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PULMONARY RESPONSES TO WELDING FUMES: ROLE OF METAL CONSTITUENTS

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It is estimated that more than 1 million workers worldwide perform some type of welding as part of their work duties. Epidemiology studies have shown that a large number of welders experience some type of respiratory illness. Respiratory effects seen in full-time welders have included bronchitis, siderosis, asthma, and a possible increase in the incidence of lung cancer. Pulmonary infections are increased in terms of severity, duration, and frequency among welders. Inhalation exposure to welding fumes may vary due to differences in the materials used and methods employed. The chemical properties of welding fumes can be quite complex. Most welding materials are alloy mixtures of metals characterized by different steels that may contain iron, manganese, chromium, and nickel. Animal studies have indicated that the presence and combination of different metal constituents is an important determinant in the potential pneumotoxic responses associated with welding fumes. Animal models have demonstrated that stainless steel (SS) welding fumes, which contain significant levels of nickel and chromium, induce more lung injury and inflammation, and are retained in the lungs longer than mild steel (MS) welding fumes, which contain mostly iron. In addition, SS fumes generated from welding processes using fluxes to protect the resulting weld contain elevated levels of soluble metals, which may affect respiratory health. Recent animal studies have indicated that the lung injury and inflammation induced by SS welding fumes that contain water-soluble metals are dependent on both the soluble and insoluble fractions of the fume. This article reviews the role that metals play in the pulmonary effects associated with welding fume exposure in workers and laboratory animals.

The Bureau of Labor Statistics has indicated that nearly a half of million workers are employed full-time as welders, cutters, solders, and brazers in the United States (Bureau of Labor Statistics, 1999). It is estimated that there are 800,000 full-time welders worldwide. Even much larger numbers, believed to be between 1 and 2 million workers, perform some welding as part of their work duties. Welders may work in a variety of settings, which include well-ventilated outdoor and indoor settings or poorly ventilated confined spaces,

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such as a hull of a ship or a building crawl space. The inhalation exposure of welders may vary according to the welding materials and processes used.

WELDING PROCESS DESCRIPTION

Electric arc welding joins metals and alloys that have been made soft or liquid by extreme heat as electricity passes from one electrical conductor to another (Howden et al., 1988). Temperatures can reach as high as 12,000 °C in the arc and heat both the base metal piece and a filler metal coming from a consumable electrode that is continuously fed into the weld. Welding operations produce gaseous and aerosol by-products composed of a complex array of metals (often containing iron, manganese, chromium, or nickel), metal oxides, and other chemical species volatilized from the welding electrode or the flux material incorporated within the electrode (Zimmer & Biswas, 2001). In addition, the use of shielding gases or paint and surface coatings on the electrode and base metal may contribute to the composition of the welding aerosol.

Welding fume is considered the vaporized metals that react with air and form particles that are primarily of respirable size. The rate at which fumes are formed is a function of the specific welding process, current level, and composition of the wire/flux used (Villaume et al., 1979). Larger current levels or the presence of fluxes give higher fume rates. The control of welding fumes and gases in the workplace has been by enclosure and local exhaust ventilation; respiratory protective equipment may be necessary in certain instances, such as welding in confined spaces (Hewitt, 2001). In the absence of good ventilation, general contamination of a welding area can occur rapidly.

The American Welding Society has identified over 80 different types of welding and allied processes in commercial use (Villaume et al., 1979). Some of the most common types include shielded manual metal arc welding (MMAW), gas metal arc welding (GMAW), flux-cored arc welding (FCAW), gas tungsten arc welding, submerged arc welding, plasma arc welding, and oxygas welding. Each method has its own metallurgical and operational advantages as well as its own potential safety hazard.

The most common type of welding process used in industry is GMAW (Figure 1A). In this process, shielding gases (usually a combination of argon, helium, oxygen, or carbon dioxide) are continually blown through the welding nozzle and over the arc to protect the formed weld from weakening caused by oxidation. Other common processes are shielded MMAW (Figure 1B) and FCAW (Figure 1C). As opposed to using shielding gases, fluxing compounds are incorporated into the electrode that provide the shielding environment to protect the weld as the electrode is consumed in the process. The fluxing agents used in MMAW and FCAW can contribute to the inhalation exposure of welders, and fumes formed during processes that use fluxes have been observed to be both chemically and physically more complex than fumes formed from GMAW processes (Zimmer & Biswas, 2001).

