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Alterations in welding process voltage affect the generation of ultrafine particles, fume composition, and pulmonary toxicity

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Abstract

The goal was to determine if increasing welding voltage changes the physico-chemical properties of the fume and influences lung responses. Rats inhaled 40 mg/m^3 (3 h/day × 3 days) of stainless steel (SS) welding fume generated at a standard voltage setting of 25 V (regular SS) or at a higher voltage (high voltage SS) of 30 V. Particle morphology, size and composition were characterized. Bronchoalveolar lavage was performed at different times after exposures to assess lung injury. Fumes collected from either of the welding conditions appeared as chain-like agglomerates of nanometer-sized primary particles. High voltage SS welding produced a greater number of ultrafine-sized particles. Fume generated by high voltage SS welding was higher in manganese. Pulmonary toxicity was more substantial and persisted longer after exposure to the regular SS fume. In summary, a modest raise in welding voltage affected fume size and elemental composition and altered the temporal lung toxicity profile.

Keywords: *Welding fume, inhalation, lung burden, nanoparticles, pulmonary toxicity*

Introduction

According to the *Occupational Outlook Handbook* 2006–2007, published by the U.S. Department of Labor, Bureau of Labor statistics, an estimated 430,000 workers are employed full-time in welding operations in the U.S., and this is projected to increase by 5% over the next 5–7 years (Bureau of Labor Statistics 2007). Globally, this figure exceeds over two million workers. Arc welding processes generate complex aerosols that are composed of potentially hazardous metals, such as manganese (Mn), hexavalent chromium (Cr), and nickel (Ni). Mn is a known neurotoxicant. Neurobehavioral changes have been reported in exposed welders (Bowler et al. 2007a, 2007b), and case reports have shown Mn to accumulate in dopaminergic brain regions of welders that have been exposed to high concentrations of welding fume (Sadek et al. 2003; Josephs et al. 2005). Reviews of epidemiology studies ave indicated that many welders have experienced some form of occupational respiratory illness (Sferlazza and Beckett 1991; Antonini 2003). Upper and lower respiratory tract infections are increased in terms of incidence, severity, and duration in welders compared to the general population. In addition, welding fume has been classified as 'possibly carcinogenic' by the International Agency for Research on Cancer (IARC 1990) because of the presence of known human carcinogens, hexavalent Cr and Ni, in stainless steel (SS) fume. Multiple epidemiology studies have reported an elevated risk for the development of lung cancer among welders (Hansen et al. 1996; Moulin 1997; Becker 1999).

Due to the health risks associated with welding processes, there is a critical need to reduce emission of welding fume and worker exposure. Welding produces gaseous and aerosol by-products composed of a complex mixture of metal oxides volatilized from the welding electrode (Zimmer and Biswas 2001). The formed welding fume is the vaporized metal that has reacted with air to form particles that

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are respirable in size. Most of the materials in the welding fume come from the electrode, which is consumed during the welding process. A number of additional factors, such as shielding gas composition, voltage, electrode and metal plate coatings, and electrode type, may affect the properties of the formed welding fume. The health effects of welders can be difficult to study due to variations in workplace setting and exposure to diverse aerosols generated from different processes. Because many welding operations are done in confined spaces or awkward positions, local exhaust ventilation may be difficult to utilize or ineffective. The best control approach may be to minimize fume generation at the source. More research is required to help identify and develop methods by which current welding practices may be modified to significantly reduce worker exposure to welding fume while sustaining workplace productivity with minimal or no added costs. Because modulation of welding process conditions can change the properties of the welding aerosol, a complete assessment of the physical and chemical properties of the generated aerosol is needed along with a toxicological analysis to determine if the potential changes in the aerosol characteristics induce adverse health effects.

A welding exposure laboratory has been established in the Health Effects Laboratory Division of the National Institute for Occupational Safety and Health (NIOSH). The laboratory is capable of generating and characterizing aerosols from welding processes most commonly used in industry (Antonini et al. 2006; Keane et al. 2009) and conducting small animal inhalation exposure studies to evaluate potentially adverse pulmonary effects (Antonini et al. 2007, 2009a) and neurotoxic effects (Antonini et al. 2009b; Sriram et al. 2010). Characterization of the generated welding aerosol in the NIOSH welding laboratory has indicated that particle morphology, size, and chemical composition are comparable to welding fume generated using similar processes in the workplace (Antonini et al. 2006). It was the goal of the current study to determine if welding at different voltages alters the physical and chemical properties of generated SS fume and results in a different lung toxicity profile in a rat model after inhalation exposure.

Materials and methods

Experimental design

Rats were exposed by inhalation for 3 h/day for three days to 40 mg/m^3 of gas metal arc-stainless steel (SS) welding fume at either 25 V (regular SS) or 30 V (high voltage SS). Control animals were similarly exposed to filtered air. Welding fume was collected in the breathing zone of the exposed animals, and particle morphology, size, and composition were determined. At 1 h (day 0), 7, 21, and 42 days after the last exposure, bronchoalveolar lavage (BAL) was performed on the right lungs to assess lung injury, whereas non-lavaged left lungs were acid-digested, and the amounts of total and specific metals present in the lungs were determined to assess lung deposition and clearance of inhaled particles.

