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Exposure Pathway Assessment at a Copper–Beryllium Alloy Facility

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Controlling beryllium inhalation exposures to comply with regulatory levels (2 μg m^{-3} of air) does not appear to prevent beryllium sensitization and chronic beryllium disease (CBD). Additionally, it has proven difficult to establish a clear inhalation exposure–response relationship for beryllium sensitization and CBD. Thus, skin may be an important route of exposure that leads to beryllium sensitization. A 2000 survey had identified prevalence of sensitization (7%) and CBD (4%) in a beryllium alloy facility. An improved particulate migration control program, including dermal protection in production areas, was completed in 2002 at the facility. The purpose of this study was to evaluate levels of beryllium in workplace air, on work surfaces, on cotton gloves worn by employees over nitrile gloves, and on necks and faces of employees subsequent to implementation of the program. Over a 6 day period, we collected general area air samples (n = 10), wipes from routinely handled work surfaces (n = 252), thin cotton glove samples (n = 113) worn by employees, and neck wipes (n = 109) and face wipes (n = 109) from the same employees. In production, production support and office areas geometric mean (GM) levels of beryllium were 0.95, 0.59 and 0.05 μg per 100 cm^2 on work surfaces; 42.8, 73.8 and 0.07 μg per sample on cotton gloves; 0.07, 0.09 and 0.003 μg on necks; and 0.07, 0.12 and 0.003 μg on faces, respectively. Correlations were strong between beryllium in air and on work surfaces (r = 0.79), and between beryllium on cotton gloves and on work surfaces (0.86), necks (0.87) and faces (0.86). This study demonstrates that, even with the implementation of control measures to reduce skin contact with beryllium as part of a comprehensive workplace protection program, measurable levels of beryllium continue to reach the skin of workers in production and production support areas. Based on our current understanding of the multiple exposure pathways that may lead to sensitization, we support prudent control practices such as use of protective gloves to minimize skin exposure to beryllium salts and fine particles.

Keywords: beryllium sensitization; chronic beryllium disease; dermal exposure; exposure methods; particle migration

INTRODUCTION

Workers exposed to beryllium may become sensitized to beryllium (Kreiss *et al*., 1996, 1997; Eisenbud, 1998; Henneberger *et al*., 2001; Schuler *et al*., 2005). Sensitization precedes the development of chronic beryllium disease (CBD) (Newman *et al*., 2005), a respiratory disorder characterized by the formation of inflammatory structures known as granulomas (i.e. compactly grouped cells that replace normally functioning tissue). Despite reductions in airborne beryllium concentration levels to below the mandated US Occupational Safety and Health Administration's permissible exposure limit (PEL) of 2 μg m^{-3} (averaged over an 8 h period), sensitization continues to be observed among exposed workers (Eisenbud, 1998; Henneberger *et al*., 2001; Schuler *et al*., 2005). The lack of a clear inhalation exposure–response relationship suggests that other routes of exposure, such as the skin, may be important

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to the development of beryllium sensitization (Day *et al*., 2006).

The possible contribution of skin exposure to beryllium sensitization has been recognized for >50 years. Curtis (1951) reported that soluble salts such as beryllium fluoride and beryllium sulfate, contained in dust that settled onto exposed surfaces of workers' skin, including the face, neck and upper extremities, were quickly dissolved by sweat, resulting in dermatitis, ostensibly caused by ionic beryllium. Skin application of beryllium salts to previously unexposed subjects could induce beryllium sensitization (Curtis, 1951). Studies indicate that relatively insoluble particles $\leq$1 μm in diameter may be transported through the skin and around hair follicles (Tan *et al*., 1996; Roed *et al*., 1998; Vollmair *et al*., 1998; Tinkle *et al*., 2003). In one animal study (Tinkle *et al*., 2003), topical application of insoluble beryllium oxide particles was sufficient to cause beryllium sensitization, which was demonstrated when the same animals were subsequently challenged by dermal exposure to a soluble beryllium salt (i.e. ear swelling) and by proliferation of harvested lymph node cells.

A comprehensive source–receptor model has been developed by Schneider *et al*. (1999) to describe the multiple compartments (source, air, surfaces, clothing and skin) and the mass transport processes (emission, deposition, resuspension/evaporation, transfer, removal, redistribution, decontamination and penetration/permeation) that may contribute to exposures of the skin. Systematic application of this model in the rubber manufacturing industry (Vermeulen *et al*., 2000) demonstrated the importance of the transfer and redistribution of contaminants from multiple compartments to various anatomical regions of the skin. Figure 1 illustrates our simplified adaptation of the Schneider *et al*. model (1999) to describe how total beryllium exposures may occur. (Unlike Schneider *et al*. (1999), our simplified model did not consider the potential contribution to exposure resulting from penetration of particles through the clothing compartment.) Sources (i.e. production processes or maintenance activities) generate airborne beryllium-containing particles, some of which may be removed by ventilation systems, some of which may settle onto surfaces and a smaller fraction that may be inhaled. Contaminated surfaces include equipment, tools, floors and stairs, work clothing and areas of exposed skin. Particles resuspended from surfaces may be removed by ventilation systems, may settle onto other surfaces or may be inhaled. Settled particles may also be transferred to clothing or hands through direct contact with contaminated surfaces. Particles transferred to the hands or clothing may then be redistributed to other areas of the skin, including the neck and face.

Given that there are no published studies regarding dermal exposure to beryllium in the workplace, the objectives of this study at a copper–beryllium alloy facility were to (i) measure the mass concentrations of beryllium in air and on work surfaces, (ii) estimate the mass of beryllium transferred from contaminated work surfaces to workers' cotton over-gloves, (iii) estimate the redistribution of beryllium from workers' cotton gloves to necks and faces and (iv) evaluate the relationships among measured levels of beryllium in air and on work surfaces, cotton gloves, and necks and faces.

