composition of the welding electrode, manganese may be present in different oxidation states and have different solubility properties. These differences may affect the biological responses to manganese after the inhalation of welding fumes. Manganese intoxication and the associated neurological symptoms have been reported in individual cases of welders who have been exposed to high concentrations of manganese-containing welding fumes due to work in poorly ventilated areas. However, the question remains as to whether welders who are exposed to low levels of welding fumes over long periods of time are at risk for the development of neurological diseases. For the most part, questions remain unanswered. There is still paucity of adequate scientific reports on welders who suffered significant neurotoxicity, hence there is a need for well-designed epidemiology studies that combine complete information on the occupational exposure of welders with both behavioral and biochemical endpoints of neurotoxicity.
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Keywords: Welding fumes; Bioavailability; Manganese; Neurotoxicity

Contents

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1. Electric arc welding process

The Bureau of Labor Statistics reported that 361,970 workers were employed full-time as welders, cutters, solders, and brazers in the United States during the year 2002 (Bureau of Labor Statistics, 2002). Greater than two million workers worldwide are believed to perform some type of welding as part of their work duties. Welders are a heterogeneous working population. They work in a variety of locations, ranging from well-ventilated outdoor and indoor settings to poorly-ventilated confined spaces (e.g., hull of a ship, building crawl space).

Welding processes produce gaseous and aerosol by-products composed of a complex mixture of metal oxides volatilized from the welding electrode or the flux material incorporated within the electrode (Zimmer and Biswas, 2001). The formed welding fume is the vaporized metal that has reacted with air to form particles that are respirable in size. Most of the materials in the welding fume come from the electrode, which is consumed during the welding process (Palmer and Eaton, 2001). The use of shielding gases, fluxes, or surface coatings on the electrode and base metal also may influence the composition of the welding aerosol.

One of the most common types of welding processes used in industry is gas metal arc welding (GMAW). In this process, shielding gases (usually a combination of argon, helium, or carbon dioxide) are continually blown through the welding nozzle and over the arc to protect the formed weld from weakening due to oxidation. Other common processes are shielded-metal arc welding (SMAW) and flux-cored arc welding (FCAW). As opposed to using shielding gases, fluxing compounds are incorporated into the electrode that provides the shielding environment to protect the weld as the electrode is consumed in the process. The fluxing agents used in SMAW and FCAW can contribute to the inhalation exposure of welders. Fumes formed during processes which use fluxes have been observed to be both chemically and physically more complex than fumes formed from GMAW processes (Antonini et al., 1999; Zimmer and Biswas, 2001; Jenkins, 2003).

Studies using electron microscopy have indicated that individual primary particles generated during welding are in the nano-size range (0.01–0.10 μm) when first formed near the arc (Clapp and Owen, 1977; Voitkevich, 1995). However, aided by the turbulent conditions caused by the heat of the welding process, these primary particles quickly accumulate together in the air to form larger agglomerated particles that usually have mean aerodynamic diameters in the range of 0.1–0.6 μm (Hewett, 1995; Voitkevich, 1995; Zimmer and Biswas, 2001; Jenkins, 2003).

The majority of all welding (∼90%) is performed using mild or carbon and low alloy steels (Beckett, 1996). Welding with stainless steel, aluminum, titanium, nickel, and all other metals accounts for less than 10% of all welding. Mild and low alloy steel electrodes are comprised of mostly iron with varying amounts of manganese, whereas stainless steel electrodes contain chromium and nickel in addition to iron and manganese. Depending on the process and materials used, other elements may be found in welding fumes, including zinc, aluminum, cadmium, copper, lead, fluorides, silicon, barium, magnesium, calcium, and tin.

Certain gases also can be formed during the welding process that may affect the respiratory health of welders. Shielding gases used during GMAW can intensify the ultraviolet radiation produced in the arc, leading to the photochemical formation of potentially harmful gases, such as nitrogen oxides and ozone. Carbon dioxide can be reduced and converted to the highly toxic gas, carbon monoxide. Also, the oxidation of vapors from degreasing agents, that are sometimes used to clean the base metals prior to welding, can produce highly toxic gases (e.g., phosgene).

