

Field Study

Cancer risk assessment for occupational exposure to chromium and nickel in welding fumes from pipeline construction, pressure container manufacturing, and shipyard building in Taiwan

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Abstract: Objective: We assessed the cancer risks resulting from the exposure to chromium, hexavalent chromium (Cr (VI)), oxidic nickel (Ni), and soluble Ni in welding fumes during pipeline and shipyard construction and pressure container manufacturing in Taiwan. We also determined the roles of welding performance and demographic characteristics during the exposure to Cr and Ni. **Methods:** Personal air samples were collected for the analysis of Cr and Ni, and the concentrations of Cr (VI), oxidic Ni, and soluble Ni were quantified. We assessed cancer slope factors for Cr, Cr (VI), oxidic Ni, and soluble Ni, and we used the Incremental Lifetime Cancer Risk model proposed by the United States Environmental Protection Agency to calculate excess risk. **Results:** The risks of exposure to Cr and Cr (VI) in welding fumes exceeded the acceptable level of occupational exposure (10^{-3}). We ranked the excess cancer risk in three industries in decreasing order as follows: pipeline construction, shipyard construction, and pressure container manufacturing. The most sensitive parameters for the risk assessment were Cr and Ni concentrations. Statistically significant determinants of Cr (VI), oxidic Ni, and soluble Ni concentrations were the following: stainless steel as the base metal and the filler metals of shielded metal arc welding (SMAW) and of gas tungsten arc welding (GTAW). **Conclusion:** The study revealed that welders belong to a high cancer-risk group. Furthermore, we demonstrated the roles of filler metals and stainless steel

in exposure to Cr and Ni.
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Key words: Cancer risk assessment, Chromium VI, Oxidic nickel, Soluble nickel, Welding fumes

Introduction

A 26% increase in the risk of lung cancer has been estimated in stainless steel welders¹, and animal studies have demonstrated that fumes from stainless steel welding are potentially mutagenic². Exposure to low-to-moderate welding fumes is associated with oxidative stress, telomere alterations, and deoxyribonucleic acid (DNA) methylation³. Though there is limited evidence to weigh the carcinogenicity of welding fumes, stainless steel welding leads to exposure to chromium (VI) and nickel (Ni), which are recognized as carcinogens⁴.

Chromium (Cr) significantly increases the risk of lung, nasal, and sinus cancers in epidemiological and animal studies⁵. A dose-response relationship between lung cancer mortality and cumulative hexavalent chromium [Cr (VI)] exposure was demonstrated in a chromate production facility⁶. Chromium damages cellular components (including DNA) because of the generation of free radicals during the reduction process of Cr (VI) to Cr (III)⁵.

The carcinogenic potency of Ni depends on its chemical form and route of entry in organisms. Soluble nickel

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Supplementary materials (Appendices) are available in the online version of this article.

introduced through intraperitoneal or intramuscular administration results in tumorigenesis⁷. A case-control study quantified the dose effect of water-soluble nickel on cancer incidence⁸. Alveolar bronchiolar adenomas or carcinomas and pheochromocytoma were found in rats inhaling nickel oxide⁹. Nickel oxide increases the incidence of lung tumors in female mice even when the dose is as low as 1.25 mg/m³¹⁰. However, metallic nickel is classified as 2B by International Agency for Research on Cancer¹¹. The carcinogenesis of Ni exposure is caused by the induction of oxidative stress, the disruption of DNA repair pathways, and modulation of the expression of several cancer-related genes¹².

Epidemiological studies are a useful tool for establishing causation between welding fumes and cancer risk, but the composition of welding fumes may vary with specific welding tasks and time. Therefore, it is difficult to apply previously established exposure profiles and determine the risk factors in welding. Recently developed risk assessment modeling techniques may provide useful approaches for quantifying the risk factors in welding. In this study, we have used exposure data and welding characteristics for welders in three scenarios to assess cancer risk. We aimed to do the following: (1) to quantify cancer risks in welders in relation to exposure to Cr, Cr (VI), oxidic Ni, and soluble Ni in pipeline construction, pressure container manufacturing, and shipyard building; (2) to analyze sensitive input parameters on cancer risk; and (3) to determine the roles of welding performance and demographic characteristics on exposure.

Subjects and methods

Study subjects

The Institute of Labor, Occupational Safety and Health (ILOSH) of the Ministry of Labor in Taiwan conducted an exposure assessment of welders' exposure to welding fumes in 2006¹³ and 2013¹⁴. Welders working in pipeline construction, pressure container manufacturing, and shipyard building were recruited. The study was approved by the Institutional Review Board of the Tri-Service General Hospital in Taiwan. All participants were aware of the study aims and participated voluntarily.