MATERIALS AND METHODS

The facility

The study was performed at a beryllium alloy strip and wire finishing facility located in Eastern

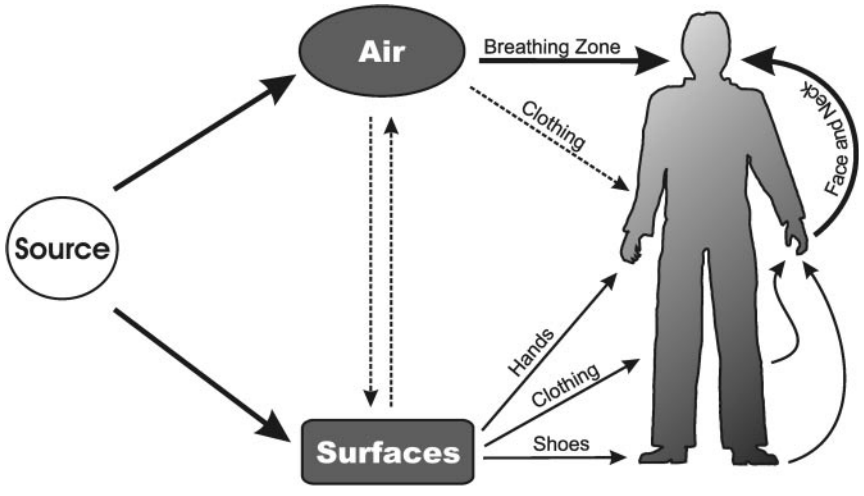

Fig. 1. Beryllium exposure-pathway model.

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United States in June 2003. Input materials at this facility primarily consisted of semi-finished copper–beryllium alloy strip and wire, the beryllium content of which varied from 0.15 to 2% by weight. We selected this facility because (i) most historical airborne concentrations of beryllium were below the PEL and (ii) prevalences of sensitization (7%) and CBD (4%) (Schuler *et al*., 2005) were comparable with those found in other facilities associated with higher average airborne beryllium exposures, including a primary beryllium production facility (Kreiss *et al*., 1997) and a beryllium oxide ceramics facility (Kreiss *et al*., 1996; Henneberger *et al*., 2001).

At the time of this study, the facility employed approximately 125 workers and ran three 8 h shifts, 5 days per week. Workers were protected by a comprehensive preventive program improved during 2000 and 2001 in response to medical surveillance findings (Schuler *et al*., 2005). The preventive program included improvements to existing ventilation and beryllium migration control strategies using integrated isolation, engineering and administrative controls, and the use of personal protective equipment (PPE), especially in work areas associated with elevated risk of beryllium sensitization. All workers wore occlusive single-use, disposable nitrile gloves and company-supplied long sleeve work clothing to minimize direct skin contact with beryllium-contaminated surfaces and materials; respirators with high-efficiency particulate air (HEPA) filters were worn when inhalation exposures were likely to exceed 0.2 $\mu g\ m^{-3}$ (8 h time-weighted average) and during the performance of designated tasks.

Characterization of work processes

Work was divided into three main categories: (i) production, (ii) production support and (iii) administration. Production was further sub-divided into (a) strip and (b) rod and wire processes. Work areas in strip production included annealing, inspection, pickling, rolling, slitting, and shipping and receiving. Work areas in rod and wire production included die grinding, point and chamfer, rod straightening, wire drawing, and wire annealing and pickling. Work in production support included maintenance (mechanics), quality assurance (metallurgical laboratory) and waste treatment. Work performed by production support required frequent entry into production areas. Administration was limited to the front office area and included human resources and accounting. Administrative work rarely required entry into production areas.

Similar exposure groups

A similar exposure group (SEG) is defined as a group of workers likely to have the same general exposure profile because of the tasks they perform, the similarity of the way tasks are performed, and the materials and processes with which they work (Mulhausen and Damiano, 1998). Table 1 describes the SEGs to which we assigned workers within this facility, potential beryllium exposure pathways and brief summaries of historical and current work practices. Note that prior to 2000, glove use was limited to wearing leather, cotton or other gloves as appropriate to protect against cuts, abrasions, solvents, acid-base and thermal injury. At the time of our study, work practices required the use of nitrile gloves to protect skin from beryllium exposure when working in production areas; outer gloves (e.g. leather or cotton) continued to be worn for protection against physical and chemical hazards.

Industrial hygiene sampling

All samples were collected over a period of six working days (3 days per week over 2 weeks). Four types of samples were collected as estimators of beryllium exposure: (i) filter cassettes from general workplace air, (ii) wipes from work surfaces handled or touched during routine work activities, (iii) cotton over-gloves worn by workers as part of this study (a relative index of historical exposure) and (iv) wipes from the skin of workers' necks and faces. The study protocol was reviewed and approved by the Human Subjects Review Board of the National Institute for Occupational Safety and Health (NIOSH), and written informed consent was obtained from each study participant.

General area air samples

General area air samples for beryllium and copper were collected near nine specific production processes throughout the facility and in one administrative area (front office). Seven of the nine production air samples were taken near strip production processes (annealing I and II, rolling mills I and II, pickling, slitting, shipping and receiving) and the remaining two were taken near rod and wire production processes (rod straightening, wire annealing and pickling). Air samples were not taken in production support areas.

General area air samples were collected continuously (i.e. 24 h per day for 3 days per week over 2 weeks) using stationary 37 mm cassette (total-dust) samplers loaded with mixed cellulose ester filters. Pumps were calibrated prior to sampling to approximately 15 $l\ min^{-1}$ using a bubble meter (Gillibrator, Gillian, Clearwater, FL). Flow rates were verified and recorded at least once per day and at the conclusion of the sampling period. The long sampling duration and high flow rate were necessary to ensure that sufficient quantities of beryllium-containing dust were collected to meet the analytical limit of detection (LOD) for beryllium (0.004 μg) and copper

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Table 1. Similar exposure groups and personal protective practices used to classify workers in this dermal exposure assessment study at a beryllium alloy facility