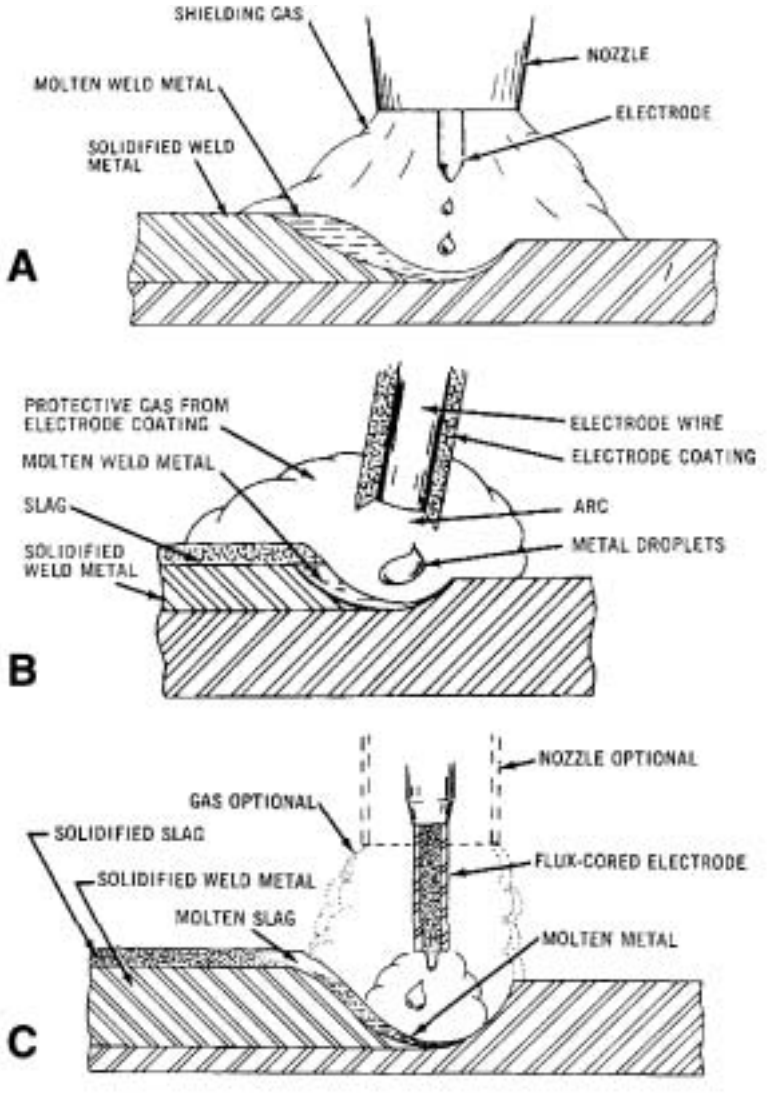

FIGURE 1. (A) Gas metal arc welding. Sometimes referred to as metal inert gas (MIG) welding. The weld is produced by heating with an arc between a continuous filler metal (consumable) electrode and the work. Shielding is obtained entirely from an externally supplied gas mixture. (B) Shielded manual metal arc welding. Sometimes referred to as "stick welding." The weld is produced by heating with an arc between a covered metal electrode and the work. Shielding is obtained from decomposition of the electrode covering. Filler metal is obtained from the electrode. (C) Flux-cored arc welding. The weld is produced by heating with an arc between a continuous filler metal (consumable) electrode and the work. Shielding is obtained from a flux contained within the electrode. Additional shielding may or may not be obtained from an externally supplied gas or gas mixture. Diagrams used by permission courtesy of Hobart Institute of Welding Technology (1977).

EXPOSURE CONCENTRATIONS AND LIMITS

It has been estimated that welding processes can generate fume concentrations in the range of 100–400 mg/m^3 in the rising column of heated air directly above the arc (Ulfarson, 1981). Typical worker breathing zone concentrations have been measured in the range of 1–5 mg/m^3 throughout the industry depending on the welding processes and materials used. The current American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value time-weighted average (TLV-TWA) is 5 mg/m^3 total fume concentration in the breathing zone of the welder or others in the area during welding of iron, mild steel, and aluminum (ACGIH, 2001).

Exposure to welding fumes is unique. There is no other material from any other source that is comparable to the complex composition and structure of welding fumes. Because of the complexity, the National Institute for Occupational Safety and Health (NIOSH) has suggested that is not feasible to establish an exposure limit for total welding emissions, and exposure limits may be needed for each welding fume constituent (NIOSH, 1992). It may be possible that the individual metal constituents (e.g., iron, manganese, chromium, or nickel) that comprise the formed welding fume may interact and produce additional or potentiated toxic effects. Currently, NIOSH has established a recommended exposure limit (REL) for welding fumes (and total particulates) of the lowest feasible concentration. However, additional studies evaluating the potential toxic effects caused by the individual metal constituents of welding fumes and their interaction with each other are greatly needed.