Welding fume generation system

The welding fume generation system (Figure 1) consisted of a welding power source (Power Wave 455, Lincoln Electric, Cleveland, OH, USA), an automated, programmable six-axis robotic arm (Model 100 Bi, Lincoln Electric), a water-cooled arc welding torch (WC 650 amp, Lincoln Electric), a wire feeder that supplied the wire to the torch at a programmed rate up to 300 inches/min, and an automatic welding torch cleaner that kept the welding nozzle free of debris and spatter (as previously described in Antonini et al. 2006). Gas metal arc welding was performed using a SS electrode (Blue Max E308LSi wire, Lincoln Electric, Cleveland, OH, USA). Welding took place on A36 carbon steel plates for daily exposures of 3 h at either a standard voltage setting of 25 V (regular SS) or at a higher voltage of 30 V (high voltage SS). During welding, a shielding gas combination of 95% Ar and 5% CO_2 was continually delivered to the welding nozzle at an air flow rate of 20 L/min.

Exposure chamber fume determinations

A flexible trunk was positioned approximately 18 inches from the arc to collect the generated fume and transport it to the exposure chamber. The generated welding fume was mixed with dry HEPA-filtered air. Continuous records of chamber fume concentration, temperature, and humidity were maintained during welding fume generation. The mass concentration in the chamber was monitored by a real time aerosol monitor (DataRAM, Thermo Electron Co., DR-4000, Franklin, MA, USA). To maintain the desired concentration of 40 mg/m^3, the diluent air in this system was normally controlled between 20 and 80 L/min. Fume was collected onto 37-mm Teflon filters at a rate of 1 L/min, and the particle mass delivered to the exposure chamber was determined gravimetrically every 30 min in duplicate during the daily 3-h exposure. Rats were exposed to a target concentration of 40 mg/m^3 for 3 h/day. Actual fume concentration was measured to be

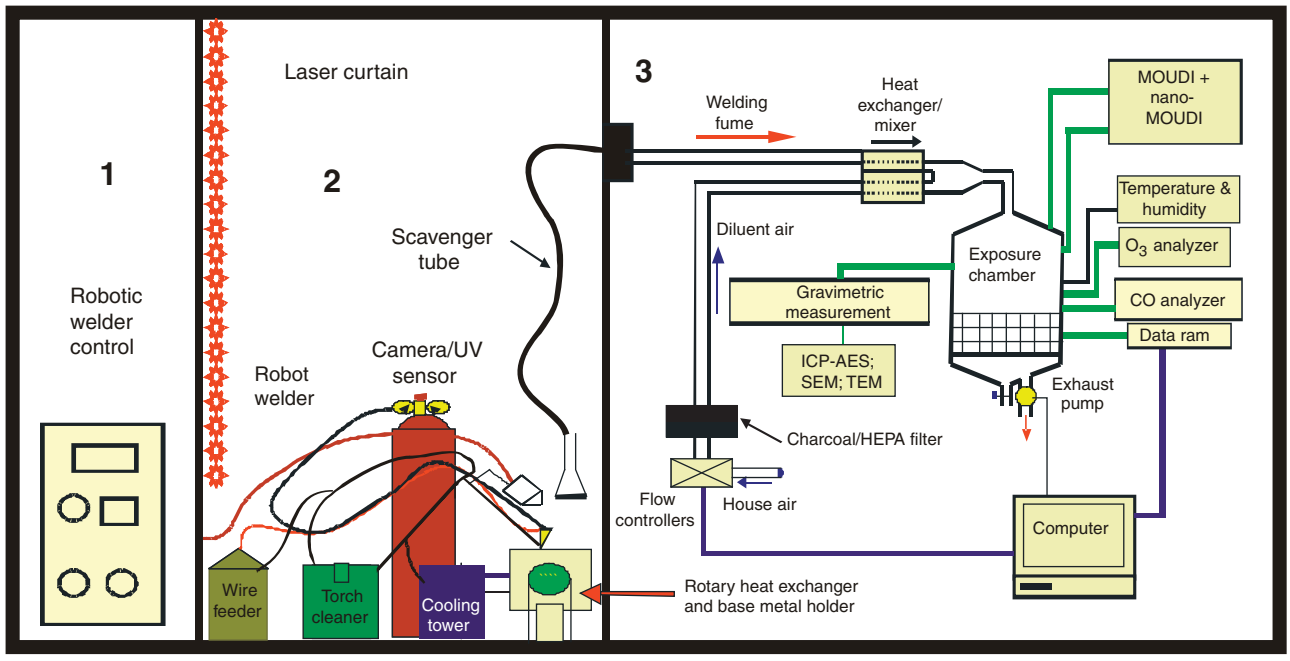

Figure 1. Diagram of the NIOSH welding fume generation system including: [1] enclosed control room that contains the welding power source and controller; [2] robotic welding fume generator that contains the six-axis robotic arm, wire feeder, torch cleaner, coolers, and base metal holder; [3] animal exposure chamber with fume and gas characterization devices. Abbreviations: ICP-AES, inductively coupled plasma-atomic emission spectroscopy; SEM, scanning electron microscopy; TEM, transmission electron microscopy; Ram, real-time aerosol monitor; MOUDI, Micro-Orifice Uniform Deposit Impactor. This is a modification of a figure that was previously published in Antonini et al. (2006).

47.90 mg/m^3 ± 1.51 (standard error) for regular SS and 48.27 mg/m^3 ± 1.33 (standard error) for high voltage SS welding for the three-day exposure period, respectively. In addition, particle samples were gravimetrically collected onto grids inside the animal exposure chamber for electron microscopy to assess particle size distribution, particle morphology, and elemental composition. Gas samples were collected from the exposure chamber through Teflon tubing with a protective particulate filter in the line during the period of welding, and ozone (ozone analyzer model #450, Advanced Pollution Instrumentation, Inc., San Diego, CA, USA) and carbon monoxide (1312 Photo-acoustic Multi-Gas Monitor, Innova Air Tech Instruments, Ballerup, Denmark) were measured. Measured ozone and carbon monoxide levels were not significantly higher than background levels (data not shown).

