Experimental Evaluation of Spray Painter Worker Orientation and Spray Distance Using a Distance Guide to Reduce Airborne Exposure to Hexavalent Chromium Paints and Primers

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Abstract

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Hexavalent chromium-based primers and paints, which are used widely in the aerospace industry as anti-corrosive coatings, pose a health risk to painters and other workers exposed to the paints and primers. Hexavalent chromium has been established as a carcinogen associated with cancers of the lung and nasal passages. Moreover, hexavalent chromium is associated with irritant and allergic contact dermatitis and gastrointestinal disorders. Previous studies have shown evidence of airborne overexposure to painters when utilizing traditional spray paint booth ventilation. The evaluation of work practices, specifically worker orientation in the spray paint booth and maintaining the proper spraying distance, may assist with further lowering the exposure to hexavalent chromium and complying with occupational exposure limits.

The objectives of this study were to evaluate the effects of worker orientation within the spray paint booth and spraying distance (distance from the spray paint nozzle to the part being coated) in reducing paint aerosol exposures as a surrogate for hexavalent chromium exposure. Four orientations with respect to the flow of air into the booth were evaluated: 0°, 45°, 90°, and 180°. Three spray distances were evaluated: 3, 6, and 12 inches. Paint aerosol concentrations were measured using a Thermo Scientific PDR 1500 real-time aerosol monitor.

Results showed an association between orientation and aerosol concentrations with the geometric mean concentration increasing as orientation moved from 0° (directly upwind) to 180° (directly downwind): 0° (0.08 µg/m^3/gram), 45° (0.47 µg/m^3/gram), 90° (2.69 µg/m^3/gram), and 180° (14.0 µg/m^3/gram). Changing the spray distance did not reveal an association with aerosol exposure concentrations.

Worker orientations that place the painter upwind of the target parts showed decreased paint aerosol exposures and potentially hexavalent chromium exposures. While additional research is required to establish the association between aerosol paint and hexavalent chromium exposures, this research suggests that optimizing spray painter work practices may aid in reducing hexavalent chromium exposures resulting from hexavalent chromium based paints and primers.

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INTRODUCTION

Hexavalent chromium (CrVI) is an occupational hazard present in many industries and processes. CrVI is a widely used in a variety of industries to add corrosion resistance to materials and products. CrVI is also a product of high heat processes, such as welding on stainless steel, where trivalent chromium (CrIII) is converted to CrVI. The more common uses of CrVI are in chrome plating and as an additive to paints and primers to provide a protective anti-corrosive barrier for various metals. Forms of CrVI include sodium dichromate, chromic acid, barium chromate, strontium chromate, zinc chromate, chromium trioxide, and lead chromate.

HEALTH EFFECTS AND EXPOSURE LIMITS

Hexavalent chromium is a known human toxicant. Exposure to CrVI compounds can result in respiratory illness, dermatitis, gastrointestinal disorders, immunological dysfunction, and cancer (lung and gastrointestinal).[1] Evidence is inconclusive as whether CrVI is associated with hematological, immunological and development effects. The Agency for Toxic Substances and Disease Registry (ATSDR) has determined the minimum risk level (MRL) for chronic exposure to aerosols and particulates to be 0.005 $\mu g/m^3$. Primary concern in an occupational setting is given to lung cancer, nasal irritation/damage, respiratory sensitization (asthma), and both irritant and allergic contact dermatitis.[2] Routes of exposure include inhalation, ingestion, and skin contact/absorption, though the systemic health effects (immunological, reproductive, and hematological) are not limited to the route of entry. Exposure to CrVI during pigment production and chrome plating processes has been shown to double the expected rates of lung cancer and lung cancer rates were higher in workers exposed to CrVI during painting processes.[2,3]

Evidence suggests that carcinogenicity, due primarily to the less soluble particulate CrVI salts, results from tissue irritation and inflammation originating from the reduction of CrVI to CrIII and the dissolution of soluble chromate ions, causing cellular damage.[1,4,5] The increased carcinogenicity of the less soluble CrVI particulates is due to greater retention time in the lung compared to the soluble counterparts. Reduction of CrVI to CrIII inside of cells is considered an important mechanism of toxicity; whereas, reduction outside the cells may prove protective. Moreover, the reduction of CrVI to CrIII produces reactive intermediates such as, chromium adducts with DNA and proteins, and free radicals that can cause cellular and DNA damage.[6]

The United States National Institute for Occupational Safety and Health (NIOSH) as of 2013 recommends an 8-hour time weighted average (TWA_8) exposure level of 0.2 $\mu g/m^3$ for all CrVI compounds. The recommended exposure level (REL) is based on a quantitative risk assessment that showed a rate of 1 per 1000 workers having respiratory health effects and lung cancer due to airborne CrVI exposure compared to an exposure level of 1 $\mu g/m^3$, which resulted in a 6 per 1000 worker rate of associated disease .[2,7] NIOSH recommends that both soluble and insoluble forms be considered carcinogenic given evidence presented in human and animal studies showing carcinogenic effects from both soluble and insoluble CrVI compounds.