PHYSICAL AND CHEMICAL PROPERTIES OF WELDING FUMES

Physical Properties

Particle size distribution is an important factor in determining the health risk associated with welding fume inhalation. Particle aerodynamic diameter is an indication of how deeply aerosolized particles may penetrate the lungs upon inhalation. Electron microscopic analysis has indicated that individual welding particles are in the submicrometer ultrafine size range (0.01–0.10 μm) when first formed near the arc (Voitkevich, 1995). But due to the turbulent conditions resulting from extreme heat generation at the arc, the welding particles quickly aggregate together in the air to form longer chains of primary particles (Clapp & Owen, 1977). In the atmosphere of the welder's breathing zone, welding particles have been observed to be 0.50–2.0 μm in aerodynamic diameter (Villaume et al., 1979; Voitkevich, 1995), giving them a high probability of being deposited in the lower respiratory tract (respiratory bronchioles and alveoli). Toxicology studies have indicated that submicrometer aerosols may cause adverse pulmonary effects due to their size (Ferin et al., 1992; Oberdorster et al., 1992). The question still remains as to whether the inhaled welding particle aggregates would dissociate into primary ultrafine particles upon interaction with pulmonary cells and lung lining fluid.

Studies have indicated that the type of process and the materials used during welding may have an effect on the morphology and size of the generated welding fume. Zimmer and Biswas (2001) observed that aerosols generated during GMAW had smaller count median diameters compared to particles formed during FCAW. In addition, they observed the morphology of the particles generated from GMAW and FCAW processes to be quite different (Figure 2). The aerosols generated during GMAW were primarily arranged in homogeneous chainlike agglomerates (Figure 2A). Alloys used during GMAW are composed of mostly iron. The formed primary particles have been observed to be predominantly magnetite (γFe_3O_4), with magnetic forces dictating the formation of the linear chainlike aggregates. In contrast, the aerosols generated during FCAW are more complex and contain a mixture of chainlike and spherical structures (Figure 2B). It was suggested that nucleation of primary particles, composed of mostly magnetite, is followed by competing dynamic mechanisms, which involve particle growth by coagulation and condensation of lighter elements that are used as fluxing agents, such as alkali metals (calcium, magnesium, and barium) and fluoride. Indeed, x-ray photoelectron spectroscopic analysis of welding particles generated during processes that utilized fluorine-containing fluxes indicated that the outer most surface of the particle consisted almost entirely (~97%) of complex fluoride compounds (Antonini et al., 1997).

Chemical Properties

Fume As mentioned previously, the chemical properties of welding fumes can be quite complex. The fume refers to the solid metal suspended in air (Howden et al., 1988). Metal oxides are formed when vaporized metal interacts

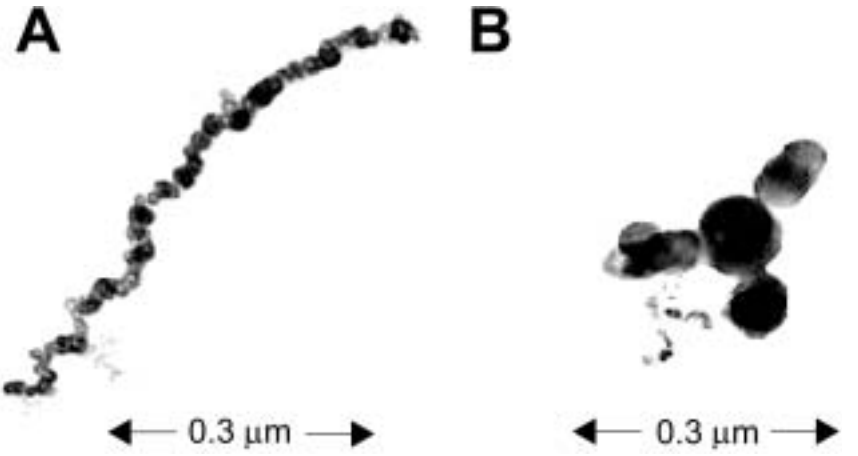

FIGURE 2. Transmission electron microscopic images of representative aerosols from (A) gas metal arc welding and (B) flux-cored arc welding processes from Zimmer and Biswas (2001).

with the oxygen in the air. The primary components of welding fumes are oxides of metals used in the manufacture of the electrode consumed during the welding process. Most welding fumes are generated using mild steel (MS) or carbon steel materials and usually contain iron (80–95%) and manganese (1–15%). Stainless steel (SS) electrodes also are commonly used in the welding industry and contain chromium (15–30%) and nickel (5–10%) in addition to iron and manganese. Depending on the process and materials used, other elements can be found in welding fumes, which may include zinc, aluminum, cadmium, copper, lead, fluorides, silica, barium, magnesium, calcium, and tin. See Table 1 for a description of elements found in welding fumes.

The toxicity of the individual metals present in welding fumes may depend on the oxidation state. Chromium has been shown to exist in various oxidation states in SS welding fumes (Sreekanthan, 1997). Both trivalent (Cr^{3+}) and hexavalent (Cr^{6+}) chromium have been measured in significant quantities in welding fumes. Analysis of welding fume demonstrated that Cr^{6+} exists as K_2CrO_4 (Minni et al., 1984), and its concentration is a function of the shielding gas used (Sreekanthan, 1997). Cr^{3+} has been considered to be of a low order toxicity because it does not enter cells, whereas Cr^{6+} has been found to be quite toxic and is currently classified as a human carcinogen (Cohen et al., 1993). In vitro studies have indicated that welding fumes containing Cr^{6+} have mutagenic activity (Maxild et al., 1978; Stern, 1977).