Welding particle size distribution

Particle size distribution was determined in the exposure chamber in the breathing zone of the rats by using a Micro-Orifice Uniform Deposit Impactor (MOUDI, MSP Model 110, MSP Corporation, Shoreview, MN, USA) that is intended for general purpose aerosol sampling, and a Nano-MOUDI (MSP Model 115) that is specifically designed for sampling aerosols in the size range down to 0.010 µm. Using the two MOUDI impactors in series or in tandem, particles were collected in the size range from 0.010–18 µm that were separated into 15 fractions. Mass median aerodynamic diameter (MMAD) and geometric standard deviation (GSD) were determined.

Welding particle composition

Welding particles were collected onto 5 µm polyvinyl chloride membrane filters in 37-mm cassettes during 30–45 min of welding. The particle samples were digested and the metals analyzed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES) by Bureau Veritas North America, Inc., Novi, MI, USA, according to NIOSH method 7300 modified for microwave digestion (NIOSH 1994). The following metals were quantified: Fe, Mn, Cr, Ni, Cu, Al, Ti, and V. Metal content of blank filters also were analyzed for control purposes.

Animals

Male Sprague-Dawley [Hla:(SD) CVF] rats from Hilltop Lab Animals (Scottdale, PA, USA), weighing 250–300 g and free of viral pathogens, parasites,

mycoplasmas, *Helicobacter*, and CAR Bacillus, were used for all exposures. The rats were acclimated for at least six days after arrival and were housed in ventilated polycarbonate cages on Alpha-Dri cellulose chips and hardwood Beta-chips as bedding, and provided HEPA-filtered air, irradiated Teklad 2918 diet, and tap water *ad libitum* when not being exposed. During the daily 3-h exposures to SS welding fume or air in the inhalation chamber, food and water were withheld from the animals. Body weight was monitored before and after each exposure. No significant changes were observed in animal body weight from any treatment group during the exposure regimen used in the study (data not shown). Temperature and humidity were measured in the animal exposure chamber were around 21°C and 38%, respectively, and remained constant in the chamber during the exposure period.

During exposure to welding fume, no animal showed any outward signs or symptoms of labored breathing or respiratory distress. The NIOSH animal facility is specific pathogen-free, environmentally controlled, and accredited by the Association for Assessment and Accreditation of Laboratory Animal Care International. All animal procedures used during the study have been reviewed and approved by the institution's Animal Care and Use Committee.

Bronchoalveolar lavage

At different time points after exposure, control and SS welding fume-exposed rats were deeply anesthetized with an intraperitoneal injection of Sleepaway (>100 mg/kg body weight of sodium pentobarbital, Fort Dodge Animal Health, Fort Dodge, IA, USA) and then exsanguinated by severing the abdominal aorta. The left lungs were tied off and collected for metal analysis. The right lungs were lavaged with 1 mL/100 g body weight aliquot of calcium- and magnesium-free phosphate buffered saline (PBS, pH 7.4). The first fraction of recovered bronchoalveolar lavage fluid (BALF) was centrifuged at 500 *g* for 10 min, and the resultant cell-free supernatant was analyzed for various biochemical parameters and cytokine levels. The right lungs were further lavaged with 6 mL aliquots of PBS until 30 mL were collected. These samples also were centrifuged for 10 min at 500 *g* and the cell-free BALF discarded. The cell pellets from all washes for each rat were combined, washed, and resuspended in 1 mL of PBS. Cells were differentiated using a Cytospin 3 centrifuge (Shandon Life Sciences International, Cheshire, UK). Cell suspensions (5×10^4 cells) were spun for 5 min at 800 rpm and pelleted onto a slide. Cells were identified after labeling with Leukostat stain (Fisher Scientific, Pittsburgh, PA, USA) as alveolar macrophages (AMs) and neutrophils (PMNs).

Biochemical parameters of injury

Using the acellular first fraction of BALF from the right lungs, albumin content, an index of increased permeability of the bronchoalveolar-capillary barrier, and lactate dehydrogenase (LDH) activity, an indicator of general cytotoxicity, were measured. Albumin content was determined colorimetrically at 628 nm based on albumin binding to bromcresol green using an albumin BCG diagnostic kit (Sigma Chemical Co., St. Louis, MO, USA). LDH activity was determined by measuring the oxidation of lactate to pyruvate coupled with the formation of NADH at 340 nm. Measurements were performed with a COBAS MIRA auto-analyzer (Roche Diagnostic Systems, Montclair, NJ, USA).

Pulmonary deposition and clearance of particles

To assess the clearance of deposited welding particles from the lungs, the metal content present in the lungs on days 0 and 42 after a three-day exposure to SS welding fumes was determined. The amount of Fe, Cr, Mn, and Ni deposited in the lung at each time point was determined by ICP-AES according to NIOSH method 7300 (NIOSH 1994). Briefly, non-lavaged left lungs from each animal were excised, weighed and lyophilized. The lung tissue samples were transferred to beakers for digestion. The sample containers were rinsed with concentrated nitric acid and three washings of deionized water and transferred to the respective digestion beakers. The samples were treated with 25 mL of concentrated nitric acid and 2 mL of concentrated perchloric acid, covered, and refluxed at 150°C until complete dissolution. The sample residues were dissolved in a dilute solution of 4% nitric acid/1% perchloric acid and then analyzed for trace metals by ICP-AES.