2. Manganese in welding fumes

Manganese is an essential ingredient in the welding of steel because it increases hardness and strength, prevents steel from cracking during manufacture, improves metallurgical properties, and acts as a deoxidizing agent to remove iron oxide from the weld pool to form a stable weld (Harris, 2002). The amount of manganese in welding rods can range from 1 to 20% of the metals present. Thus, most welders are exposed to mixed metal fumes that contain a small percentage of manganese (<5% per total metal present). However, some welders are exposed to aerosols generated from hard-facing electrodes that contain a higher percentage of manganese (10–20%). Such hard-facing materials are typically applied to dredge pump shells and cutter heads, tractor rollers, heads, sprockets, wheel excavator teeth, power shovel teeth, rail ends, frogs, and crossovers, and railroad car castings.

Using X-ray photoelectron spectroscopy, Minni et al. (1984) observed that Mn^{2+} and Mn^{3+} (existing as MnO and Mn_2O_3) are the most probable oxidation states of manganese in welding fume generated using SMAW-stainless steel and GMAW-stainless steel processes. Voitkevich (1995) demonstrated with X-ray diffraction that the core of particles generated by mild steel electrodes was comprised of an insoluble complex of iron and manganese in the forms of Fe_3O_4 and $MnFe_2O_4$. However, with flux-cored electrodes containing fluorine, the distribution of the iron and manganese within the welding particles was more complex. Fluorine complexes of the more soluble forms of iron and manganese (K_3FeF_6, FeF_3, MnF_2, and MnF_3) were concentrated at the particle surfaces, whereas the oxide compounds (less soluble forms) of iron and manganese were concentrated in the particle core in the form of Fe_3O_4 and $MnFe_2O_4$.

3. Welding fume workplace exposure limits

Before 2005, the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value-Time Weighted Average (TLV-TWA) was 5 mg/m^3 total fume concentration in the breathing zone of the welder or others in the area during the welding of iron, mild steel, and aluminum (ACGIH, 2001a). However, ACGIH retracted the TLV for welding fume in 2004, without giving an explanation for the change (ACGIH, 2004). In 1989, Occupational Safety and

Health Administration (OSHA) set a Permissible Exposure Limit (PEL) for total welding fume at 5 mg/m^3 as an 8-h TWA. However, the OHSA PEL was eventually rescinded and no new PEL for welding fumes has since been established. NIOSH has established a Recommended Exposure Limit (REL) for welding fumes (and total particulates) of the lowest feasible concentration (NIOSH, 2003).

ACGIH adapted since 1970 several times the tolerable exposure to total airborne Mn. In 1970, a TLV-CEILING of 5 mg/m^3 (as Mn) was adopted for manganese and compounds. From 1979 to 1994, a TLV-TWA of 1 mg/m^3 and a Short Term Exposure Level (STEL) of 3 mg/m^3 (as Mn) was adopted for total welding fume. From 1988 to 1994, a TLV-TWA of 5 mg/m^3 (as Mn) was adopted for manganese dust and compounds, which has been drastically decreased in 1995 to 0.2 mg/m^3 (as Mn) for manganese, elemental, and inorganic compounds, including total welding fume as well (ACGIH, 2001b).

Studies have measured workplace manganese levels in welding fumes that exceeded the NIOSH REL or original ACGIH TLV-TWA. An evaluation of airborne fume concentration levels in eight welding companies was completed by the Workplace Safety and Health Branch in Manitoba, Canada (Korczynski, 2000). Approximately 90% of welding studied was GMAW of mild steel. A total of 42 welders were monitored for personal exposure to welding fumes, and it was observed that 19% of welders were exposed to levels of iron that exceeded the original ACGIH TLV-TWA of 5 mg/m^3. The personal exposures to iron ranged from 0.04 to 16.29 mg/m^3. Moreover, 62% of the welders studied were reportedly exposed to levels of manganese that exceeded the ACGIH TLV-TWA of 0.2 mg/m^3. The personal exposures to manganese ranged from 0.01 to 4.93 mg/m^3. Between 1995 and 1996, Susi et al. (2000) collected approximately 130 personal exposure measurements for manganese at nine construction sites among the welding and torch cutting trades (e.g., boilermakers, pipe and welder fitters, and iron workers). It was observed that the probability of exceeding the ACGIH TLV for manganese was sufficiently high to cause concern among the construction trades (Rappaport et al., 1999).