Similar exposure groups	Potential beryllium exposure pathways	Historical dermal protection work practice	Current dermal protection work practice
Administrative	Skin and clothing contact with beryllium carried from production areas into office areas	No use of gloves or other protective clothing	No use of gloves or other protective clothing while in office areas
	Inhalation of beryllium resuspended from contaminated surfaces in office areas		Nitrile gloves, lab coats, and shoe covers worn while in production areas
	Inhalation of beryllium released from production areas		
Production	Skin and clothing contact with beryllium during production	Leather, cotton, or other work gloves worn in some circumstances to protect against cuts, abrasions, chemicals, and thermal injuries	Nitrile gloves and company-issued long-sleeved clothing worn during time spent in production areas
	Inhalation of beryllium released from processes	Company-issued work clothing with and without long sleeves	Leather, cotton, or other work gloves worn over nitrile gloves as needed to protect against cuts, abrasions, chemicals and thermal injuries
	Inhalation of beryllium resuspended from contaminated surfaces		Powered air-purifying respirators and additional protective clothing worn when performing work in designated areas
Production support	Skin and clothing contact with beryllium during time spent in the production areas	Leather, cotton, or other work gloves worn in some circumstances to protect against cuts, abrasions, chemicals, and thermal injuries	Nitrile gloves and company-issued long-sleeved clothing worn during time spent in production areas
	Inhalation of released or resuspended beryllium during time spent in production areas	Company-issued work clothing with and without long sleeves	Leather, cotton, or other work gloves worn over nitrile gloves as needed to protect against cuts, abrasions, chemicals and thermal injuries
			Powered air-purifying respirators and additional protective clothing worn when performing work in designated areas

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(0.1 μg) on air filter media. Samples were digested and analyzed using NIOSH Analytical Method 7300: Elements by Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) (NIOSH, 2003a). Neither beryllium nor copper was detected on submitted field and laboratory quality control samples. Results were normalized to the average volume of air sampled based on pre-calibration and post-calibration of air flow rates and were expressed as airborne mass concentrations of beryllium and copper (μg m^{-3}). To evaluate the relative proportion of beryllium in the dust sampled throughout the facility, we calculated the ratio of the masses of beryllium to the sums of the masses of beryllium and copper (referred to as the Be content, expressed as percentage) for all sample types. Values of this ratio were compared with the percentage beryllium in handled semi-finished strip and wire input materials (i.e. 0.15–2%) to investigate the composition of particles generated during diverse work processes.

Surface wipe samples

Twelve surfaces likely to be contacted by workers on a daily basis were selected for wipe sampling within each of 21 separate work areas (N = 252). Specific examples of wiped surfaces included process equipment, tools, bench tops and control panels. Samples were collected in a manner consistent with NIOSH Method 9102 (NIOSH, 2003b). Briefly, donning a pair of clean nitrile gloves, the surveyor used a disposable template to delineate an area equal to 100 cm^2 and wiped by applying firm pressure to the delineated surface in an overlapping s-shaped pattern with a Ghost Wipe™ (Environmental Express, Mt Pleasant, SC). The exposed side of the wipe was folded inward and the area inside the template wiped again. The exposed side of the wipe was again folded inward and the area inside the template wiped a third time. Professional judgment was used, when necessary, to estimate an area equivalent to 100 cm^2, such as when sampling from irregular-shaped surfaces (e.g. tools). Wipe samples were primarily collected by a single surveyor during week 1 and by another during week 2 of the study. Each wipe sample was placed into an individually labeled and sealed plastic bag. Samples were analyzed in a single, sequential batch using NIOSH Analytical Method 7300; the LOD was 0.005 μg for beryllium and 1 μg for copper collected on Ghost Wipes™. Results were expressed as the area mass concentrations of beryllium and copper (μg per 100 cm^2) and the percentage Be was calculated.

Cotton glove samples

The method used to estimate the levels of beryllium on the hands of workers involved the analysis of the thin cotton gloves worn by the workers, rather than directly wiping the skin, and was similar to methods used by Ness (1994) and Linnainmaa and Kiilunen (1997). Cotton gloves (Lisle 3301, Johnson Wilshire Inc., Downey, CA), commonly used for inspection of fine parts, were worn by at least one employee from each of the 21 surface wipe-sampled work areas to provide an index of relative historical beryllium mass hand exposures (i.e. before the required use of nitrile gloves in production areas). Of the 27 participating employees, 16 only worked production, four only worked production support, one worked either production or production support as dictated by changing schedules and six only worked administration.

At the beginning of each of the six work shifts, employees donned a clean pair of thin cotton gloves, affixed at the wrist by a strip of medical tape to ensure that they remained on the hands for the duration of the sampling period, typically the first 2 h of each shift. Employees in production and production support wore the thin cotton gloves over nitrile gloves; administrative employees wore thin cotton gloves only. At the end of each sampling period (typically at the beginning of a break period), gloves were collected and placed into individually labeled and sealed plastic bags (one per hand). NIOSH Method 7300 was modified to digest and analyze cotton glove samples, providing an LOD of 0.0069 μg for beryllium and 0.084 μg for copper. Note that this modified NIOSH 7300 method uses large quantities of acid (40–60 ml nitric, 5 ml perchloric) to ensure complete digestion of the cotton glove and metallic oxides (Stefaniak *et al*., 2005). Results were expressed as the total masses of beryllium and copper (μg) per glove. Percentage Be was also calculated.

For each employee, the results for each glove (i.e. left and right hand) were added together to arrive at a total mass. Note that on a few occasions, the initial pair of cotton gloves was removed owing to unscheduled interruptions and replaced by a clean pair. For these cases in which two pairs of gloves were worn for the 2 h sampling period, results from the four individual gloves were added together to determine the total masses of beryllium and copper. Results were expressed as total masses of beryllium and copper/sample (μg) and percentage Be was calculated.

Skin wipe samples

At the end of the shift, wipe samples were collected from the skin of the same employees' necks and faces who wore cotton gloves regardless of the use of respiratory protection. After first donning a clean pair of nitrile gloves, each employee wiped his or her own neck for the area delimited from ear to ear and under the chin down to the top of the Adam's apple sequentially with each of two Ghost Wipes™ for ∼1 min. Both wet wipes were placed into the same individually labeled plastic bag and sealed. Each employee then replaced his or her gloves with another clean

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pair of nitrile gloves and wiped his or her own face (nose/perinasal area) with two Ghost Wipes™ for no more than 1 min. These wipes were placed into another individual plastic bag and sealed. All samples were digested and analyzed using NIOSH Analytical Method 7300. LODs were the same as for surface wipes (0.005 μg for beryllium and 1 μg for copper). Because no attempt was made to control for inherent variability associated with employees wiping their own skin, results were expressed as total masses of beryllium and copper/sample (μg). Percentage Be was also calculated.