Statistical analysis

Results are expressed as means ± standard error of measurement. Statistical analysis was performed using JMP statistical software (SAS, Inc., Belmont, CA, USA). As our facility is equipped with only one welding fume generator and inhalation exposure system, a complete block experiment could not be designed. Consequently, animals were exposed to SS welding fumes generated at two different voltages in tandem. Corresponding control animals were exposed to filtered air during each fume exposure. Data are presented as % of air control for each the

lung toxicity parameters. The significance of difference between treatment groups within a time point was analyzed using a two-way analysis of variance (ANOVA) and the Tukey-Kramer post-hoc test. For all analyses, the criterion of significance was set at $p < 0.05$.

Results

Welding fume was collected in the breathing zone of the exposed animals to determine the effect of process voltage on the physical and chemical properties of the generated fume. Particle morphology as determined by electron microscopy was typical for what has been observed previously for gas metal arc-welding fume (Zimmer and Biswas 2001; Antonini et al. 2006) and appeared the same when comparing fume collected after regular SS and high voltage SS welding (Figure 2). The particles were arranged as homogeneous, chain-like agglomerates of ultrafine-sized primary particles. In assessing the effect of voltage on particle size distribution, there was an increase in the number of ultrafine-sized welding particles on the lower stages (10–12) of the MOUDI size classifiers after high voltage SS welding compared to regular SS welding (Figure 3). Stages 10–12 have particle size cut-offs of 100, 56, and 32 nm, respectively. However, there was no difference in comparing the size distribution of the fume generated during high voltage SS (MMAD = 0.36 μm, GSD = 1.59) or regular SS (MMAD = 0.39 μm, GSD = 1.65) welding when based on particle mass (Figure 4). In comparing the metal composition of the fume generated from different voltages, Fe, Mn, Cr, and Ni were the predominant metals in each SS fume (Table I). Compared with regular SS welding, high voltage SS welding produced particles composed of greater amounts of Mn and lower levels of Cr and Ni.

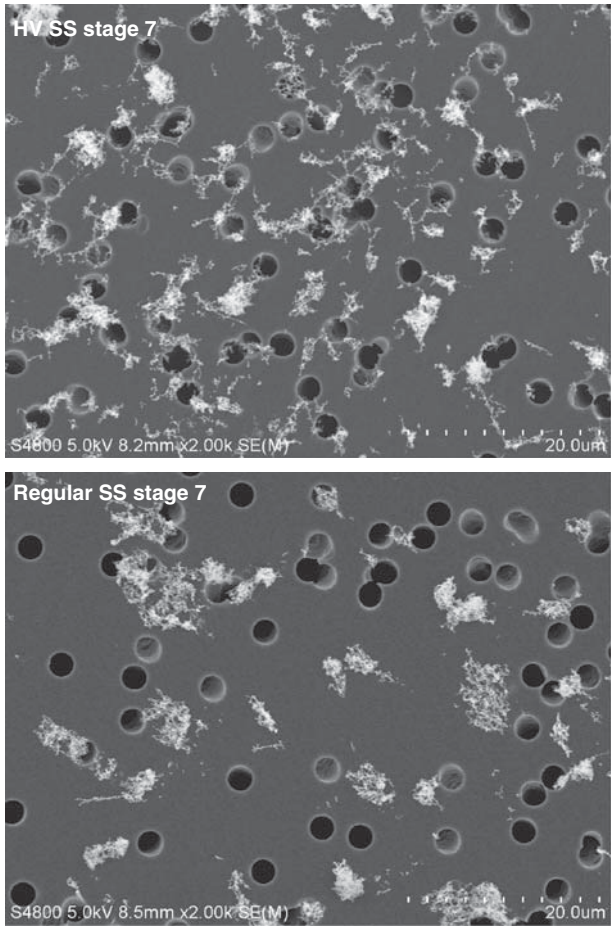

Figure 2. Scanning electron micrographs depicting collected particles on stage 7 of a MOUDI particle sizer after high voltage (HV) SS and regular SS welding. Note the similar particle morphology of chain-like agglomerates produced during welding at the different voltages. Stage 7 has a particle size cut-off of 0.5 μm.

To assess the effect of welding at different voltages on pulmonary responses, albumin levels and LDH activity were measured in acellular BALF from exposed animals (Figure 5). Compared to high voltage SS welding, exposure to fume generated during regular SS welding caused a significant increase in both albumin and LDH at 7 and 21 days after the last exposure, indicating a difference in the lung response to fume generated at different welding settings. In the examination of representative cytospin slides for the different groups, numerous lung macrophages recovered from both SS groups contained welding particles early after exposure (Figure 6A, 6B). The particles persisted in lung macrophages as a significant number of cells still contained particles from each SS group from 21 (Figure 6E, 6F) to 42 days after exposure (Figure 6G, 6H). Note the presence of neutrophils (Figure 6D, 6F; asterisks) recovered from the regular SS welding group but not the high voltage SS group at days 7 (Figure 6C, 6D) and 21 (Figure 6E, 6F), validating the elevated pneumotoxic response of the regular SS welding fume that was observed in Figure 5.