Welders in pipeline construction

A total of 50 individuals were sampled between the 5th and the 10th of September 2013. The participants were recruited from full-time project welders working in the construction of transportation pipelines in an oil refinery factory in Mailiao Industry Park, Taiwan. They performed shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) on butt-welding joints, flange neck, and fillet weld on pipes. The filler for GTAW was ER70S-G, and the filler for SMAW was E7016. In addition, 20% of the pipes were made of carbon steel, and 80% of the pipes

were made of stainless steel. The welders worked outdoors at temperatures of 24.1°C-35.5°C and in wind speeds averaging 24.8 km/h, with a maximum of 37.8 km/h.

Welders in pressure container manufacturing

A total of 35 full-time welders were recruited and worked at pressure container manufacturing factories, including three factories located in Taoyuan County and one factory in Hsinchu City, Taiwan. The welding mainly applied GTAW with a non-consumable tungsten electrode, and only 10% of the welding employed SMAW. Welding was used to form a layer on the outside of hollow cylindrical containers. The base metal of the work pieces was 70% stainless steel and 30% carbon steel. The welders worked indoors at temperatures of 24.0°C-30.0°C, with fans operating in the workplace for ventilation.

Welders in shipyard building

Twenty full-time welders employed in shipyard manufacturing were recruited as study subjects¹³. The welders mainly used SMAW, but 20% of the welding was completed using gas metal arc welding (GMAW). Carbon steel was used as the base metal. The welders worked indoors at temperatures of 25.0°C-32.0°C, with fans for ventilation in the workplace.

Personal air sampling and quantification of Cr and Ni in welding fumes

Air samplers with 37 mm mixed cellulose ester membranes (0.8 µm pore size; SKC Corp., USA) were mounted on the shoulders of welders and operated at a flow rate of 2 l/min for 6 hours. A total of 105 air samples were taken. To analyze Cr and Ni in welding fumes, we followed the NIOSH analytical method 7301¹⁵ and used inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7500ce, WA, USA). For every 10 samples, recovery of sample analysis was checked by two consecutive spikes of a quality control standard, which found a range of 90%-110%. The limits of quantification (LOQs) of metals were 8.9 and 8.5 ng/sample for Cr and Ni, respectively.

Estimation of Cr (VI), oxidic Ni, and soluble Ni concentrations

The Cr (VI), oxidic Ni, and soluble Ni concentrations were estimated using the following equation:

$$\text{Equation 1: } C_{mi} = \sum C_i \times F_i \times W_i,$$

where C_{mi} is the concentration of Cr (VI), oxidic Ni, or soluble Ni ($\mu\text{g}/\text{m}^3$); C_i is the concentration of total Cr or total Ni ($\mu\text{g}/\text{m}^3$); F_i is the percentage of SMAW, GMAW, or GTAW used in 8-h work shifts (%); and W_i is the percentage of Cr (VI), oxidic Ni, or soluble Ni in Cr or Ni corresponding to the welding methods presented in Table 1. For SMAW, which is performed primarily on stainless

Table 1. Proportion of Cr (VI), oxidic Ni, or soluble Ni found in chromium (Cr) or nickel (Ni) according to welding methods

Welding methods	Chemical species in Cr and Ni (%)		
	Cr (VI)	Oxidic Ni	Soluble Ni
SMAW	46.2 ± 5.0 ⁽¹⁾	33.0 ± 1.5 ⁽²⁾	44.0 ± 2.0 ⁽²⁾
GMAW	6.0 ± 5.4 ⁽³⁾	79.0 ± 0.5 ⁽²⁾	15.0 ± 0.5 ⁽²⁾
GTAW	13.2 ± 2.5 ⁽⁴⁾	88.0 ± 2.0 ⁽⁵⁾	2.5 ± 0.5 ⁽⁶⁾

(1) Matczak et al., 1993¹⁶⁾(2) Berlinger et al., 2009¹⁹⁾(3) Cena et al., 2014¹⁷⁾(4) Topham et al., 2009¹⁸⁾(5) The percentage of oxidic nickel with the GTAW method was inferred to be 88%²⁰⁾.(6) The allotted percentage of soluble Ni with GTAW was 2.5%²³⁾.