4. Possible fate of manganese after welding fume inhalation

The potential health impact of inhaling welding fumes, and the metals associated within them, is dependent on the sites of deposition in the respiratory tract, as well as the clearance mechanisms involved in removing the particles from the lungs. The three major subdivisions of the respiratory tract include the nasal/head airways, the tracheo-bronchial region, and the alveolar or pulmonary region. Zimmer and Biswas (2001) determined the particle number size distributions during GMAW and FCAW and found that the aerosols generated from GMAW alloy were smaller with a mean count diameter of 0.149 μm, as compared to FCAW particles that had a mean diameter size of 0.352 μm. The majority of inhaled welding particles would deposit in the alveolar or pulmonary region of the respiratory tract. However, due to presence of a significant number of welding particles that are <0.1 μm in size as measured by Zimmer and Biswas (2001), it is likely that some of the inhaled particles would deposit in the tracheo-bronchial region and the nasal/head airways as well.

Welding particles that deposit in the tracheo-bronchial region most likely would have a short half-time in the respiratory tract due to removal by the mucociliary escalator. In this instance, inhaled particulate matter deposited in the region encounters a layer of mucus and become entrapped. The particles are carried up the mucociliary escalator by beating cilia to the pharynx, where the material is swallowed, processed, and excreted from the body via the gastrointestinal tract. Because of the fast elimination time of the particles from the body by this process, the insoluble nature of most welding particles, and the limited rate of gastrointestinal manganese absorption, it is unlikely that manganese associated with welding fume would be reabsorb back into the body via the gastrointestinal tract. One should be cautious, however, as data on the solubility of welding particles in gastric juice is lacking. The time period for tracheo-bronchial clearance is on the order of hours (McClellan, 2000).

Welding particles that deposit in the nasal/head airway region may reach the brain via olfactory transport—a potential route of delivery as manganese travels from the nose to the brain (Tjalve and Henriksson, 1999). During olfactory transport, the blood-brain barrier is bypassed, and the inhaled chemicals are conveyed along cell processes to synaptic junctions with neurons of the olfactory bulb. Soluble metals that have been reported to undergo transport via olfactory processes in laboratory animals include manganese, cadmium, nickel, and mercury (Tjalve and Henriksson, 1999). Early studies by Howe and Bodian (1941) and de Lorenzo (1970) have shown that insoluble nano-size particles may be rapidly transported along the olfactory bulb into the olfactory nerve in primates. In addition, Oberdorster (2004) reported that, for rats, inhaled nano-size radio-labeled carbon particles were rapidly transported by olfactory uptake and accumulated in the olfactory bulb in rats. However, because of anatomical differences between rats and humans, the relevance of these findings to human manganese inhalation exposure and the risks for neurotoxicity are unknown (Brenneman et al., 2000).

In the third instance, inhaled particles that reach the alveolar regions are most likely engulfed by alveolar macrophages (McClellan, 2000). Particles can remain in macrophages for extended periods of time. The retention half-time of non-toxic, solid particles in the alveolar region has been estimated to be up to 700 days in humans (Oberdorster, 2004). Over time, a portion of the ingested particles may reach the terminal bronchioles, are taken up by the mucociliary escalator, swallowed, and removed from the body via the gastrointestinal tract. Some remaining particles may be carried to interstitial spaces by macrophages and other phagocytic cells (e.g., neutrophils) or to lung-associated lymph nodes through the lymphatic system. However, because of the very short distance (~0.5 μm) from the alveolar space and the pulmonary capillary, some particles may gain direct access to the bloodstream via uptake by alveolar type I cells that line the epithelium of the airspaces.

Lam et al. (1979) evaluated the fate of neutron activated-welding fumes and their constituents in rats and guinea pigs after inhalation or intratracheal instillation. Measuring the radioactivity of individual metals of welding fumes in different organs at different times after exposure, they indicated that the removal of certain metallic components of the fume after deposition in the lungs occurred in three phases. All of which were dependent on the in vivo solubility of the specific metal. Phase I represented mucociliary clearance deposited particles which were removed from the body via the gastrointestinal tract as previously described. The eliminated metal constituents appeared in the fecal material and had quick elimination half-times of less than 1 day. The clearance rates of each element of the welding fumes were similar during this initial phase, indicating that the eliminated particles were transported in their entirety, without separation of the constituents. Phase II was a slower process with a retention half-time of up to a week. The clearance rates for the various welding fume components were very consistent, indicating that the particles were still being transported in an unchanged state. Phase III was a much slower process with the welding constituents having biological half-times of several weeks. Unlike phases I and II, the various elements of a particular fume were cleared from the lungs at very different rates, indicating a separation of the material during phase III which was attributable to the solubility in tissue of each metal present in the welding fume.