Using x-ray photoelectron spectroscopy and x-ray diffraction, it has been observed that Mn^{2+} and Mn^{3+} are the most probable oxidation states of manganese in welding fume generated from both GMAW and MMAW processes, existing as MnO and Mn_2O_3, respectively (Minni et al., 1984; Voitkevich, 1995). In addition, x-ray photoelectron spectroscopy has indicated that nickel is present in mixed forms of Ni^{2+} (NiO) and Ni^{3+} (Ni_2O_3). Because nickel and manganese are transition metals and exist in various valence states, they have the capacity to promote redox reactions and affect health by forming cytotoxic free radicals.

TABLE 1. Elemental Constituents Commonly Found in Welding Fumes

Elements	Uses, potential health hazard
Iron	Predominant component in most welding fumes, mostly inert, siderosis
Chromium, nickel	Stainless steel alloys, lung carcinogens
Manganese	Steel alloy, potential neurotoxin
Crystalline silica, silicates	Fluxing agents, noncytotoxic amorphous form
Zinc	Galvanized steel, metal fume fever
Fluorides, Barium	Fluxing agents, lung irritants
Aluminum	Alloy and filler metal, conducive to ozone generation
Copper, Cadmium	Alloys and coating materials, lung irritant, metal fume fever
Lead	Brass, bronze, and steel alloy, potential neurotoxin
Tin	Bronze and solder alloy, metal fume fever

Gases During the welding process, different gases are formed that may be harmful to the respiratory tract. In GMAW, shielding gases are used to protect the weld from oxygen and nitrogen in the air by flowing an inert gas mixture (e.g., argon, helium, or carbon dioxide) directly over the weld. The shielding gas can intensify ultraviolet radiation produced in the arc leading to the photochemical formation of potentially toxic gases, such as nitrogen oxides and ozone. Carbon dioxide present in the shielding gas may be reduced and converted to the more stable, but highly toxic, carbon monoxide. In addition, gases also may be produced from the decomposition of cleaning and degreasing agents present on the metal to be welded. For example, chlorinated hydrocarbons, such as trichloroethylene, are used to clean the metal pieces prior to welding (Howden et al., 1988). Trichloroethylene has a high vapor pressure; thus, its airborne vapors are prone to oxidation due to ultraviolet radiation from the welding arc, leading to the formation of the pulmonary irritant phosgene.

PULMONARY EFFECTS

Epidemiology

The health effects of welding fume exposure have been extensively studied. Numerous worker studies have been performed that have evaluated the pulmonary effects caused by welding fume inhalation exposure (as reviewed by Antonini et al., 2003; Martin et al., 1997; Sferlazza & Beckett, 1991). However, less information is available concerning the nonpulmonary effects (e.g., neurological, dermal, and reproductive) caused by welding fume exposure (Antonini, 2003). Worker studies are difficult to compare. Welders are not a homogeneous worker population. Accurate welding fume exposure assessment of workers is often difficult. Some studies have been conducted in controlled work environments, others during actual workplace conditions, and some in laboratories. Moreover, the severity of exposure to welding fumes may vary due to differences in welding processes and materials, duration of exposure, industrial setting, ventilation of the exposure area, and the technique and skill of the welder (Stern, 1981).

In surveys of full-time welders, a significant increase in the prevalence of bronchitis is the most frequent chronic complaint associated with respiratory health (Sferlazza & Beckett, 1991). However, a definitive association between welding and occupational asthma has yet to be determined. Some investigators have indicated that the inhalation of welding fumes may possibly induce asthma (Beach et al., 1996; Simonsson et al., 1995; Wang et al., 1994). In terms of lung function changes, Sferlazza and Beckett (1991) indicated that most worker studies suggest that there are little to no measurable effects of welding fume exposure on lung function measurements. When observed, the lung function changes are likely transient and return to normal during nonexposed periods (Akbar-Khanzadeh, 1993; Sobaszek et al., 2000). It has been demonstrated that workers who are exposed to high fume concentrations because of

work in confined, poorly ventilated areas, such as shipyard welders, had greater decrements in lung function than welders who worked in well-ventilated areas (Akbar-Khanzadeh, 1980; Mur et al., 1985; Oxhoj et al., 1979).

The most frequent acute respiratory complaint of welders is metal fume fever. The condition is a self-limited, flulike illness characterized by an acute onset of 4–8 h with symptoms that may include thirst, dry cough, chills, fever, dyspnea, malaise, headache, and nausea. The illness is most often caused by the inhalation of welding fumes that contain zinc oxide generated during the joining of galvanized zinc-coated steel and can last for 24–48 h. The development of a short-term tolerance to metal fume fever has been observed in welders in that they are asymptomatic during repeated exposures, but develop fume fever upon initial exposure after weekend breaks and work vacations (Martin et al., 1997). Other metals that may be present in welding fumes, such as cadmium, copper, and tin, also can induce metal fume fever in exposed workers.