Abbreviations: SMAW: shielded metal arc welding; GTAW: gas tungsten arc welding; GMAW: gas metal arc welding.

steel, Cr (VI) occupies 46.2 ± 5.0% of total Cr¹⁶⁾. Cr (VI) accounted for 6.0 ± 5.4% of total Cr when GMAW was used on stainless steel in a laboratory study¹⁷⁾, and Cr (VI) accounted for 13.2 ± 2.5% of total Cr when GTAW was used on stainless steel plates in a welding chamber¹⁸⁾.

For the proportions of oxidic Ni and soluble Ni in total Ni, 79% oxidic nickel and 15% soluble nickel were found when GMAW was applied on corrosion-resistant steel, and 33% oxidic nickel and 44% soluble nickel were measured when SMAW was used¹⁹⁾. However, previously established percentages of oxidic and soluble Ni corresponding with GTAW were not available. We inferred the percentage of oxidic Ni in GTAW using the assumption that the percentage of oxidic Ni is proportional to the deposition efficiency (%) of the welding method. The percentages of oxidic Ni in welding fumes from SMAW and GMAW are 33% and 79%, respectively¹⁹⁾; and the deposition efficiencies of SMAW, GMAW, and GTAW are 70%, 95%, and 100%, respectively²⁰⁾. The percentage of oxidic Ni used in GTAW was therefore inferred to be 88%.

Deposition efficiency indicates the percentage of weight of the electrode (fillers) deposited in work pieces during the welding process. High deposition efficiency implies low loss of welding materials and reduced fume formation. GTAW has ~ 100% deposition efficiency and primarily forms insoluble oxidic Ni owing to an oxidation reaction^{21,22)}. Thus, the allotted percentage of soluble Ni with GTAW was 2.5%. The tungsten electrode of GTAW is difficult to melt and consume, so GTAW generates few welding fumes. The generation of welding fumes by GTAW is 0.18 fold of that produced by GMAW,²³⁾ which has a 15% proportion of soluble Ni. The allotted percentage of soluble Ni generated by GTAW was founded on the assumption that the low generation of fumes by GTAW also reduces the proportion of soluble Ni, due to the lower number of alkali elements and fluoride present

in the filler of the GTAW electrode^{24,25)}.

Dose-response assessment for Cr and Ni compounds

Cancer slope factors for Cr, Cr (VI), and soluble Ni have been proposed by Health Canada²⁶⁾ and the United States Environmental Protection Agency²⁷⁾. The cancer slope factors for Cr and Cr (VI) by inhalation were found to be 47.6 (mg/kg/day)⁻¹ and 41 (mg/kg/day)⁻¹, respectively^{26,27)}. The cancer slope factor for soluble Ni by inhalation was 3.0 (mg/kg/day)⁻¹^{26,28)}. The cancer slope factor for oxidic Ni was assessed based on the dose-response dataset from a toxicology test on male rats⁹⁾, in which F344/N rats inhaled 0.5-2.0 mg Ni/m³ of Ni oxide for 6 h/day, 5 d/wk for 104 weeks, leading to neoplastic effects including alveolar/bronchiolar adenoma in the lung and pheochromocytoma in the adrenal medulla. The benchmark dose method (BMD)²⁹⁾ was applied to determine a benchmark dose lower-confidence limit (BMDL) of 1.416 mg/kg/day. Then, the human equivalent dose (HED) was calculated using the following equation:

$$\text{Equation 2: HED (mg/kg/day)} = \text{animal BMDL (mg/kg/day)} \times \text{Km},$$

where the factor Km was 0.162, given to a human with a body weight of 60 kg and a body surface area of 1.62 m²³⁰⁾. Thus, the HED was 0.229 mg/kg/day. Accordingly, the cancer slope factor of Ni oxide was estimated to be 4.4 (mg/kg/day)⁻¹, which is between 3 (mg/kg/day)⁻¹ for soluble Ni and 5.5 (mg/kg/day)⁻¹ for refinery dust, which is mainly composed of insoluble Ni.