Quality assurance and statistical analysis

Field and laboratory blanks were each submitted at a proportion of approximately one per every 15–20 samples for each sample type. Analytical results specified not only the LOD but also the limit of quantification (LOQ, typically 3.3 times the LOD and considered to be the lowest value that the laboratory could confidently report for the matrix of interest). Results between the LOD and LOQ (one of 252 surface wipes; 16 of 218 neck and face wipes) were assigned the actual reported value. Based on recommendations for handling data sets with geometric standard deviations (GSDs) greater than three (Hornung and Reed, 1990), results below the LOD (1 of 113 cotton glove samples; 17 of 218 skin wipes) were assigned a value equal to one-half the LOD.

With respect to air and surface wipe measurements, the basic sampling unit was a single work area. For cotton glove, and neck and face wipe measurements, the basic sampling unit was an individual worker within a work area. The correlation between air and surface measurements was calculated by matching the one air measurement to 12 surface measurements in each work area. To calculate correlations for glove, neck and face measurements, sample means were calculated for each worker, resulting in 31 sets of means (of the 27 participants, four worked in different work areas on different days). The correlations between cotton glove, neck or face measurements and surface wipe measurements were calculated by matching glove, neck or face means to surface wipe means in each work area. In the case of multiple workers within the same work area, the correlations were calculated by matching the mean measurement on each worker's cotton glove, neck or face to the mean of surface wipe measurements.

To describe the central tendency and variability of the glove, neck and face measurements, we estimated within-worker and between-worker geometric means (GMs) and GSDs. Estimates of the variance components and the resulting GSDs were calculated using the method of restricted maximum-likelihood (Robinson, 1987). Estimates of the between-worker GSDs provide indications of exposure variability among workers in identical or similar work areas. To evaluate the relationships among the various sample types, we calculated Pearson correlations. Using Levene's test (Milliken and Johnson, 1984), we rejected the hypothesis ($P < 0.01$) that the variances for the log-transformed surface wipe measurements were equal among the various work areas throughout the facility; therefore, correlations involving these measurements were calculated using weighted least-squares. SEGs were examined using analysis of variance and the Bonferroni method was used to make multiple comparisons among exposure groups (Milliken and Johnson, 1984). All statistical analyses were performed using SAS software (SAS Institute, 2004).

RESULTS

General area air samples

Results for all general area air samples are summarized in Table 2. The GM beryllium concentration among all general area air samples collected over the 144 h period was 0.003 μg m^{-3} (GSD = 3.4) and ranged from 0.0007 μg m^{-3} (administration) to 0.02 μg m^{-3} (wire annealing and pickling). Percentage Be for all general area air samples are summarized in Table 3. The GM Be content was 3.1% and ranged from 1.2 (slitting) to 19.7% (wire annealing and pickling).

Surface wipe samples

Results for all surface wipe samples are summarized in Table 4. There was considerable variability in the GM beryllium surface concentrations within production and production support categories. For example, GSDs were 6.0 in the wire drawing work

Table 2. Beryllium concentration results for general area air samples by work area[a]

Similar exposure group	Work area	μg beryllium/m^3
Administration	Front offices	0.0007
Strip production	Annealing—I	0.0009
	Annealing—II	0.0014
	Pickling	0.0159
	Rolling—I	0.0013
	Rolling—II	0.0030
	Shipping & receiving	0.0010
	Slitting	0.0061
Rod & wire production	Rod straightening	0.0021
	Wire annealing & pickling	0.0238

[a]Determined by sampling 24 h per day for 3 days per week at 15 l min^{-1} over the 2 week period of the study.

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Table 3. Be content of air, surface wipe, cotton glove, and neck and face wipe samples by work area

Similar exposure group	Work area	Be content[a]				
		Air	Surfaces	Cotton gloves	Necks	Faces
Administration	Front offices	8.0[b]	0.91	0.29	*	*
Production support	Maintenance mechanics	**	1.1	2.9	0.63	0.74
	Metallurgical laboratory	**	1.4	4.7	0.75	0.78
	Waste treatment	**	2.5	2.3	1.6	1.6
Strip production	Annealing—I	1.8	1.1	0.77	0.22	0.10
	Annealing—II	3.1	1.9	1.2	0.91	0.95
	Annealing—III	**	3.4	2.8	0.64	0.93
	Annealing—IV	**	2.2	1.2	0.66	0.94
	Inspection	**	1.6	1.4	0.46	0.34
	Pickling	1.3	3.3	1.6	1.2	1.0
	Rolling—I	2.4	1.2	1.2	0.39	0.24
	Rolling—II	3.3	1.8	1.6	0.77	0.81
	Rolling—III	**	1.5	1.5	0.13	0.08
	Rolling—IV	**	1.8	1.5	0.54	0.50
	Shipping & receiving	2.1	1.2	1.2	0.49	0.34
	Slitting	1.2	1.5	1.2	0.65	0.83
Rod & wire production	Die grinding	**	2.1	1.3	0.69	0.45
	Point & chamfer	**	2.1	1.7	0.77	0.73
	Rod straightening	3.3	1.7	3.5	1.4	1.4
	Wire annealing & pickling	19.7	11.6	10.1	0.90	0.81
	Wire drawing	**	1.7	2.1	0.93	1.2

[a]Be content has units of percentage and is the product of the mass of beryllium divided by the combined masses of beryllium and copper, multiplied by 100.
[b]Analytical results for beryllium and copper in the air sample collected from the front offices work area approached the limits of quantification for each element, thus precluding accurate calculation of the Be content in air for the administration similar exposure group.
*Analytical results for beryllium below limits of detection, precluding calculation of the Be content.
**No sample taken.

area and 7.8 in the maintenance mechanic category. The GM beryllium concentration was 0.77 μg per 100 cm^2 and ranged from 0.05 μg per 100 cm^2 in administration to 13.6 μg per 100 cm^2 in wire annealing and pickling. GM concentrations of beryllium on work surfaces were highest in production areas (0.95 μg per 100 cm^2), lower in production support areas (0.59 μg per 100 cm^2) and lowest in administrative office areas (0.05 μg per 100 cm^2). The GM beryllium concentration on work surfaces in rod and wire production (1.99 μg per 100 cm^2) was roughly a factor of three higher than in strip production (0.70 μg per 100 cm^2). Note that about one-third of the combined beryllium mass among all surface wipe samples (752 μg) was represented by the 12 samples collected from the wire annealing and pickling work area. The GM Be content (Table 3) among all surface wipe samples was 1.9%, and ranged from 0.91% (administration) to 11.6% (wire annealing and pickling).