To assess particle clearance, total metal was measured in non-lavaged left lungs at days 0 and 42 after exposure (Figure 7). At 1 h (day 0) after the last exposure, there was a non-significant increase in total metal present in the lungs after exposure to high voltage SS fume compared to regular SS fume. No significant difference was observed in total metal present for the two SS fume at 42 days, indicating that the clearance of the particles at the end of the time course used in the study was similar and not altered by the change in welding voltage. By 42 days after exposure, there was no significant difference in the percentage of total deposited metal present in the

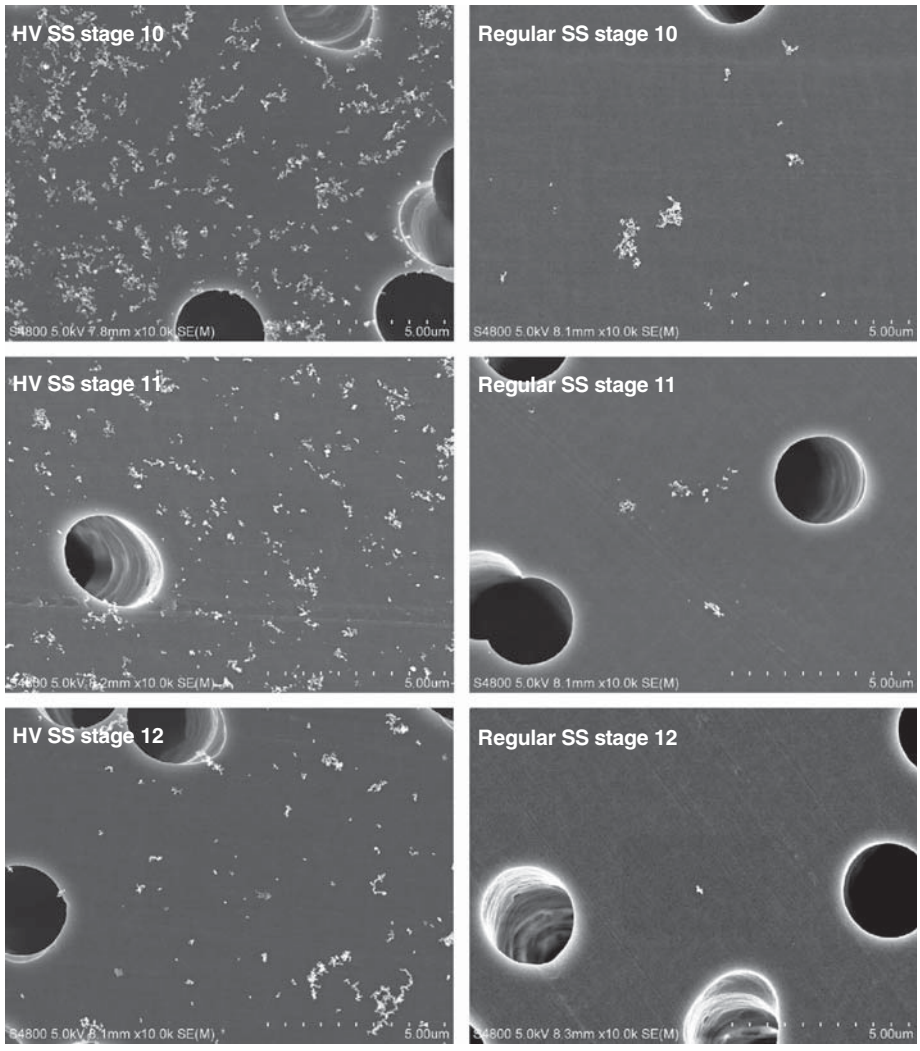

Figure 3. Scanning electron micrographs depicting collected particles on different stages of a nano-MOUDI particle sizer after high voltage (HV) SS and regular SS welding. Stages 10–12 have particle size cut-offs of 100, 56, and 32 nm, respectively.

lungs of the rats exposed to fume from regular SS (46.7%) or high voltage SS (36.7%) welding, confirming that the clearance of the particles was similar and not altered by the change in welding voltage (Figure 8A). No significant differences were observed in the percentage of the specific metals present in the lungs 42 days after exposure to welding at either two voltages (Figure 8B).

Discussion

The basic mechanism of welding fume generation is believed to consist of two steps: (1) Vaporization of the elements and oxides from the welding area where the electrode is consumed, and (2) rapid condensation of the vapors to form particles (Harris 2002). The major source of fume is derived from the electrode or wire that is consumed during the welding process. The type and quantity of welding fume produced greatly depends on the process and process variables (e.g., electrode type, arc voltage, shielding gas, metal transfer mode). This is the first study of which we are aware that attempts to identify welding parameters which affect toxicity. Our findings imply that common welding practices may be modified in order to reduce the potential adverse lung effects associated with exposure to fumes. The understanding of how process conditions influence welding aerosol formation and biological response can significantly contribute to process improvement, development of new and novel process technologies, and use of appropriate personal protection and ventilation systems to avert adverse health outcomes. Previous studies by our group have indicated that modifications in welding processes and conditions can significantly influence the physical and chemical characteristics of the resulting fume