Cancer risk assessment

We applied the US EPA Incremental Lifetime Cancer Risk (ILCR) model³¹⁾ to determine the cancer risk for exposure to Cr, Cr (VI), oxidic Ni, or soluble Ni through inhalation of welding fumes. The ILCR was calculated using the following equation:

Table 2. Summary of input parameters in the ILCR model

Parameters		Input estimates	Distribution type	Data source
Breathing rate	m ³ /h	1.37 ± 0.042	Normal	US EPA, 2009 ³⁵⁾
Average work hours	h/day	8.87	Point estimate	DBAS, 2016 ³²⁾
Exposure frequency	d/yr	246 ± 1.5	Normal	MOL, 2016 ³³⁾
Exposure duration	year	45	Point estimate	MOL, 2016 ³⁴⁾
Body weight	kg	69.81 ± 1.39	Normal	MHW, 2016 ⁵²⁾
Time to cancer	year	77.01 ± 2.01	Normal	MOI, 2016 ⁵³⁾
Cancer slope factor	(mg/kg/day) ⁻¹			
- Cr		47.6	Point estimate	Health Canada, 2007 ²⁶⁾
- Cr (VI)		41	Point estimate	US EPA, 2007 ²⁷⁾
- Oxidic nickel		4.4	Point estimate	NTP, 1996 ⁹⁾
- Soluble nickel		3.0	Point estimate	Health Canada, 2007 ²⁶⁾
Concentration				
- Cr	10 ⁻³ mg/m ³			
Pipeline construction		1361.6 ± 639.8	Log-normal	Field sampling
Pressure container manufacturing		33.8 ± 59.8	Log-normal	Field sampling
Shipyards building		1.1 ± 0.9	Log-normal	Field sampling
- Cr (VI)	10 ⁻³ mg/m ³			
Pipeline construction		503.8 ± 294.7	Log-normal	Field sampling
Pressure container manufacturing		4.4 ± 8.0	Log-normal	Field sampling
Shipyards building		0.4 ± 0.3	Log-normal	Field sampling
- Oxidic Ni	10 ⁻³ mg/m ³			
Pipeline construction		145.2 ± 119.4	Log-normal	Field sampling
Pressure container manufacturing		13.0 ± 11.5	Log-normal	Field sampling
Shipyards building		0.1 ± 0.1	Log-normal	Field sampling
- Soluble Ni	10 ⁻³ mg/m ³			
Pipeline construction		101.8 ± 85.8	Log-normal	Field sampling
Pressure container manufacturing		1.0 ± 0.9	Log-normal	Field sampling
Shipyards building		0.1 ± 0.1	Log-normal	Field sampling

Abbreviations: ILCR, Incremental Lifetime Cancer Risk

$$\text{Equation 3: ILCR} = \left(\frac{C \times BR \times DS \times EF \times ED}{BW \times AT \times 365} \right) \times SF,$$

where C is the exposure concentration (mg/m³), BR is the breathing rate (m³/h), DS is the average work hours per day (h), EF is the exposure frequency in a year (day/yr), ED is the exposure duration during the work life (years), BW is the body weight (kg), AT is the time to cancer expressed in life expectancy (years), and SF is the cancer slope factor (mg/kg/day)⁻¹ (Table 2).

The concentrations of total Cr and total Ni in welding fumes were determined by ICP-MS analysis. The concentrations of Cr (VI), oxidic Ni, and soluble Ni were estimated according to Equation 1 and Table 1. Average work hours per day (DS) were 8 h/day, with an extra work period of 0.87 h/day in this industry sector in Taiwan³²⁾. The exposure frequency in a year (EF) was 246 ± 1.5 d/year, based on statistics in Taiwan³³⁾. Exposure duration (ED) was set at 45 years, provided that an employee begins working at 20 years old and retires at 65 years old, which is the proposed age of retirement by the Ministry

of Labor in Taiwan³⁴⁾. The breathing rate (BR) of 1.37 ± 0.042 m³/h was given for an adult male with a body weight of 69.8 kg (the average body weight of male adult in Taiwan) and moderate activities with metabolic equivalents between 3.0 and 6.0³⁵⁾. Cancer slope factors for Cr, Cr (VI), nickel oxide and soluble nickel are given in the previously mentioned dose-response assessment.

Statistical analysis

The distribution frequency of risk and sensitive parameters for ILCR were obtained using Monte Carlo simulations (n = 10,000) using Crystal Ball 11.1.1.1.00 (Oracle, Redwood Shores, CA, USA) in the Excel[®] environment. SPSS software (SPSS, Inc., Chicago, IL, version 16) was used for statistical analyses. A non-parametric one-way analysis of variance (the Kruskal-Wallis test) was performed to test the differences in workers' age, length of employment, and exposure to Cr and Ni between the exposure groups.