It has been reported that acute upper and lower respiratory-tract infections are increased in terms of frequency, severity, and duration among welders as compared to the general population (Howden et al., 1988). There is some evidence to indicate that welding fume exposure may cause changes in immune responses of welders (Boshnakova et al., 1989; Tuschl et al., 1997). Wergeland and Iverson (2001) warned of a serious possible health risk involving an association of pneumonia with the inhalation of metal fumes that are formed during welding, cutting, or grinding. It has been observed that the excesses in mortality observed in welders were due to pneumonia (Doig & Challen, 1964). Interestingly, retired welders did not demonstrate an increase in pneumonia-related deaths, thus ruling out nonoccupational confounding factors (Coggon et al., 1994).

The lungs of full-time welders may display multiple deposits of accumulated iron oxide without the presence of interstitial fibrosis. The deposited iron oxide particles have been observed in alveolar macrophages in the absence of alveolar septa thickening and alveolitis (Morgan, 1989). This condition is referred to as siderosis, a benign form of pneumoconiosis. It has been observed that a significant number of welders develop siderosis (Attfield & Ross, 1978). Pulmonary function in welders with siderosis has been reported within normal limits (Kleinfeld et al., 1969). However, excessively high fume exposure levels and improper ventilation in the welder's working area may lead to a chronic debilitating lung disease, such as interstitial pulmonary fibrosis (Buerke et al., 2002; Rosler & Woitowitz, 1996).

The association between welding fume inhalation and lung cancer development has been extensively studied over the past 25 years. After review of 23 worker studies evaluating the incidence of cancer in welders, the International Agency for Research on Cancer (IARC) concluded that welding fumes were "possibly carcinogenic" to humans (IARC, 1990). However, this finding was based on limited evidence in humans, and to date, the results of epidemiology studies have been inconclusive. Some studies have observed a significant elevated risk for lung cancer among welders (Becker, 1999; Danielson et al.,

1993; Moulin et al., 1993; Moulin, 1997), whereas others have not (Danielson et al., 2000; Hansen et al., 1996; Steenland et al., 1991).

The interpretation of an increase in lung cancer risk in welders can be difficult because of uncertain exposure assessment of workers in different settings, using different processes and materials, as well as inadequate information on exposure to other potential lung carcinogens, such as tobacco smoke, silica, and asbestos (Hansen et al., 1996). It has been suggested that welding using MS materials, which accounts for 80–90% of all welding in industry, poses little risk for the development of lung cancer (Stern, 1983). Some investigators have hypothesized that the risk of lung cancer is confined to SS welding, in which chromium and nickel (both human carcinogens) have been measured in significant quantities in welding fumes (Sjogren et al., 1987, 1994).

Animal Studies

Limited information exists regarding the causality and possible underlying mechanisms associated with pulmonary disease after inhalation of welding fumes. Lung toxicology studies of welding fumes in animals are lacking in number. The use of animal models and the ability to control the welding fume exposure in toxicology studies could be used to develop a better understanding of the fume effect on pulmonary health, and the possible underlying mechanisms that may be involved. Thus, the objectives of ongoing studies have been: (1) to use a rat model to assess the potential of welding fume to induce lung injury and inflammation; (2) to compare welding fumes of different metal compositions that had been generated using various processes and materials; and (3) to examine the possible mechanisms by which different welding fumes may injure the lungs.

For these studies, different welding fumes that are commonly used in industry were collected onto filters by the American Welding Society. The chemical composition and particle size of the collected fumes were determined. The welding particles were suspended in sterile saline and intratracheally instilled into the lungs of male Sprague-Dawley rats at doses of 0.2, 1.0, and 5.0 mg/100 g body weight. Bronchoalveolar lavage (BAL) fluid was recovered from the treated animals and analyzed for various indicators of injury and inflammation at 1, 3, 7, 14, and 35 d after instillation. The pulmonary responses to the welding fumes were compared to the responses to crystalline silica, a highly pneumotoxic, fibrogenic particle (Antonini et al., 1994), and iron oxide, a relatively inert particle (Beck et al., 1982), which served as positive and negative particle controls, respectively.

Three welding fumes with vastly different metal profiles were collected for study. The fume samples were generated in three different ways: (1) gas metal arc welding using a mild steel electrode (GMAW-MS); (2) gas metal arc welding using a stainless steel electrode (GMAW-SS) with argon and CO_2 shielding gases; and (3) manual metal arc welding using a flux-covered stainless steel electrode (MMAW-SS). The welding fume samples were suspended in saline and the relative amounts of different metals were measured by inductively

coupled argon plasma atomic emission spectroscopy as weight percent (NIOSH, 1994). The size of three collected fumes were comparable and within the respirable range (Table 2). The elemental composition of the three fumes was found to be quite different. The GMAW-MS sample was comprised almost entirely of iron (85%) and manganese (14%). The two SS samples (MMAW-SS and GMAW-SS) were composed of similar manganese levels but much less iron as compared to the GMAW-MS fume. Chromium and nickel were also present in the two SS samples, but they were absent in the GMAW-MS sample.