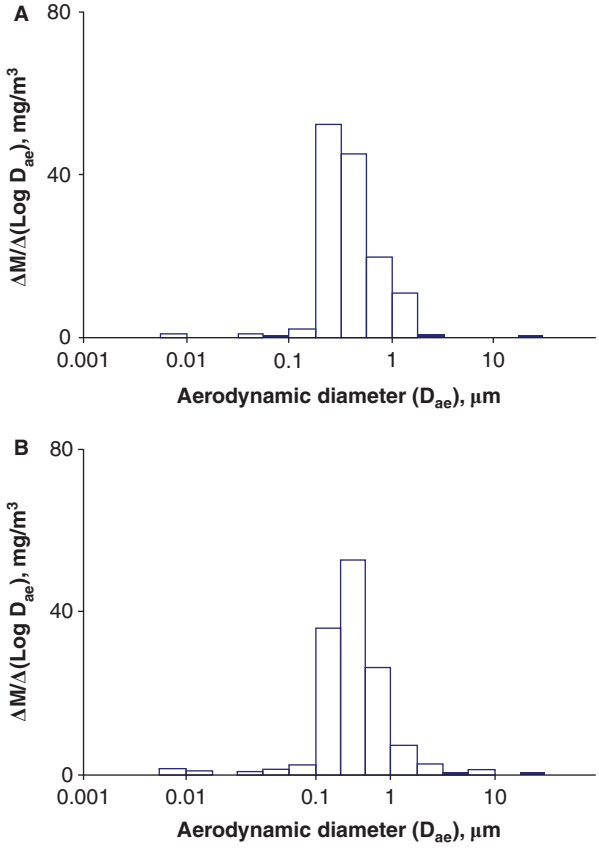

Figure 4. Representative particle size distribution graphs of generated welding particles during (A) high voltage SS or (B) regular SS welding that compares mass concentration, M, versus particle size, aerodynamic diameter. Random daily measurements of particle size distribution were made during welding fume exposure throughout the course of the study.

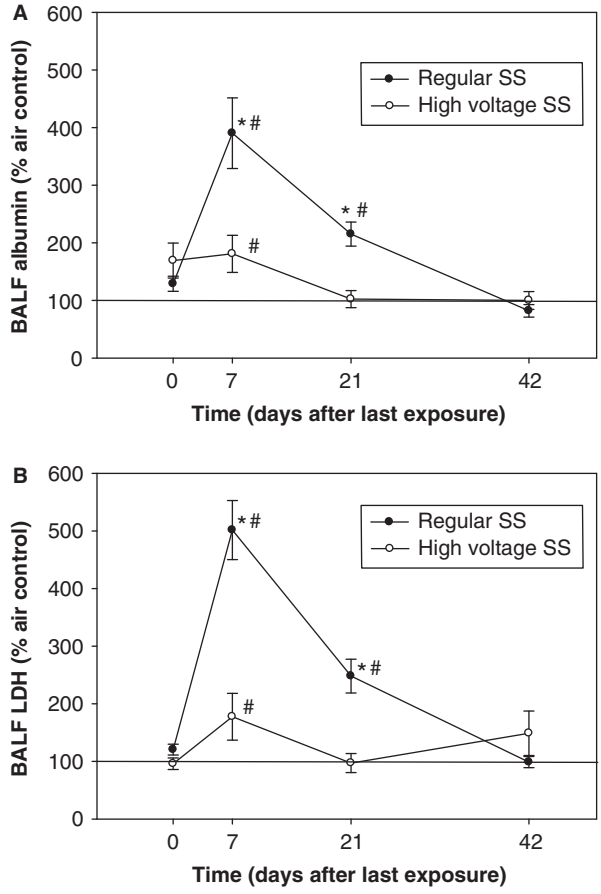

Figure 5. Lung injury: (A) albumin (mg/mL) and (B) LDH activity (U/L) in acellular bronchoalveolar lavage fluid (BALF) at days 0, 7, 21, and 42 after inhalation of 40 mg/m^3 of regular SS and high voltage SS welding fume for 3 h/day for three days. Values are means ± standard error (n = 4–5). Control animals were exposed to filtered air. #significantly different from control group within a time point; *significantly different than other welding fume group within a time point, $p < 0.05$.

(Keane et al. 2009, 2010). In the current study, we assess the effect of welding voltage on fume size, particle elemental composition, and pulmonary toxicity.

By raising the voltage from 25 V to 30 V, there appeared to be an increase in the number of ultrafine-sized particles of deposited particles on different stages of a particle sampler as examined by electron microscopy. Previously, Hovde and Raynor (2007) observed ultrafine particle concentrations to be more than three times greater at a higher welding voltage during gas metal arc welding as determined by an optical particle counter. As the voltage level increases during welding, the type of metal transfer changes from short-circuit to spray arc, affecting the heat of the weld and the molten surface area (Gray and Hewitt 1982; Hovde and Raynor 2007). At lower voltages, the electrode short circuits, keeping the temperature lower which reduces the amount of metal vaporization and subsequent recondensation (Hovde and Raynor 2007). During spray arc transfer at higher voltages, more molten surface area and the constant current of spray transfer increase heat output, likely producing more vaporization from the spray transfer droplets. Together with the increased surface area of the spray transfer droplets, the increase in heat may

Table I. Metal composition of generated stainless steel welding fumes.

Metals analyzed	Regular SS welding (weight % of metal)	High voltage SS welding (weight % of metal)
Iron (Fe)	57.0 ± 2.6	51.7 ± 1.0
Manganese (Mn)	13.8 ± 0.9	25.3 ± 1.0
Chromium (Cr)	20.2 ± 3.0	17.0 ± 0.2
Nickel (Ni)	8.80 ± 0.4	5.64 ± 0.2
Copper (Cu)	0.20 ± 0.0	0.40 ± 0.0

Values are means ± standard error; n = 4–5 welding collection periods of 30–45 min. SS, stainless steel.