To assess the factors associated with Cr or Ni exposure

Table 3. Demographics of the participants in the three exposure groups

Characteristics	Pipeline construction	Pressure container manufacturing	Shipyards building
Number of participants	50	35	20
Sex	male	male	male
Age (year) *	43.7±7.9	40.7±12.4	48.9±7.5
Length of employment (year) *	22.2±13.9	15.3±12.7	25.0±10.0
Percentage use of welding method	GTAW (25%), SMAW (75%)	GTAW (90%), SMAW (10%)	GMAW (20%), SMAW (80%)
Welding type	manual	manual or automatic	manual or automatic
Percentage use of base metal	stainless steel (80%), carbon steel (20%)	stainless steel (70%), carbon steel (30%)	carbon steel (100%)
Filler materials	E7016, ER308, ER70S-2	ER70S-G, ER308	ER70S-G, E7016

*Kruskal-Wallis test, *p*-value < 0.05

Abbreviations: SMAW: shielded metal arc welding; GTAW: gas tungsten arc welding; GMAW: gas metal arc welding.

concentrations (µg/m³), we applied a multiple linear regression model:

$$\text{Equation 3: } Y_i = \beta_0 + \beta_1 \chi_{i1} + \beta_2 \chi_{i2} + \dots + \beta_p \chi_{ip} + \epsilon_i, \quad (4)$$

where the dependent variable (*Y*) was the log-transformed exposure concentration of Cr or Ni, and the explanatory variables were the demographic characteristics (age and length of employment), welding methods (GTAW, SMAW, or GMAW), welding types (manual or automatic), base metals (stainless steel or carbon steel), and filler materials (ER70S-G, E7016, ER308, or ER70S-2). Information is shown in Table 3 and Supplementary Table 1. Base metals and fillers were expressed as the percentage of Cr or Ni in base metals or fillers. A *p*-value < 0.05 was considered statistically significant.

Results

Demographics of study subjects

All welders were male. The ages and lengths of employment were statistically different between the three work groups. Welders' ages were ranked by work group in decreasing order: shipyard building, pressure container manufacturing, and pipeline construction. Welders' lengths of employment were ranked in decreasing order: shipyard building, pipeline construction, and pressure container manufacturing. Welders in the three groups were subject to different welding methods, base metals, and filler electrodes (Table 3).

Determination of Cr(VI), oxidic Ni, and soluble Ni concentrations of welders

The levels of exposure to Cr and Ni in the three groups significantly differed (*p*-value < 0.05). The average level of Cr was always higher than that of Ni in all groups. Ranges of estimated mean concentrations of Cr, Cr(VI), Ni, oxidic Ni, and soluble Ni were 1.1-1361.6 µg/m³, 0.4-503.8 µg/m³, 0.3-307.3 µg/m³, 0.1-145.2 µg/m³, and 0.1-

101.8 µg/m³, respectively (Table 2 and Supplementary Table 2). The percentages of Cr(VI) in Cr, oxidic Ni in Ni, and soluble Ni in Ni were estimated at 13.1%-38.2%, 8.4%-47.3%, and 4.9%-41.8% among groups, respectively (Supplementary Table 2).

Lifetime cancer risk assessment for exposure to Cr, Cr(VI), oxidic Ni, and soluble Ni in welding fumes

The excess cancer risk due to exposure to Cr, Cr(VI), oxidic Ni, and soluble Ni for welders in pipeline construction ranged from 6.2×10^{-2} - 3.7×10^1 , 8.5×10^{-2} - 1.0×10^1 , 1.5×10^{-3} - 3.6×10^{-1} , and 4.9×10^{-4} - 2.9×10^{-1} , respectively (Table 4). The cancer risks of exposure to Cr and Cr(VI) in all three groups and Ni (oxidic and soluble Ni) in pipeline construction were over 10^{-3} . The cancer risks due to exposure to Ni in pressure container manufacturing and shipyard building were below 10^{-3} . The probability density of risk fitted a logistic distribution with kurtosis > 3. Sensitive parameters for modeling included exposure concentration and breathing rate, which contributed to approximately 99.5% of the total variance. Life expectancy and body weight had minor negative contributions (Fig. 1).

Determinants associated with Cr(VI), oxidic Ni, and soluble Ni concentrations

Cr(VI) and oxidic Ni concentrations were significantly associated with the percentages of Cr or Ni in the filler of stainless steel (SS) with SMAW (SMAW-SS, χ_1) and the percentages of Cr or Ni in the filler of stainless steel (SS) with GTAW (GTAW-SS, χ_2). Soluble Ni concentration was significantly associated with the percentages of Ni in the filler of SMAW-SS (χ_1) and the percentages of Ni in the base metal stainless steel (SS, χ_3) (Table 5).