Cotton glove samples

Results of the masses of beryllium collected on cotton glove samples are summarized in Table 5. Variability in surface contamination levels was reflected in the variability of beryllium mass on cotton gloves. For example, the GM beryllium mass on the glove samples of rod and wire production employees (196.5 μg) was a factor of roughly nine higher than strip production employees (22.3 μg). The grand GM beryllium mass on cotton glove samples was 13.4 μg and ranged from 0.007 μg for a worker in administration to 2534 μg for a worker in rod straightening. GM beryllium masses were, on average, highest among production support employees (73.8 μg), lower among production employees (42.8 μg) and lowest among administrative office employees (0.07 μg). The estimated pooled within-worker GSD was 2.5. The GM Be content (Table 3) among all cotton glove samples was 1.7% and ranged from 0.29% (administration) to 10.1% (wire annealing and pickling).

Skin wipe samples

Results for the masses of beryllium collected on all skin wipe samples are summarized in Tables 6 and 7. The grand GM beryllium mass on neck wipe samples was 0.04 μg and ranged from less than LOD in administration to 0.58 μg for a worker in rod straightening.

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Table 4. Beryllium concentration results for surface wipe samples by work area

Similar exposure group	Category or work area	µg beryllium per 100 cm^2	
		n	GM (GSD)[a]
Administration	Front offices	12	0.05 (2.7)
Production support	Maintenance mechanics	12	0.55 (7.8)
	Metallurgical laboratory	12	0.54 (4.4)
	Waste treatment	12	0.67 (4.3)
Strip production	Annealing—I	12	0.14 (2.3)
	Annealing—II	12	1.05 (2.9)
	Annealing—III	12	0.96 (3.0)
	Annealing—IV	12	1.07 (2.5)
	Inspection	12	1.08 (4.1)
	Pickling	12	2.20 (3.8)
	Rolling—I	12	0.57 (4.0)
	Rolling—II	12	0.85 (5.4)
	Rolling—III	12	0.42 (2.3)
	Rolling—IV	12	0.67 (2.3)
	Shipping & receiving	12	0.12 (2.5)
	Slitting	12	2.24 (2.1)
Rod & wire production	Die grinding	12	0.51 (3.8)
	Point & chamfer	12	2.15 (2.3)
	Rod straightening	12	2.59 (4.3)
	Wire annealing & pickling	12	13.60 (2.6)
	Wire drawing	12	0.81 (6.0)

[a]GM is the geometric mean; GSD (in parentheses) is geometric standard deviation.

Similarly, the grand GM of the face wipe samples was 0.04 µg and ranged from less than LOD in administration to 1.44 µg for a worker in rod straightening. GM beryllium masses from skin wipe samples were, on average, highest among production support employees (0.09 µg neck; 0.12 µg face), lower among production employees (0.07 µg neck; 0.07 µg face) and lowest among administrative office employees (0.003 µg neck; 0.003 µg face). GM beryllium masses from the neck and face wipes of rod and wire production employees (0.14 µg necks; 0.13 µg faces) appeared higher than wipes from the necks and faces of strip production employees (0.06 µg necks; 0.05 µg faces). The estimated pooled within-worker GSDs for neck and face measurements were 2.1 and 2.3, respectively. The GM Be content (Table 3) among all neck wipe samples was 0.57% and ranged from 0.04% (administration) to 1.6% (waste treatment). The GM Be content among all face wipe samples was 0.52% and ranged from 0.05% (administration) to 1.6% (waste treatment). Caution should be taken regarding the reliability of the calculated percentage Be for the neck and face samples as ~15% of the measurements were less than the LOQ.

Relationships among air, surface wipe, cotton glove and skin wipe samples

Figure 2 illustrates relationships (i.e. Pearson correlations) among the various sample types corresponding to the exposure pathway model. A strong correlation ($r = 0.79$, $P < 0.01$) was observed between concentrations of beryllium in general area air and on work surfaces (Fig. 2a). Similarly, a strong correlation ($r = 0.86$, $P < 0.01$) was observed between concentrations of beryllium on work surfaces and masses of beryllium on cotton gloves (Fig. 2b). As shown in Figures 2c and d, strong correlations were also observed between masses of beryllium on cotton gloves and necks ($r = 0.87$, $P < 0.01$) and masses of beryllium on cotton gloves and faces ($r = 0.86$, $P < 0.01$). Table 8 summarizes the statistical correlations among all sample types using data from all exposure groups.

Because the very low measurements from administrative areas could have been relatively influential in determining correlations, we temporarily excluded those measurements and reassessed the relationships among the various sample types in order to determine the strength of the correlation for the data from production and production support. Recalculated correlations were very similar for concentrations of beryllium in air and on work surfaces ($r = 0.76$, $P < 0.01$, $n = 108$) but were somewhat lower when concentrations of beryllium on work surfaces were related to masses of beryllium on cotton gloves ($r = 0.62$, $P < 0.01$, $n = 25$). Similarly, more pronounced reductions were also observed in the magnitude of the correlations between masses of beryllium on cotton gloves and necks ($r = 0.54$, $P < 0.01$, $n = 25$), and on cotton gloves and faces ($r = 0.58$, $P < 0.01$, $n = 25$).