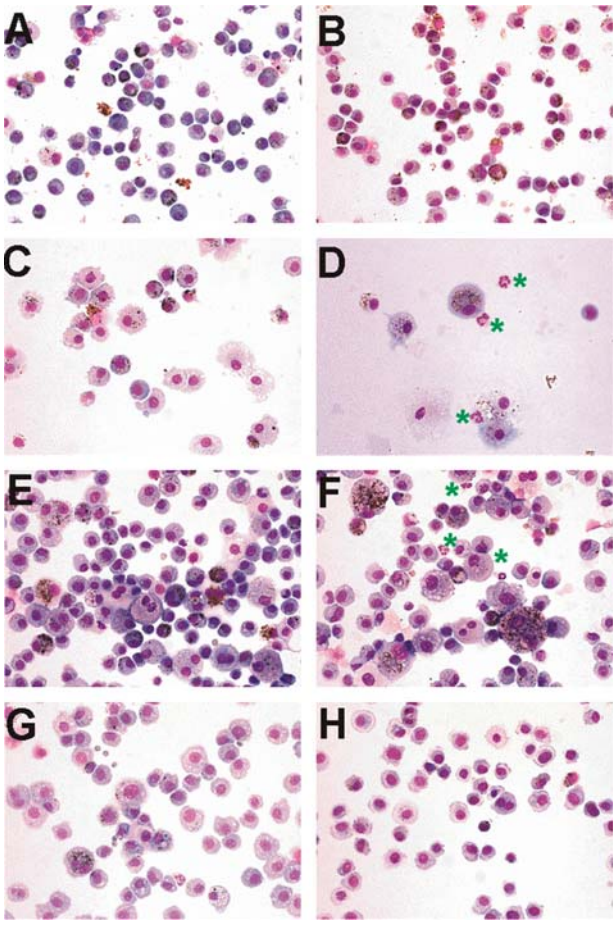

Figure 6. Representative images of cytopsin-stained lung cells recovered from exposed animals at days 0 (A: high voltage SS; B: regular SS), 7 (C: high voltage SS; D: regular SS), 21 (E: high voltage SS; F: regular SS), and 42 (G: high voltage SS; H: regular SS) after exposure to 40 mg/m^3 of SS welding fume for 3 h/day for three days. Asterisks highlight neutrophils that were recovered from the regular SS group.

speed up metal volatilization, producing a greater number of ultrafine particles and likely changing the metal profile of the fume. Indeed, the percentage of Mn increased in the fume at the higher welding voltage in the current study. This change in metal content of the resulting fume, with the increase in the number of ultrafine particles, likely will affect the lung responses after inhalation. Importantly, however, when particle size was based on a mass comparison in the current study, there was no difference in the size distribution curves of the welding fumes generated from the two voltages. This is not surprising due to the negligible contribution to the mass by the ultrafine-size component of the total amount of collected welding fume.

In assessing the lung responses to SS welding fume, an increase in process voltage altered the lung toxicity profile. After three days of inhalation exposure, both

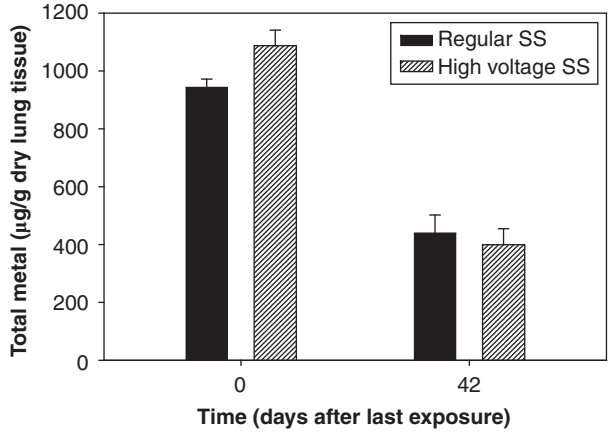

Figure 7. Total metal measured in non-lavaged left lungs at days 0 and 42 after inhalation of 40 mg/m^3 of regular SS and high voltage SS welding fume for 3 h/day for three days. Values are means ± standard error (n = 4–5).

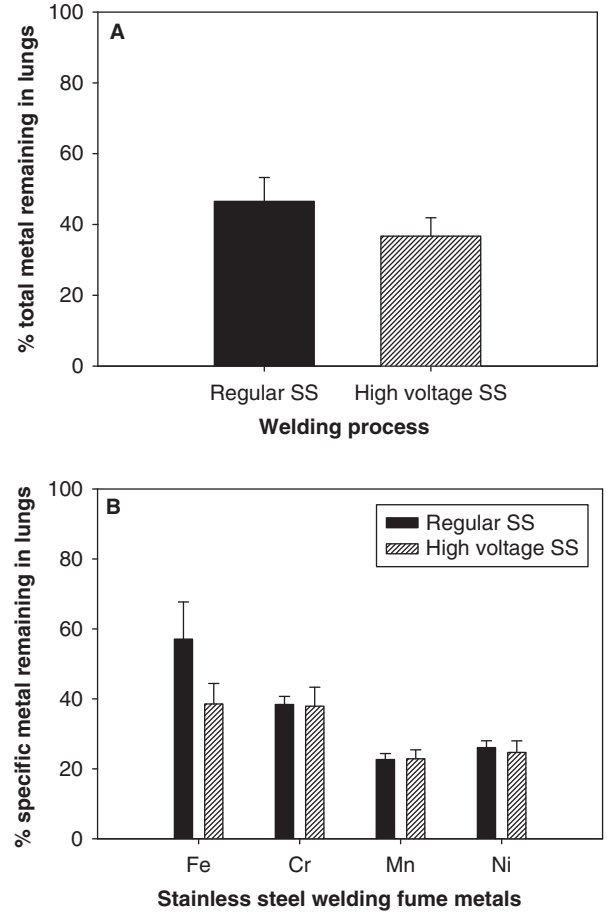

Figure 8. Percentage of (A) total metal and (B) specific metals measured in non-lavaged left lungs at day 42 after inhalation of 40 mg/m^3 of regular SS and high voltage SS welding fume for 3 h/day for three days. Values are means ± standard error (n = 4–5).

the high voltage SS and regular SS fumes significantly increased parameters of lung injury early after the last exposure. However, the toxic pulmonary response was more substantial and persisted longer after exposure to the regular SS fume. The pattern of response for the regular SS fume generated at a more standard voltage of 25V was comparable to what was observed in a previous study under similar exposure conditions (Antonini et al. 2007), in that lung injury peaked between six and 14 days after exposure and remained elevated at 21 days before eventually subsiding over time. In contrast, a significantly lesser lung toxicity response, peaking at seven days and returning to control levels by 21 days, was observed after exposure to high voltage SS fume. The observed variations in lung responses were likely due to differences in particle size, elemental composition, or particle deposition and clearance after exposure to the SS fumes. It was not surprising that a different temporal toxicity profile was observed for the two SS fumes because of the observed differences in particle size and chemical composition.