Table 4. Estimated incremental lifetime cancer risk from exposure to Cr, Cr (VI), oxidic Ni, and soluble Ni in welding by groups

Work facilities	Metals	Incremental lifetime cancer risk			
		Mean	SD	Minimum	Maximum
Pipeline construction	Cr	4.2	2.8	6.2×10^{-2}	3.7×10^1
	Cr (VI)	1.4	9.6×10^{-1}	8.5×10^{-2}	1.0×10^1
	Oxidic Ni	3.6×10^{-2}	1.6×10^{-2}	1.5×10^{-3}	3.6×10^{-1}
	Soluble Ni	2.1×10^{-2}	1.8×10^{-2}	4.9×10^{-4}	2.9×10^{-1}
Pressure container manufacturing	Cr	1.1×10^{-1}	9.9×10^{-2}	1.2×10^{-3}	1.3
	Cr (VI)	1.3×10^{-2}	1.2×10^{-2}	1.8×10^{-4}	2.8×10^{-1}
	Oxidic Ni	3.3×10^{-4}	2.8×10^{-4}	4.8×10^{-6}	3.0×10^{-3}
	Soluble Ni	1.2×10^{-4}	7.1×10^{-5}	3.2×10^{-5}	7.5×10^{-4}
Shipyards building	Cr	3.4×10^{-3}	3.1×10^{-3}	7.4×10^{-5}	6.6×10^{-2}
	Cr (VI)	1.1×10^{-3}	8.7×10^{-4}	9.8×10^{-6}	1.1×10^{-2}
	Oxidic Ni	3.1×10^{-5}	2.8×10^{-5}	9.2×10^{-7}	6.5×10^{-4}
	Soluble Ni	9.8×10^{-5}	3.5×10^{-6}	2.0×10^{-7}	2.8×10^{-4}