Multiple comparisons of the GM concentrations of beryllium on surfaces indicated a significant difference between concentrations in the rod and wire production area and all other categories or work areas (i.e. strip production, production support and administration) ($\alpha = 0.05$). GM masses of beryllium on cotton gloves among rod and wire production workers were significantly different from that among workers in strip production and administration, but not production support. No statistical differences in the GM masses of beryllium on necks and faces were observed among workers in rod and wire production, strip production and production support; however, beryllium on the necks and faces of administrative workers was significantly different from all other similar exposure groups.

DISCUSSION

General area airborne concentration measurements can be considered an approximation of non-task or passerby exposure and are not representative of personal exposure measurements. In this beryllium

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Table 5. Beryllium mass results for cotton glove samples by work area

Similar exposure group	Category or work area	Worker	μg beryllium/sample			
			Within worker		Between worker	
			n	GM[a]	GM	GSD[b]
Administration	Front offices	A	1	0.22	0.07	2.2
		B	1	0.14		
		C	1	0.09		
		D	1	0.09		
		E	1	0.05		
		F	1	0.007		
Production support	Maintenance mechanics	A	3	34.2	73.8	3.0
		B	3	340		
	Metallurgical laboratory	A	3	97.3		
		B	2	122		
	Waste treatment	A	6	15.9		
Strip production	Annealing—I	A	6	4.2	22.3	2.3
	Annealing—II	A	6	38.7		
	Annealing—III	A	2	10.9		
	Annealing—IV	A	2	15.3		
	Inspection	A	6	8.5		
		B	3	41.0		
	Pickling	A	6	20.9		
	Rolling—I	A	6	8.8		
	Rolling—II	A	5	13.8		
		B	1	292		
	Rolling—III	A	6	21.7		
	Rolling—IV	A	6	58.7		
	Shipping & receiving	A	6	12.4		
	Slitting	A	6	67.7		
Rod & wire production	Die grinding	A	5	12.2	196.5	5.3
	Point & chamfer	A	3	223		
	Rod straightening	A	2	392		
		B	3	2534		
	Wire annealing & pickling	A	6	127		
	Wire drawing	A	4	168		

[a]GM is geometric mean.
[b]GSD is geometric standard deviation.

alloy strip and wire finishing facility, general area airborne beryllium concentrations were used as an indirect measure of personal exposure and were at least two orders of magnitude below the current PEL. Although a strong correlation was observed between the concentrations of beryllium in air and the levels of beryllium on necks and faces (Table 8), these very low airborne beryllium concentrations suggest that the air-to-skin exposure may be of less importance in this facility than in more dusty environments (Gudmundsson and Schneider, 1997; Vermeulen *et al*., 2000). The strong correlation observed between concentrations of beryllium in air and on surfaces in this facility emphasizes the potential importance of the air-to-surface or surface-to air migration pathways (Fig. 1). In contrast, Vermeulen *et al*. (2000) observed in the rubber manufacturing industry low to moderate correlations among levels of particulate matter in general workplace air and on surfaces ($r = 0.41$, $P < 0.0001$), in general workplace air and on skin ($r = 0.17$, $P < 0.001$), and on surfaces and skin ($r = 0.22$, $P < 0.001$).

The calculated percentage Be values provide a useful insight into the relationship among work processes and the relative proportion of beryllium in the dust sampled throughout the facility. It is interesting to note from Table 3 that airborne particles collected from the wire annealing and pickling work area, an area isolated from other processes, had the highest Be content (19.7%) among all air samples, representing a 10-fold enrichment of beryllium relative to the mass fraction of beryllium in the

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Table 6. Beryllium mass results for neck wipe samples by work area

Similar exposure group	Category or work area	Worker	μg beryllium per sample			
			Within worker		Between worker	
			n	GM[a]	GM	GSD[b]
Administration	Front offices	A–F	6	≤LOD[c]	0.003	1.0[d]
Production support	Maintenance mechanics	A	3	0.06	0.09	1.5
		B	3	0.05		
	Metallurgical laboratory	A	2	0.09		
		B	2	0.16		
	Waste treatment	A	6	0.17		
Strip production	Annealing—I	A	6	0.02	0.06	2.5
	Annealing—II	A	6	0.09		
	Annealing—III	A	2	0.04		
	Annealing—IV	A	1	0.07		
	Inspection	A	6	0.07		
		B	3	0.03		
	Pickling	A	5	0.32		
	Rolling—I	A	6	0.04		
	Rolling—II	A	5	0.10		
		B	1	0.13		
	Rolling – III	A	5	0.01		
	Rolling – IV	A	6	0.09		
	Shipping & receiving	A	6	0.04		
	Slitting	A	6	0.09		
Rod & wire production	Die grinding	A	5	0.06	0.14	2.3
	Point & chamfer	A	3	0.06		
	Rod straightening	A	2	0.58		
		B	3	0.39		
	Wire annealing & pickling	A	6	0.09		
	Wire drawing	A	4	0.10		

[a]GM is geometric mean.
[b]GSD is geometric standard deviation.
[c]LOD is limit of detection, (0.005 μg beryllium).
[d]The estimated standard deviation for the log-transformed data was exactly zero using restricted maximum-likelihood.

input material (0.15–2%). This enrichment may be an important parameter of exposure. It is well known that beryllium has a stronger affinity for oxygen compared to copper and that beryllium-rich oxides are formed when copper–beryllium is annealed in air. Thus, the enrichment of beryllium in airborne dust can be attributed to dispersion of the enriched oxide layer during mechanical handling and chemical treatment (pickling) of the annealed material. Note that enrichment of beryllium in airborne particles formed by fuming during the production of copper–beryllium alloy ingots has also been reported by Stefaniak *et al*. (2004). As expected, the GM Be content was also highest in the wire annealing and pickling work area among surface wipe (11.6%) and cotton glove samples (10.1%).

According to Fenske (1993), surface sampling can also be considered a first approximation of personal dermal exposure. This observation supports the value of controlling the migration of beryllium-containing particles in the workplace. The wire annealing and pickling area had by far the highest air levels and surface contamination. Within this work area, controls were designed to minimize exposure and migration of contamination to other areas. Engineering controls included isolation from the remainder of the facility, increased ventilation and tacky floor mats. Administrative controls included restricting access, minimizing the number of employees in the area, dedicating tools and equipment to the area and specific protocols for entering and exiting the area. Personnel who performed work in the area were required to wear PPE, including hooded powered-air-purifying respirators equipped with HEPA filters, coveralls, rubber boots, and inner (nitrile) and outer (cotton, acid-resistant or leather) gloves.