It was somewhat surprising; however, in that the more substantial lung response was not observed after exposure to high voltage SS. The generation of a greater number of ultrafine-sized particles and a higher percentage of Mn in the fume relative to the other metals were observed for the high voltage welding as compared to the regular SS fume. Previous toxicology studies have observed that nanoparticles, those similar in composition when compared on a mass basis, may be more pneumotoxic (Oberdörster et al. 1992; Brown et al. 2001) and have an elevated deposition in the lungs (Jaques and Kim 2000; Brown et al. 2002; Oberdörster et al. 2005; NIOSH 2007) as compared to their larger-sized counterparts. Because the same mass of particles was delivered to the lungs, regardless of the welding process conditions, it is unlikely that the particle size changes that were observed by electron microscopy were responsible for the differences seen in the lung responses in the current study. Particle lung burden was not significantly different when comparing the total metal deposited in the lungs after exposure to either fume. It also has been hypothesized that certain ultrafine particles, as compared to fine- and coarse-sized particles, may escape alveolar macrophage phagocytosis after deposition in the lungs (Oberdörster et al. 2005), thus altering inflammatory cell signaling and responses. Microscopic analysis of alveolar macrophages collected by BAL after exposure to either process revealed no alteration in phagocytosis of the inhaled particles in the current study, as particles were observed to persist in macrophages for 42 days after exposure to either of the fumes. This is additional proof that the variation in the number of ultrafine welding particles was likely not the primary reason for the observed difference in lung toxicity in the current study.

In regards to the effect of the alteration in chemical composition changes on toxicity due to welding voltage, it has been clearly established that welding fumes which possess differential elemental profiles induce varied toxic responses in the lungs and lung cells (Antonini et al. 1996, 1999; Taylor et al. 2003). Mn and Cr, two potentially toxic metals, were generated in significant quantities during the high voltage SS and regular SS welding performed in the current study. Although there was an increase in the percentage of Mn in the high voltage SS fume (the one of lower toxicity) and a minimal change in the percentage of Cr at the two voltages, the differences in pulmonary response may reflect a change in the oxidation state of the metal and not the quantity of each metal present in the fume. Recent studies by our group indicate that metal oxidation state and other chemical properties (e.g., solubility) are highly dependent on welding process, transfer modes, and shield gas composition (Keane et al. 2009, 2010). Multiple Mn species, including Mn^{2+}, Mn^{3+}, Mn^{4+}, were observed in the generated fume, and the proportions of the different Mn species varied with the welding process and settings (Keane et al. 2010). Similarly, concentrations of Cr^{6+}, a highly pneumotoxic and carcinogenic metal, were observed to vary significantly with welding type, process, and shield gas type (Keane et al. 2009). Based on the findings of our previous work, examining the effect on welding process on oxidation states of Mn and Cr, and the findings of the current study, it is plausible that the difference in the lung toxicity profile of welding fume generated at different voltages is due to alterations in the levels of different metal oxidation species that may be toxic to lung tissues and cells.

To determine if the difference in lung responses between the two SS fumes used in the current study was due to variations in particle clearance after exposure, total deposited metal was measured in the lungs of the animals at 1 h and 42 days after the last exposure. The clearance of deposited particles from the lungs after welding fume treatment has been shown to be dependent on the properties of the specific welding fume (Antonini et al. 1996, 2010a). No significant differences were observed in the amount of metal deposited at the end of a three-day inhalation exposure or in the amount of the metal cleared from the lungs 42 days after exposure when comparing the two fumes in the current study. In addition, no differences were observed in the percentage of the specific metals present in the lungs

42 days after exposure when comparing the regular SS and high voltage SS fumes. Interestingly, a greater percentage of Mn and Ni were cleared from the lungs at 42 days compared to Fe and Cr for each type of SS fume. Previously, we have observed specific deposited metals, in particular Mn, to clear from the lungs at different rates, which is likely due to the tissue solubility of each metal present in the welding fume (Antonini et al. 2010b).

In summary, welding produces complex metal particles that may affect health after inhalation exposure. Elemental composition, particle size, and lung toxicity all can be altered by modest, but feasible, changes to specific welding settings, in particular, voltage. By increasing welding voltage during SS welding, the percentage of Mn in the fume increased; a greater number of ultrafine particles were generated; and lung toxicity was less substantial and subsided more quickly compared to welding at a lower voltage in the current study. The significance of this research indicates that the physical and chemical properties of generated welding fume can vary depending on welding process parameters, thereby altering the resulting toxic effect to welding fume exposure. Unfortunately, it is doubtful that a single and practical set of recommendations can be established to minimize exposures to specific Mn and Cr species across a variety of industrial welding settings as the primary means to protect workers. The technical requirements for specific welding operations are quite complex and too diverse to develop a universal protocol to minimize Mn and Cr generation in the welding industry. However, certain protocols could be established for specific welding tasks that would help reduce exposures to toxic metals, particularly where the options of welding consumable substitution or worksite ventilation controls are limited.

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