Using magnetometry to study the fate of the metallic iron particles from the lungs of shipyard arc welders, Kalliomaki et al. (1983) estimated that approximately 70 mg of iron was deposited in the lungs of full-time welders per year and the average lung burden of ferrous metal particles to be 1 g after 10 years of welding. Retired welders were determined to clear approximately 10–20% of the accumulated particulate burden per year. It appears that even after removal from the welding exposure, significant amounts of particles and the associated metals can persist in the lungs, and thus potentially leach into the pulmonary circulation for extended periods of time.

Once in the blood, the metals that have dissociated from welding particles could be transported directly to the brain bypassing first-pass hepatic clearance. In the case of manganese, approximately 80% in the plasma is bound to β_1-globulin and albumin, and a small fraction is bound to transferrin (Aschner, 2000). The mechanisms and chemical form by which manganese is transported across the blood-brain barrier are not completely understood. However, it appears that a number of processes are involved. They include facilitated diffusion, active transport, and two distinct carrier-mediated transport systems—transferrin-dependent and transferring-independent pathways. Both of these carrier-mediated systems utilize a divalent metal transporter (DMT1) as the transport protein (as reviewed by Aschner, 1999, 2000; Roth and Garrick, 2003).

Due to the chemical similarities between manganese and iron, these metals can compete at two loci—for binding to transport processes in the circulation, and for uptake mechanisms at the blood-brain barrier. The consequences of this competition are of great importance, as plasma iron overload has been shown to significantly decrease the uptake of manganese across the blood-brain barrier (Aschner and Aschner, 1990), whereas iron deficiency has been associated with increased concentrations of manganese in the brain (Mena et al., 1974). In an experimental animal study, the effect of iron status of the body on the fate of $^{54}MnCl_2$, which was delivered directly to the lungs of rats was examined (Molina et al., 2000). One group of rats was bled every other day for 1 week to reduce iron, whereas another group inhaled aerosol Fe_2O_3 particles (100 mg/m^3) for 4 h, five times over a 2-week period to increase body iron before intratracheal instillation of $^{54}MnCl_2$. In the assessment of the iron status after treatment, the non-heme iron in the lungs was found to be significantly increased in the Fe_2O_3-exposed rats, and decreased in the livers of the bled rats. It was observed that $^{54}MnCl_2$ transport from the lungs to the blood was increased in the group that had been depleted of iron and lowered in the group that had been exposed by inhalation to Fe_2O_3. Thus, the fate and toxicological implications of manganese associated with welding fumes may be influenced by the systemic iron stores and by the presence of increased amounts of iron that have been deposited in the lungs of welders.

5. Neurotoxic effects of manganese

Manganese is an essential element, is found in all brain regions, and is necessary for proper brain function. Mechanisms exist to transport and store manganese innately, as opposed to other metals that do not have an essential role. Some brain regions are more susceptible to manganese accumulation, as the brain does not accumulate manganese equally. The inhalation of excess manganese can cause a neurodegenerative disorder characterized by both central nervous system abnormalities and neuropsychiatric disturbances. In its early stages, manganese toxicity may be detected as neurofunctional alterations in groups of exposed persons. Later it appears as subclinical signs in individuals who seek medical attention. It ends with development of the chronic neurological condition known as ‘‘manganism’’ (Mergler, 1999).

Manganism is a neurological syndrome that resembles Parkinson’s disease, but there is considerable evidence that manganese preferentially damages different areas of the brain from those that are affected in Parkinson’s disease (Calne et al., 1994; Olanow, 2004). Parkinson’s disease and manganism may be differentiated based on their clinical, pharmacological, imaging and pathological features.