The samples were further divided into soluble and insoluble components. The particle suspensions were incubated for 24 h at 37 °C, and the samples were centrifuged at $12{,}000 \times g$ for 30 min. The supernatants of the samples (soluble fraction) were recovered and filtered with 0.22-μm filters. The pellets (insoluble fraction) were resuspended in saline. The GMAW-SS and GMAW-MS samples were relatively insoluble with soluble-to-insoluble ratios of 0.006 and 0.020, respectively (Table 2). The flux-covered MMAW-SS sample was much more soluble than the other two samples with a soluble-to-insoluble ratio of 0.345. The majority of the soluble fraction of the MMAW-SS fume was comprised of mostly chromium with some manganese.

The pulmonary responses of the three welding fumes are summarized in Table 3 (as referenced from Antonini et al., 1996, 1997). Intratracheal instillation of the GMAW-MS fume caused no toxic response, other than an initial mild inflammation, which quickly subsided by 3 d after treatment. The response was similar to what was observed for treatment with the iron oxide control. This result was not surprising because the GMAW-MS fume was 85% iron oxide. Using magnetometry, it was determined that the GMAW-MS fume had an elimination half-time of 18 d, which was comparable to the iron oxide control. However, when assessing the pulmonary effects of the two SS fumes (MMAW-SS

TABLE 2. Welding Fume Characterization

Sample	Size: count mean diameter	Metal composition (weight %)[a]	Soluble/insoluble ratio
GMAW-MS: gas metal arc—mild steel	1.22 μm	85% Fe 14% Mn	0.020
GMAW-SS: gas metal arc—stainless steel	1.38 μm	53% Fe 23% Mn 19% Cr 5% Ni	0.006
MMAW-SS: manual metal arc—stainless steel	0.92 μm	41% Fe 28% Cr 17% Mn 3% Ni	0.345 (87% Cr, 11% Mn)

Note. Data are referenced from Antonini et al. (1999).
[a] Relative to all metals analyzed.

TABLE 3. Lung Toxicology Summary of Animal Studies

Groups	Lung injury[a]	Lung PMNs	Lung cytokines	Oxidant production	Lung persistence
Saline, vehicle control	+/–	+/–	+/–	+/–	+/–
GMAW-MS	+/–	+/–	+/–	+/–	+
GMAW-SS	++	++	+	+	++
MMAW-SS	+++	+++	++	++	n. d.[b]
Silica, positive control	+++++	+++++	+++++	++++	++++
Iron oxide, negative control	+/–	+/–	+/–	+/–	+

Note. Data is referenced and modified from Antonini et al. (1996, 1997).

[a] Rating scale: little to no effect, +/–; slight effect, + or + +; significant effect, + + +; highly significant effect, ++++ or +++++.

[b] n. d., Not determined.

and GMAW-SS), lung injury, neutrophil (PMN) number, inflammatory cytokine (tumor necrosis factor-α and interleukin-1β) secretion, and macrophage oxidant production were all significantly elevated compared to the response of the GMAW-MS fume. The GMAW-SS also persisted in the lungs longer than the GMAW-MS fume. An elimination half-time of 47 d was observed for the GMAW-SS fume. In comparison with the highly toxic particle crystalline silica, the lung injury and inflammation observed after treatment with MMAW-SS and GMAW-SS were much less.

From these initial toxicology studies, it was concluded that the GMAW-MS fume was relatively nontoxic, and the potential for serious chronic lung damage is low if recommended workplace exposure limits are observed. This is an important observation because the majority (80–90%) of welders in industry are exposed to GMAW-MS fumes. However, SS welding fumes are more toxic and persist in the lungs longer than MS fumes. The elevated toxic lung response may be due to enhanced macrophage production of highly reactive oxygen radicals and inflammatory cytokines. In addition, the toxicity may be associated with the presence of chromium and nickel in the SS fumes, which are absent in MS fumes. It also was observed that the more water-soluble SS fume generated from MMAW processes (where fluxes were used) was more toxic than GMAW-SS fumes. Was this result then due to the presence of water-soluble metals associated with the MMAW-SS fume?

In the next series of experiments, the soluble MMAW-SS fume was divided into its soluble (SS-sol) and insoluble (SS-insol) fractions as described previously for the chemical characterization analysis. The soluble fraction was comprised of 87% chromium and 11% manganese (Table 2). Male Sprague-Dawley rats were intratracheally instilled with the total MMAW-SS sample (SS-tot) at 2 mg/rat, or the equivalent volume of the MMAW-SS fractions (SS-sol and SS-insol). Lung injury and inflammation were assessed by analysis of the BAL fluid. Treatment with SS-tot caused significant increases in lung injury (by measuring BAL

fluid lactate dehydrogenase activity and albumin) compared with control and the SS-sol and SS-insol fractions 3 d after instillation (Figure 3). The lung injury associated with the SS-sol and SS-insol fractions was equal and when compared to the SS-tot appeared to be additive when the response of the soluble and insoluble fractions were combined (Figure 3, A and B).