As a percentage of the total beryllium mass on all surface wipes, ∼47% was collected from control panels, 18% from tools and 7% from manual crane

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Table 7. Beryllium mass results for face wipe samples by work area

Similar exposure group	Category or work area	Worker	µg beryllium per sample			
			Within worker		Between worker	
			n	GM[a]	GM	GSD[b]
Administration	Front offices	A–F	6	<LOQ[c]	0.003	1.0[d]
Production support	Maintenance mechanics	A	3	0.05	0.12	1.7
		B	3	0.08		
	Metallurgical laboratory	A	2	0.11		
		B	2	0.38		
	Waste treatment	A	6	0.17		
Strip production	Annealing—I	A	6	0.01		
	Annealing—II	A	6	0.08		
	Annealing—III	A	2	0.07		
	Annealing—IV	A	1	0.08		
	Inspection	A	6	0.04		
		B	3	0.02		
	Pickling	A	5	0.29	0.05	3.0
	Rolling—I	A	6	0.04		
	Rolling—II	A	5	0.15		
		B	1	0.10		
	Rolling—III	A	5	0.01		
	Rolling—IV	A	6	0.11		
	Shipping & receiving	A	6	0.03		
	Slitting	A	6	0.19		
Rod & wire production	Die grinding	A	5	0.03	0.13	3.3
	Point & chamfer	A	3	0.07		
	Rod straightening	A	2	0.12		
		B	3	1.44		
	Wire annealing & pickling	A	6	0.10		
	Wire drawing	A	4	0.13		

[a]GM is geometric mean.
[b]GSD is geometric standard deviation.
[c]LOQ is limit of quantification, (0.02 µg beryllium).
[d]The estimated standard deviation for the log-transformed data was exactly zero using restricted maximum-likelihood.

pendants. These surfaces were not only located in wire annealing and pickling but also in most other work areas throughout the facility (data not shown). These observations suggest that efforts to control the migration of surface contamination should not only be limited to good control and work practices within individual work areas but should also mitigate the contribution of migration from the transfer of tools and equipment between work areas.

Settled particles may be transferred to clothing or hands through direct contact with contaminated surfaces. Surface-to-skin transfer involves complex factors including contact pressure and motion, work practices and hygienic behavior (Fenske, 1993). Particles on hands or clothes then become potentially available for redistribution to other areas of the skin, including the neck and face. In this study, we observed strong relationships between the levels of beryllium on cotton gloves and on necks and faces (see Fig. 2). Among the 21 work areas surveyed, levels of beryllium on surfaces and cotton gloves were among the highest in the wire annealing and pickling area, yet levels of beryllium on neck and face wipe samples ranked lower in the same area. This rank reduction is most probably attributable to the use of PPE (i.e. hooded powered-air-purifying respirators covering the neck and face). In this work area, the additional use of outer gloves to protect against cuts, abrasions, chemicals and thermal injury may have contributed to contamination of the thin cotton glove samples. It is possible to contaminate inner gloves by placing the hands into previously contaminated outer gloves. Note that the protective inner glove barrier may be bypassed by placing already-contaminated hands into a clean pair of gloves (e.g. putting on and tying the laces of contaminated shoes before gloving). In these situations, the thickness and condition of the skin (e.g. abraded, diseased, defatted or water-soaked) may be important factors for beryllium dosimetry.

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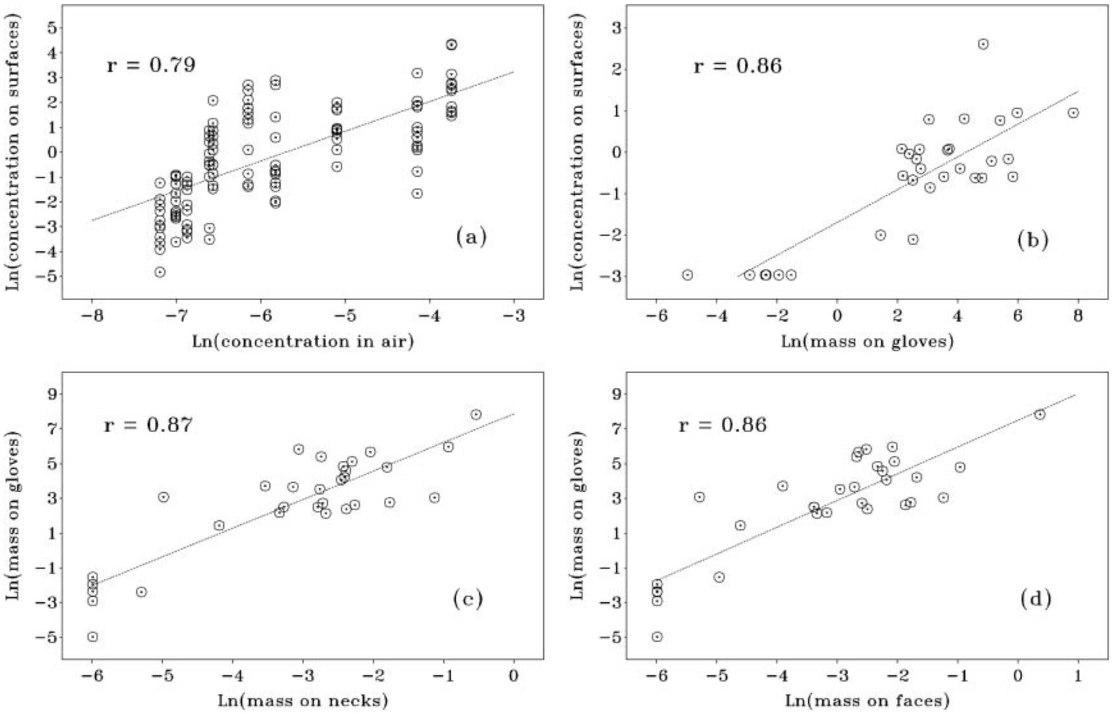

Fig. 2. Comparison plots illustrating the relationships of beryllium levels among (a) surface and air measurements, (b) surface and glove measurements, (c) glove and neck measurements and (d) glove and face measurements.