The similarities between the clinical manifestations of Parkinson’s disease and manganism include the presence of generalized bradykinesia and widespread rigidity. Manganism dissimilarities from Parkinson’s disease include less-frequent resting tremor, more frequent dystonia, symmetry of effects, a particular propensity to fall backward, a characteristic ‘‘cock-walk’’, in which patients walk on their toes with elbows flexed and spine erect (Calne et al., 1994). The similarities between the two disorders can be partially explained by the fact that in manganism the basal ganglia accumulate most of the excess manganese compared with other brain regions, and dysfunction in the basal ganglia is also the etiology of Parkinson’s disease (Dobson et al., 2004). However, Parkinson’s disease is

primarily associated with the loss of dopaminergic neurons within the substantia nigra, allowing the caudate and putamen to become overly active and possibly cause continuous output of excitatory signals to the corticospinal motor control system (Guyton and Hall, 1996). The substantia nigra is spared in manganism, which is linked to the degeneration of GABAminergic neurons within the globus pallidus in pathways postsynaptic to the nigrostriatal system (Pal et al., 1999; McMillan, 1999). Another difference is the presence of Lewy bodies in the substantia nigra and other regions of the brain in Parkinson's disease but not in manganism (Olanow, 2004).

There also are a few imaging procedures that have been used to distinguish manganism from Parkinson's disease, including positron emission tomography (PET), computerized tomography (CT), and magnetic resonance imaging (MRI). The CTs and MRIs are typically normal in Parkinson's disease patients and are not of diagnostic value, whereas the PET is abnormal in patients with Parkinson's disease (Calne et al., 1994). PET provides a means of discriminating between Parkinson's disease and manganism, as there is typically a reduced uptake of ^{18}F-6-fluorodopa in the striatum of Parkinson's disease patients due to the loss of downstream dopaminergic cells in the nigrostriatal pathway, whereas PET is generally normal in manganism (Calne et al., 1994; Olanow, 2004). Manganism is generally associated with hyperintense signal abnormalities in the globus pallidus, striatum, and substantia nigra bilaterally on an MRI, whereas the MRI is normal in Parkinson's disease patients (Nelson et al., 1993; Kim et al., 1999; Olanow, 2004). There are also differences with respect to treatment response. Although there may be an initial response to levodopa, the primary treatment option for Parkinson's disease, there is typically a failure to achieve a sustained therapeutic response in patients with manganism (Calne et al., 1994). In at least one case of manganese intoxication, EDTA chelation therapy has been shown to reduce the neurological symptoms of welders overexposed to manganese (Discalzi et al., 2000).

6. Welder studies

Several hundred studies have evaluated the health effects associated with welding fume inhalation. However, these effects are oftentimes difficult to assess because of differences in worker populations, industrial settings, work area ventilation, welding processes and materials used, and other occupational exposures besides welding fumes. It has been established that most full-time welders experience some type of respiratory disorder during their time of employment (Sferlazza and Beckettt, 1991; Martin et al., 1997; Antonini et al., 2003b, 2004). Pulmonary effects have included metal fume fever, bronchitis, lung function decrements, increased susceptibility to infection, and a possible increase in the incidence of lung cancer. Importantly, much less information is available concerning the non-respiratory effects (e.g., neurological) of welding fume exposure (Antonini, 2003a). Still, a limited number of case reports and worker studies have evaluated the possible neurological changes associated with welding fume inhalation.

As for those case reports of neurological disease in welders, airborne manganese levels in most cases were excessive as the affected welders had worked in railroad industries in which the manganese content of the welding rods was high (Nelson et al., 1993; Franek, 1994), in confined spaces like a ship's hold (Sadek et al., 2003), where workplace hygiene was poor (Rasmussen and Jepsen, 1987), or where welding tasks were associated with an excessive risk of exposure (Discalzi et al., 2000). Additionally, a positive brain MRI T1 hyperintensity signal in the globus pallidus, indicative of manganese poisoning, was observed during examination in several of the cases (Nelson et al., 1993; Discalzi et al., 2000; Sadek et al., 2003). Furthermore, Kim et al. (1999) described a case of a 48-year-old man who had worked for 10 years as a welder whose brain MRI also showed high signal intensities in the globus pallidus on a T1 weighted image. Interestingly, however, a PET scan indicated that ^{18}F-6-fluorodopa uptake was reduced in the left putamen, findings which appear in idiopathic Parkinson's disease.