A different pattern in the response was observed when evaluating lung inflammation (Figure 4). BAL fluid PMN number was significantly elevated 3 d after treatment with SS-insol compared with SS-sol, indicating the recruitment of PMNs into the lungs associated with exposure to MMAW-SS fumes was primarily due to the insoluble particulate fraction and not to water-soluble metals (Figure 4A). However, in the assessment of BAL fluid eosinophil number at 3 d, the opposite to the PMN response was true (Figure 4B). Treatment with SS-sol caused a significantly greater lung eosinophilia than SS-insol, suggesting that the water-soluble metals (most likely chromium) are responsible for eosinophil influx into the lungs after instillation of MMAW-SS fumes.

From these recent animal studies, it appears that both the soluble and insoluble fractions of the MMAW-SS fume are required to produce the observed lung responses. Lung injury and inflammation are not dependent exclusively on water-soluble metals. This is unique in that studies of other environmental and occupational metal-containing particulates, such as residual oil fly ash and urban air particulates, have attributed many of their pneumotoxic effects to the presence of soluble metals (Dreher et al., 1997; Kodavanti et al., 1998; Lewis et al., 2003).

CONCLUSIONS

Inhalation exposure to welding fumes is unique. Welding fumes are a complex mixture of metals and metal oxides. Epidemiology indicates that large numbers of welders may be at increased risk for respiratory disease. Unfortunately, many questions remain unanswered concerning the effects of welding fume exposure on respiratory health. Animal models have been used in toxicology studies to control the welding exposure and to elucidate the mechanisms by which the formed fumes may injure the lungs. Results from animal studies have indicated that welding fumes of differing metal composition produce vastly different lung toxicity. SS welding fumes pose a greater risk to the respiratory health of welders as compared to MS fumes. This may be due to the presence of potentially toxic metals (e.g., chromium and nickel) present in the SS fume. Lung responses of animals to soluble welding fumes generated from SS flux-coated electrodes appeared to be dependent on both the soluble and insoluble metals present. However, more studies are needed to further evaluate the role by which different individual metals commonly found in welding fumes affect pulmonary health.