Abbreviations: Cr: chromium; Ni: nickel

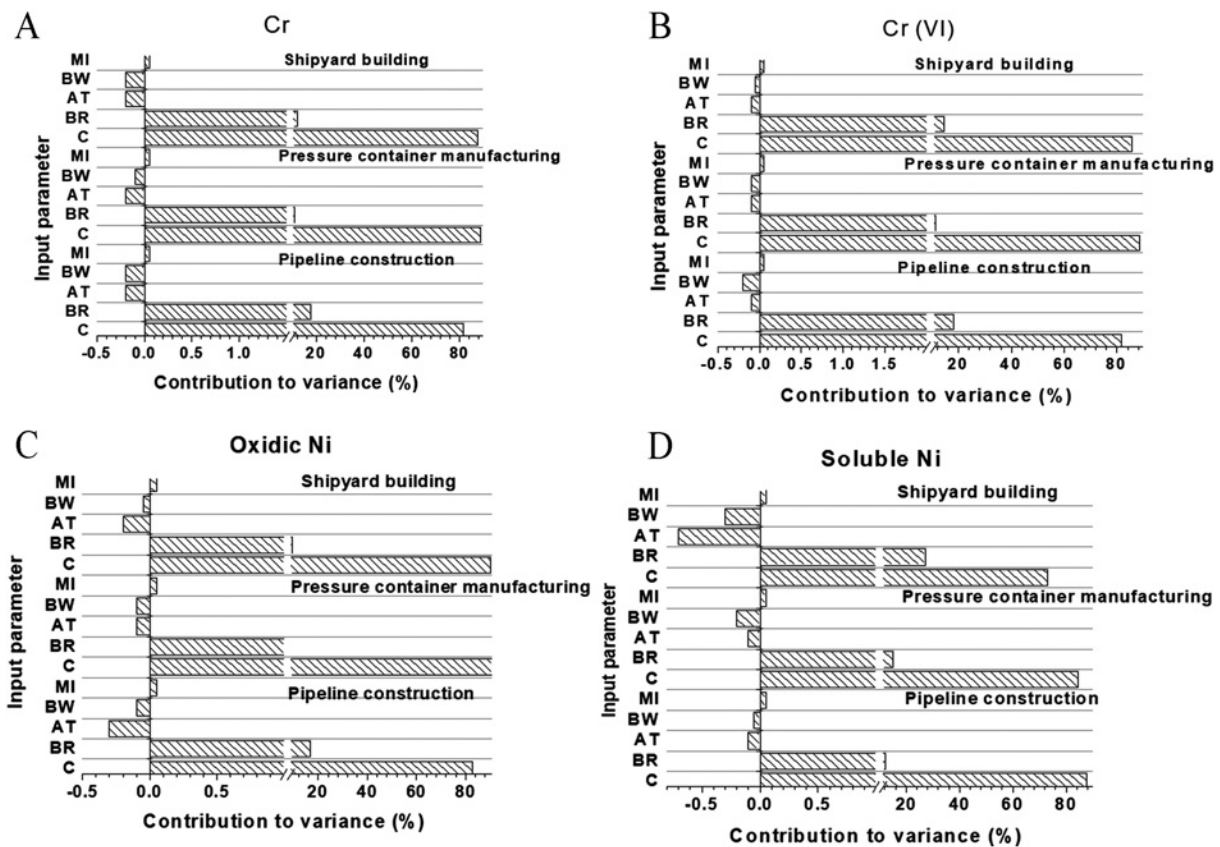


Fig. 1. Input parameters contributing to total variance in chromium (Cr), hexavalent chromium (Cr (VI)), oxidic nickel (Ni), and soluble Ni in three welding exposure groups. Exposure concentration and breathing rate were the dominant contributors to total variance. A: Cr; B: Cr (VI); C: oxidic Ni; D: soluble Ni.

Abbreviations: C: exposure concentration; BR: breathing rate; AT: life expectancy; BW: body weight; MI: miscellaneous.

Table 5. Multiple regression analysis of Cr (VI), oxidic Ni, and soluble Ni concentrations corresponding to significant independent variables

Dependent variable	Independent variables	β	SE	<i>p</i> -value	R ²
Cr VI concentration ⁽¹⁾	Intercept	-0.508	0.086	<0.05	0.96; 0.93 (adjusted)
	χ_1 (filler of SMAW-SS) ⁽⁴⁾	0.239	0.007	<0.05	
	χ_2 (filler of GTAW-SS) ⁽⁵⁾	0.101	0.013	<0.05	
Oxidic Ni concentration ⁽²⁾	Intercept	-1.247	0.095	<0.05	0.95; 0.90 (adjusted)
	χ_1 (filler of SMAW-SS)	0.293	0.011	<0.05	
	χ_2 (filler of GTAW-SS)	0.542	0.030	<0.05	
Soluble Ni concentration ⁽³⁾	Intercept	-1.047	0.095	<0.05	0.95; 0.90 (adjusted)
	χ_1 (filler of SMAW-SS) ⁽⁶⁾	0.103	0.017	<0.05	
	χ_3 (base metal of SS)	0.285	0.013	<0.05	

(1) $\text{Log (Cr (VI) concentration, } \mu\text{g/m}^3) = -0.508 + 0.239 \chi_1 + 0.101 \chi_2$

(2) $\text{Log (oxidic Ni concentration, } \mu\text{g/m}^3) = -1.247 + 0.293 \chi_1 + 0.542 \chi_2$

(3) $\text{Log (soluble Ni concentration, } \mu\text{g/m}^3) = -1.047 + 0.103 \chi_1 + 0.285 \chi_3$

(4) The percentage of Cr or Ni content in the filler welding on stainless steel (SS) with the SMAW method.

(5) The percentage of Cr or Ni content in the filler welding on stainless steel (SS) with the GTAW method.

(6) The percentage of Cr or Ni content in stainless steel (SS) base metal.

Abbreviations: Cr: chromium; Ni: nickel; SE: standard error; R²: R-squared value.

Discussion

The risks of exposure to Cr and Cr (VI) in the welding fumes generated by pipeline construction, pressure container manufacturing, and shipyard building were over the acceptable level of risks in occupational exposure (10^{-3}), which is equivalent to 1.3 excess cases per 100,000 person-years. The risk of exposure to oxidic Ni and soluble Ni in welding fumes in pipeline construction also exceeded 10^{-3} . A similar risk was found in a gas and oil factory in Iran, where the risks for Cr (VI) and Ni exceeded 10^{-2} for project welders and exceeded 10^{-3} for maintenance welders³⁶.

Welding is a common working task in industrialized countries. Studies have estimated that approximately 1% of workers engage in welding³⁷. In 2016, the workforce in Taiwan was around 11.7 million³⁸, and the number of welders was estimated to be 117,000. Using the ILCR assessment, the excess cases of cancer for pipeline construction, pressure container manufacturing and shipyard building would be 1892.0, 17.5, and 1.6 per 100,000 person-years, respectively. The incidence rate of cancer in Taiwan is 520.12 per 100,000 person-years for males³⁹.