Table 8. Summary of correlations among sample types

	Face wipes	Neck wipes	Cotton gloves	Surface wipes	General area air
General area air	0.71 (n = 17)	0.71 (n = 17)	0.63 (n = 17)	0.79 (n = 120)	1
Surface wipes	0.83 (n = 31)	0.84 (n = 31)	0.86 (n = 31)	1	
Cotton gloves	0.86 (n = 31)	0.87 (n = 31)	1		
Neck wipes	0.96 (n = 31)	1			
Face wipes	1				

Values are the Pearson correlation coefficients for comparison among sample types for 21 work areas; n = number of observations (in parentheses); all P-values <0.01.

Implications for beryllium epidemiology

Schuler *et al*. (2005) reported elevated risk of beryllium sensitization and CBD among workers who had ever worked in the rod and wire production area. In terms of exposure, our findings are consistent with their results. In both studies, results indicated the highest airborne mass beryllium exposure levels were in the rod and wire production area. Additionally, both studies indicated that within rod and wire production, the highest airborne beryllium concentrations were in the wire annealing and pickling process. Schuler *et al*. (2005) expressed the epidemiological need to classify subjects according to different exposure types and intensities that may be unrealized with mass-based air sampling measurements alone. Our results suggest the opportunity for skin exposure via direct and indirect contact with beryllium-contaminated surfaces. Thus, a better understanding of risk of beryllium sensitization may be elucidated by accounting for the potential contribution of skin exposure to total-body exposure.

Methodological issues

Our choice to estimate a relative index of beryllium exposure to hands using thin cotton gloves was driven by the active and ongoing effort to minimize skin exposure through the use of nitrile gloves in this workplace. Because of this effort to reduce skin exposures, collecting skin wipes directly from hands could be problematic for practical reasons. For example, one difficulty could be to obtain sufficient masses of beryllium from under nitrile gloves necessary to exceed our analytical detection limit. In contrast, we chose to collect skin wipes directly

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from the necks and faces of employees, because these areas of the skin were not covered, except in the case of hooded-respirator usage.

In this study, exposures were assessed through the use of interception (i.e. cotton gloves) and removal techniques (i.e. surface wipes and skin wipes) (CEN, 2005a, b). The major assumption underlying all interception techniques is that the collection medium captures and retains chemicals in a relative manner similar to that of the skin. Brouwer *et al*. (1999) investigated the transfer of particles from contaminated surfaces to uncontaminated hands and to cotton gloves through a set of controlled laboratory experiments. Their results indicated that the mass of particles transferred from contaminated surfaces to cotton gloves was ~70-fold higher than that transferred to uncovered hands. Thus, the analytical results from our cotton glove samples may considerably overestimate exposure. In contrast, the major assumption underlying all removal techniques is that the majority of the contamination residing on a surface is captured by the collection medium. Que Hee *et al*. (1985) observed experimentally that serial wipe sampling is insufficient to remove all lead-containing dust from the hands of study subjects. Thus, results from our surface and skin wipe samples may underestimate the mass of beryllium that is present.

With regard to skin sampling, interception and removal techniques consider only the level of contaminant deposited on the skin surface over a given period of time. According to Cherrie and Robertson (1995), a biologically relevant measure of dermal exposure includes consideration not only for the level of contamination and duration of exposure but also the area of exposed skin. When a permeability coefficient is available for the contaminant of interest, then it may be possible to estimate total mass uptake through the skin. Given the lack of a permeability coefficient or a validated biological monitoring technique for beryllium-containing particles, the results of our cotton glove and skin wipe samples provide a reasonable estimate of relative skin exposure, but not actual exposure or uptake, among workers assigned to various processes in this facility. Uptake, both in the lung and the skin, may also vary with chemical form and particle size (Curtis, 1951; Tinkle *et al*., 2003), neither of which was considered in this study.

Because of changing production schedules, collection of all sample types by work area was not possible on a given day; therefore, we estimated correlations by matching means of workers' measurements (cotton gloves, necks and faces) to work areas (air and work surfaces). Using means rather than the raw data itself generally leads to higher estimates of correlation. If we had matched measurements from all sample types by worker and sampling day, some work areas, including administration, would have in some instances contributed little or no data, thereby possibly leading to lower correlations among sample types.

Regarding the collection of surface wipe samples by multiple surveyors on different days, we observed evidence of a sampling-day effect, accounting for ~8% of the variability of measurements. In contrast, we did not observe a similar effect for the glove, face or neck measurements. This sampling-day difference affecting surface-wipe measurements could be due to differences in the way that the two surveyors collected samples (e.g. varying degrees of hand pressure applied to sampled surfaces). Adjusting surface measurements to account for the possible inter-surveyor difference tended to slightly improve the observed correlations among sample types in this study but did not change our findings. In future studies, when there is potential for large differences among measurements collected by multiple surveyors, it may be prudent to limit sample collection to a single surveyor.

SUMMARY STATEMENT

The results of this study demonstrate strong positive correlations between air and surface, surface and glove, and glove and skin contamination; however, the sequence by which exposures may occur (e.g. air-to-surface → surface-to-cotton glove → glove-to-neck → glove-to-face) cannot be distinguished from these data. Much work is still needed to properly assess total-body exposure to beryllium, particularly to further develop and validate dermal exposure sampling methods and to confirm or deny the hypothesis that skin exposure can cause beryllium sensitization. Epidemiological studies should incorporate skin exposure measurements to assess whether the dermal route is of importance to risk in occupational settings. Based on our current understanding of the multiple exposure pathways that may lead to sensitization, a prudent industrial hygiene approach is to minimize both skin and inhalation exposures to beryllium salts and fine particles in the workplace. Further research is needed to better understand the role of solubility and particle characteristics as well as other factors such as skin thickness and integrity in relation to the hypothesis that skin exposure is sufficient to cause beryllium sensitization.

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