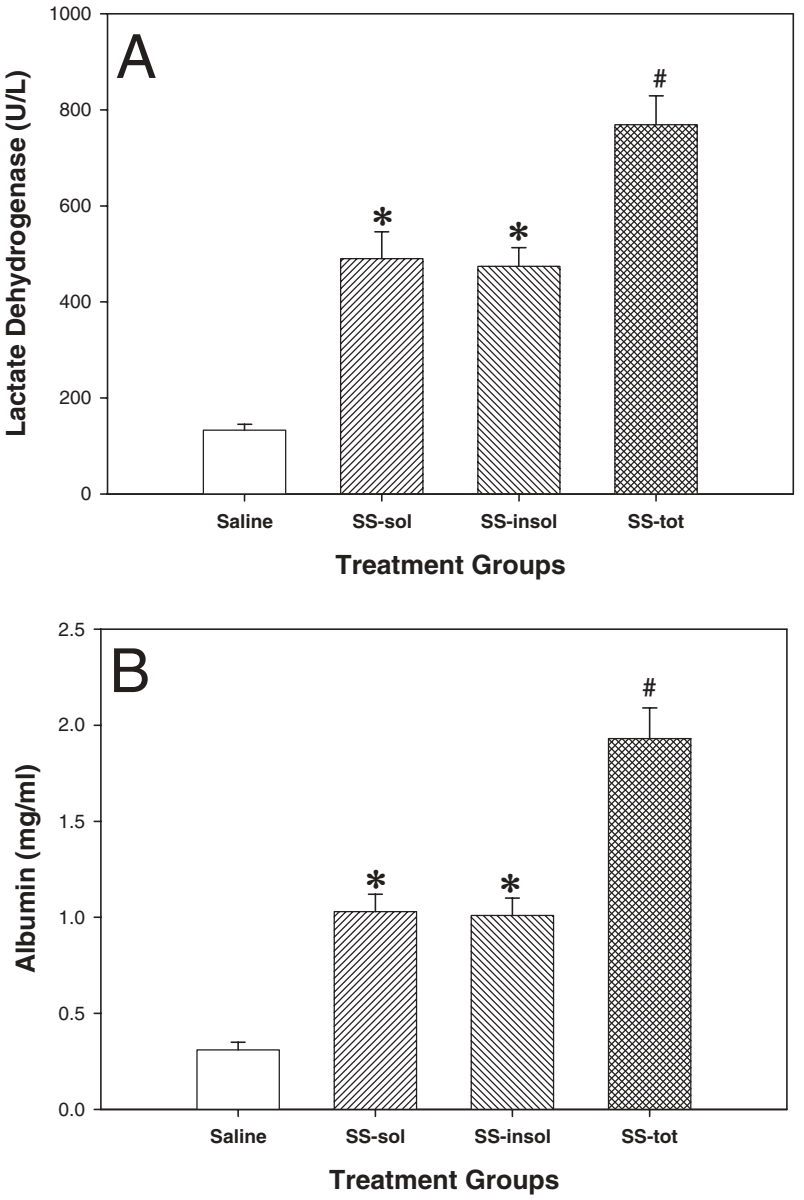

FIGURE 3. (A) Lactate dehydrogenase activity and (B) albumin content in the acellular bronchoalveolar lavage fluid recovered from rats 3 d after intratracheal treatment with the soluble (SS-sol), insoluble (SS-insol), and total (SS-tot) sample of MMAW-SS welding fumes. Comparisons were made between groups for each parameter using analysis of variance (ANOVA) followed by Tukey's post hoc test. Values are means ±standard error (n = 5–11 per group); asterisk indicates significantly greater than saline; #, significantly greater than SS-sol and SS-insol, $p < .05$.

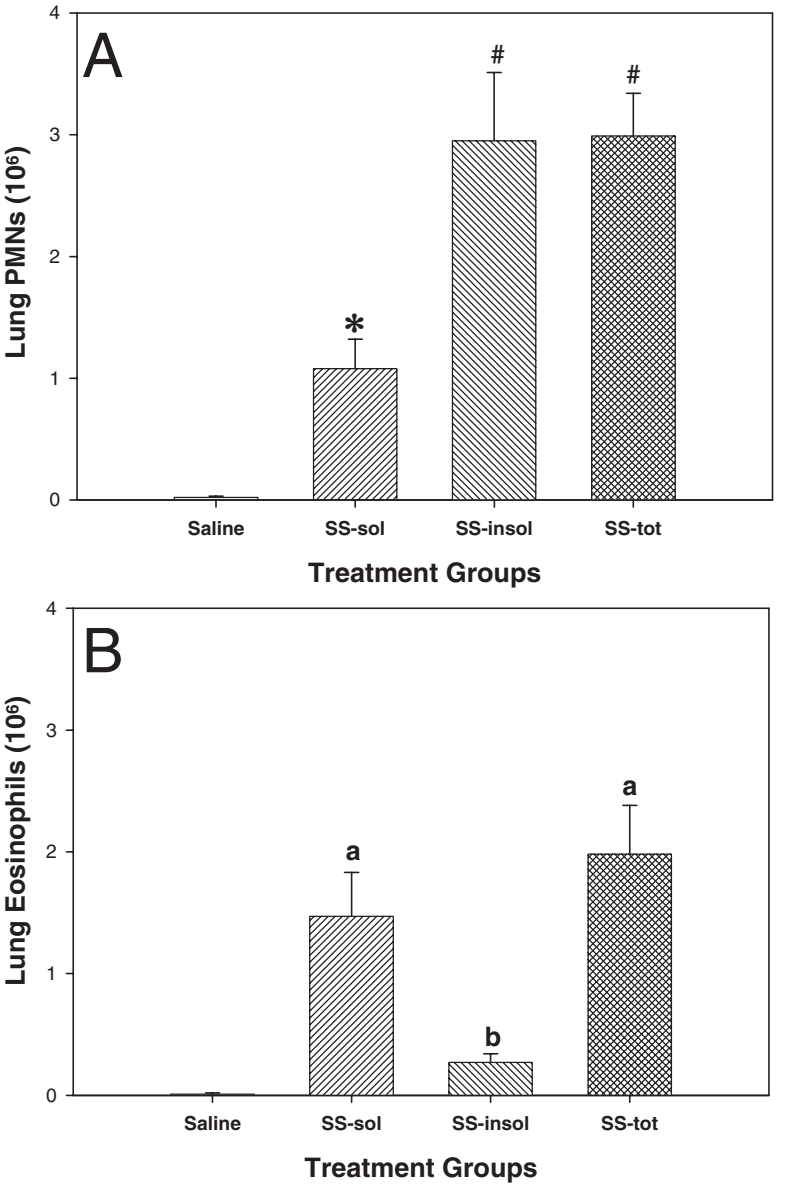

FIGURE 4. (A) Lung neutrophils (PMNs) and (B) eosinophils recovered in the bronchoalveolar lavage fluid from rats 3 d after intratracheal treatment with the soluble (SS-sol), insoluble (SS-insol), and total (SS-tot) sample of MMAW-SS welding fumes. Comparisons were made between groups for each parameter using ANOVA followed by Tukey's post hoc test. Values are means ± standard error (n = 5–11 per group); groups with different symbols are statistically different from each other, $p < .05$.

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