The American Conference of Governmental Industrial Hygienists (ACGIH) as of 2004 set the voluntary Threshold Limit Value (TLV) at 50 $\mu g/m^3$ for water soluble forms of CrVI and 10 $\mu g/m^3$ for insoluble CrVI.[8] In 2001 the ACGIH set the TLV level to 0.5 $\mu g/m^3$ for strontium chromate, a known carcinogen and commonly used in aerospace painting. Calcium, lead, and zinc chromates also have specific TLVs, published in 2001, of 1 $\mu g/m^3$, 12 $\mu g/m^3$, and 10 $\mu g/m^3$, respectively. The compound specific TLVs are a result of increased carcinogenicity and other health effects as in the case of lead chromate. The TLVs were established based on the IARC A1 carcinogenicity designation and to reduce the potential for respiratory irritation, dermatitis and potentially kidney disease.

In the United States, the regulatory limit is set by the Occupational Safety and Health Administration (OSHA). In 2006 OSHA set the work place TWA_8 permissible exposure limit (PEL) for CrVI at 5 µg/m^3 with an action level (AL) of 2.5 µg/m^3 for General Industry, Construction, and Marine industries due to the increased risk of developing lung cancer, asthma, nasal damage, and skin damage.[9] OSHA PELs are determined based on scientific evidence in conjunction with economic feasibility. Exposure found at or above the action level of 2.5 µg/m^3 requires the adoption of specific practices to maintain compliance with OSHA CrVI Standard (General Industry (1910.1026), Shipyards (1915.1026), and Construction (1926.1126). OSHA made an exemption for the painting of aircraft, defined as the interior or exterior of the entire aircraft, and/or large aircraft parts, defined as a wing or tail wing or similar sized part. The exemption, the result of feasibility constraints, sets the exposure limit at 25 µg/m^3 for these activities with the requirement that engineering controls and supplemental PPE be used to reduce the remaining health risk.

The concern over exposure to CrVI via painting processes is supported by recorded occupational exposures. Previously unpublished data presented by the University of Washington Department of Environmental and Occupational Exposure Sciences showed personal CrVI exposures in the aerospace industry during chromate spray painting and supporting tasks range from 0.7 – 634 µg/m^3.[10] A NIOSH study found that workers performing painting or coating application with chromate paints had exposures ranging from 2.4-55 µg/m^3.[11] Similar conclusions were made after evaluating CrVI exposure in French industries where paint manufacturing exposures had a mean occupational concentration of 47.2 $\mu g/m^3$.[12] Further, another study found mean strontium chromate exposures during full aircraft painting operation at 83.8 $\mu g/m^3$.[13] A high exposure level of strontium chromate is particularly concerning given the evidence for increased carcinogenicity.

EXPOSURE CONTROLS

The hierarchy of controls dictates that exposures be managed with an emphasis towards elimination followed by substitution, engineering controls, administrative controls, and personal protective equipment. In this context, the common approach to controlling CrVI exposures incorporates ventilation and personal protective equipment. Alternatives to CrVI used in paints, such as trivalent chromium and tungsten carbide, have been explored, but none have yielded properties consistent with CrVI.[14] Further, job rotation, considered an administrative control, is prohibited by the OSHA CrVI standard. With respect to well-designed engineering controls, relatively high exposures can still occur due to worker practices, painting techniques, and the very low occupational exposure limit. A 2007 NIOSH study, concluded that painting and coating processes were very difficult to control with even the most current and best engineering practices, such as local exhaust ventilation (LEV) and spray paint booths.[11] Certain techniques can contribute to increased exposure when transfer efficiency, the fraction of paint that is deposited on the part surface, is reduced. Examples of these techniques, assuming proper spray paint gun setup, include arcing (varying the spray angle), inconsistent spray distance, and increased lead and lag (distances from where the paint starts and stops from the part edges).[15] In addition, the part size and geometry can also affect transfer efficiency. Estimates of transfer efficiencies in auto painting have been calculated as low as 37%, suggesting that large proportions of paint aerosols miss their target and may stay airborne and potentially available for inhalation or dermal exposure.[16]