Unfortunately, large-scale epidemiological studies addressing the association of welding fume inhalation with the development of neurological disease are currently lacking. A few neurological studies of welders have indicated that welding fume inhalation may possibly increase subclinical neurological effects (Chandra et al., 1981; Wang et al., 1989; Sjogren et al., 1990, 1996; Sinczuk-Walczak et al., 2001; Bowler et al., 2003). However, some of these studies have limitations due to a lack of complete and accurate workplace exposure data, little information on exposures to other neurotoxicants in the workplace, and evaluation of small exposure population groups. In an important study, Racette et al. (2001) compared the clinical features of Parkinson's disease in 15 full-time welders with two control groups with an idiopathic form of the disease. It was observed that the welders had a younger onset (46 years) of Parkinson's disease that was significantly different than the onset (63 years) in the controls. The authors concluded that Parkinson's disease in welders was distinguished only by age at onset, suggesting that welding may be a possible risk factor for the development of early onset Parkinson's disease. The findings of this study pose an important question that needs to be examined further in a greater number of welders.

Recently, Racette et al. (2005) conducted a study to estimate the prevalence of parkinsonism in 1423 welders from Alabama. The investigators concluded that the estimated prevalence of parkinsonism was higher in the sample of male welders tested compared to the general population of male residents from a county in Mississippi. However, several limitations of the study were noted by the investigators. The use of different screening techniques for the welder and control groups were used. Medical reviewers knew that many of the subjects were welders which may potentially lead to reviewer bias and possibly overestimate the prevalence of parkinsonism in the welder group examined. In addition, the question of subject selection bias may be a problem as the welder group consisted of selected individuals who were referred to the study by an attorney involved in litigation.

7. Possible risk factors other than manganese

In addition to manganese exposure, risk factors that can influence the incidence of neurological disease amongst welders include liver impairment, carbon monoxide poisoning, organic solvent exposure, and brain accumulation of iron. It has been observed that a significant number of liver cirrhosis patients exhibited moderate to severe parkinsonism (Burkhard et al., 2003). Therefore, along with standard liver function tests, alcohol consumption should be evaluated when studying neurological effects in welders. Parkinsonism is a possible neurological result of carbon monoxide poisoning (Sohn et al., 2000). It is possible that the poisoning effects of carbon monoxide generated during welding processes have been mistakenly attributed to manganese intoxication. In addition, welders may be exposed to organic solvents through activities that are typically performed in the workplace. Exposure to a number of solvents has been associated with alterations of cognitive and psychomotor function following short-term exposures at or near the TLV (Spiker and Morris, 2001). Also, most welders are continuously exposed to airborne concentrations of iron that are considerably higher than that of manganese. It has been hypothesized that accumulation of iron in the brain may be associated with Parkinson's disease (Jellinger, 1999; Berg et al., 2001; Riederer et al., 2001). Iron levels are increased in the substantia nigra of patients with Parkinson's disease post-mortem (Dexter et al., 1987; Sofic et al., 1988).

8. Conclusions

Manganese is an essential component in most welding alloys and is present in varying concentrations. It is apparent that manganese can reach the body's circulation after inhalation of welding fumes and be transported directly to the central nervous system. It has been observed by using brain MRI that manganese can accumulate in the globus pallidum after exposure to high concentrations of welding fumes (Nelson et al., 1993; Kim et al., 1999; Discalzi et al., 2000; Sadek et al., 2003). It has been hypothesized that manganese-containing welding fumes are a possible neurological hazard. A number of issues regarding the association of welding fume inhalation and neurotoxicity need to be addressed with future studies. It appears that the case reports of manganese intoxication in welders are mostly limited to exposure to very high levels of welding fumes, where welding has taken place in confined spaces or during welding that has used electrodes high in manganese content. In addition, questions exist as to whether the risk of neurotoxicity is dependent on the welding process or industry, where fume concentrations may be potentially higher or more hazardous. Furthermore, it needs to be determined whether or not exposure to long-term, low levels of manganese in welding fumes can lead to neurotoxicity in welders. Lucchini et al. (1999) have shown in ferroalloy workers that cumulative exposure to low levels of manganese oxides may cause neurofunctional changes. However, no large scale, well-controlled epidemiology study that includes complete and accurate workplace exposure data examining this issue in welders currently exists. There are hundreds of thousands of workers who are exposed to welding fume worldwide, but very little is known or has been reported about the association of welding fume inhalation and the potential development of neurotoxicity.

DISCLAIMER

The findings and conclusions of this review are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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