Concentrations of Cr and Ni are sensitive parameters in risk modeling. Concentrations of Cr and Ni in welding fumes vary with welding methods, base metals, and filler materials. In this study, about 75% of the welding in pipeline construction employed SMAW on stainless steel, and 70% of the welding in pressure container manufacturing employed GTAW on stainless steel. Approximately 80% of welding in shipyard building employed SMAW on carbon steel.

The three welding tasks resulted in different profiles of exposure to Cr (VI) and Ni. The concentrations of Cr (VI) and Ni in the different groups in decreasing order are pipeline construction, pressure container manufacturing, and shipyard building. A recent study showed that 90%-95% of fumes are generated from the filler metal and flux coating/core of consumable electrodes^{22,40}. Only small amounts of fumes are formed from the base metal, because the base metal weld pool is much cooler than the electrode tip²². Our study shows that the concentrations of Cr (VI), oxidic Ni, and soluble Ni correspond to the Cr and Ni contents of the fillers used in different welding methods (χ_1 with SMAW and χ_2 with GTAW), and the Cr and Ni contents in the base metal of stainless steel (χ_3). Thus, the statistically significant determinants are the filler materials (χ_1 and χ_2) and the base metal of stainless steel (χ_3). Stainless steel is the only base metal that is a significant determinant, possibly because stainless steel is composed of 16%-18% Cr and 10%-14% Ni. Carbon steel is composed of only 0.04% Cr and 0.04% Ni (Supplementary Table 1). Ranking welding methods by the amount of fumes formed in decreasing order resulted in the following sequence: flux cored arc welding (FCAW), SMAW, GMAW, and GTAW²². Alkali metals, such as sodium and potassium present in the SMAW electrode, stabilize the formation of Cr (VI).

To reduce the exposure to Cr and Ni in welding fumes, source control is a fundamental solution. Designed according to a systematic plan for the work process, work pieces are first sorted and then welded by a robot in an enclosed space^{37,41}. To minimize fume emission, selection of welding processes should consider fume generation rates. For example, the GTAW method has the lowest

fume generation rate^{37,41}). For the SMAW method, parameters such as welding voltage, current, and speed should be optimized to reduce fume emission³⁷. The use of stable welding fillers to reduce Cr (VI) generation has been previously reported⁴². The use of local exhaust equipment with extended and movable tubes to efficiently capture fumes in accordance with the welding operation, in addition to the use of on-gun extraction, which is compatible with weld fume exhaust systems and welding machines, has also been reported⁴³.

Employers are responsible for conducting working environment measurement regularly or on important occasions such as when the working process, materials, or equipment are changed, which might increase the risks of exposure to hazardous substances⁴⁴. Further, exposure levels of hazardous substances should be below the permissible exposure limits (PELs)⁴⁵. Appropriate sampling strategies are required to execute working environment measurements. Several studies have reported sampling strategies appropriate for measurement of the work environment⁴⁶⁻⁴⁸.

If engineering controls cannot adequately reduce exposure levels, employers must provide respiratory protection equipment (respirators), which should be worn by employees when necessary to protect their health⁴⁹. Employers must also establish and implement a respiratory protection program comprising worksite-specific procedures, respirator selection, employee training, fit testing, etc.^{49,50}. Employee training should include instructions regarding respirator use, maintenance, cleaning, and storage^{49,51}. Welding fumes contain particulates that can only be trapped using particulate filters. Determining the maximum concentration of a hazardous substance at which a respirator can be used is necessary. In Taiwan, the PEL for Cr (VI) is 50 µg/m³⁴⁵, and pipeline construction welders may be exposed to Cr (VI) levels as high as 800 µg/m³ during welding. Therefore, the respiratory protection equipment selected should be such that it has an assigned protection factor (APF) of >16; for example, a full face-piece air-purifying respirator with an APF of 50^{49,51}.

Conclusions

The risks of exposure to Cr and Ni in welding fumes were high for the three exposure groups. Our results imply that cancer risks from exposure to Cr and Ni in welding fumes are comparable in different exposure groups because welding performance affected the formation of fumes. The most sensitive parameters in risk modeling were the concentrations of Cr and Ni. Multiple regression analysis showed that the determinants of Cr and Ni concentrations were the filler materials in SMAW and GTAW and base metal materials, particularly stainless steel. Thus, the management of risk through engineering controls and/or respiratory protection should account for

the characteristics of welding methods, fillers, and base metals.

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