The most common engineering controls used in aerospace spray painting are ventilated downdraft tables, downdraft spray paint booths, and back-draft spray paint booths in addition to high volume low pressure (HVLP) spray paint guns.[11] Strict adherence to engineering control best practices is critical to reducing spray paint related exposures. A smooth laminar flow of approximately 75-150 ft./min cross sectional velocity is recommended by the ACGIH to control exposures in ventilated spray paint booths.[17] Deviations from this velocity range may lead to ineffective control by either not having sufficient flow to move the contaminant away from the worker or too much flow, which can cause unwanted eddies of high contaminant concentrations near the worker. High-volume low-pressure spray paint guns are designed to reduce the velocity of the paint as it exits the spray paint gun by maintaining pressure at or below 10psi.[15,18] In doing so, the aerosolized paint is larger in mean aerodynamic diameter and fugitive aerosol spray is reduced.[18] Many factors contribute to the aerosol characteristics and related occupational exposure including paint volume, paint flow rate, fluid pressure, airline pressure, spray tips, solvent volatility, and coating viscosity.[16] A deviation from the specified coating specifications and spray paint gun settings can not only lead to overexposures, but can also reduce the quality of the coating.[19]

Potential Determinants Of Exposure

There are three primary determinants of exposure: ventilation (previously discussed), transfer efficiency and worker orientation. Transfer efficiency is of particular interest because it can be increased by training the worker to maintain consistent angles and distance. Therefore, efforts to increase transfer efficiency have the potential to decrease exposure and waste to the environment. Methods for increasing transfer efficiency involve optimizing worker technique and spray paint gun set-up in accordance with the specifications of the paint coating. Maintaining a constant distance between the spray paint gun and the part being sprayed is one aspect of optimal worker technique. Deviations in this distance increase the likelihood of reduced transfer efficiency and increased exposure, while also reducing the quality of the coating. This is due to solvents in the paints and primers "flashing" or volatilizing when the distance is increased, in contrast to, the paint or primer "bouncing back" when the distance is decreased. Computational Fluid Dynamics (CFD) paint aerosol modeling research has shown that variability in spray distance can affect predicted exposures.[20] Additionally, changing the angle also affects the deposition of paint particles on the surface, leading to decreased transfer efficiency. While many of the parameters that affect transfer efficiency and exposure have been identified, few of these parameters can be as easily controlled by the worker as spray distance. Further, many of the parameters, such as spray velocity, gun pressure, and overall generation rate can only be minimally changed by the worker due to the equipment specification and coating requirements. Therefore, one goal of this work is to evaluate simple and affordable methods that enable workers to maintain ideal and constant spray distances.

Workers can determine the quality of the coating by visual inspection and measuring the thickness with a film gauge. Yet, measuring the transfer efficiency is a challenge due to the need to measure not only the paint that adhered to the work piece, but also the percentage of paint that coated adjacent surfaces, became entrained in the airflow, and was captured by engineering controls. Therefore, using techniques that are known to improve transfer efficiency without needing direct measurement are required.

Worker orientation in relation to the part being spray painted and the moving air in the spray paint booth also has the ability to affect exposure. Past research evaluating organic vapor exposures using mannequins suggested that workers should orient themselves to the side or perpendicular (approximately 90^o) to the spray paint booth ventilation, avoiding positions directly upwind (0^o) or back facing of spray paint activity where eddy effects may contribute significantly to exposure.[21] This same research showed that increased air velocity increased exposure in the upwind (0^o) position. In contrast, research focused on particulate exposures utilizing computational fluid dynamics, modeling, and simulated exposure monitoring with mannequins suggests that 0^o may be the best position for reducing exposures.[22,23] The ACGIH merely recommends not positioning the worker directly downwind of spray painting.[17] As a result, additional research is needed to assess how various orientations within the spray paint booth affect exposure on actual workers while spray painting.

The potential for CrVI exposures to exceed regulatory levels despite the use of ventilation warrants the investigation of novel controls and practices to reduce occupational exposures. Specifically, focus on worker technique is warranted because the engineering specifications of the coatings are explicitly defined by the contractor, limiting the exposure control options available to the subcontractor. Therefore, paint substitution or changes that affect the coating are often not feasible. As a result, emphasis is placed on properly functioning ventilation, worker technique, and personal protective equipment (PPE).

Control strategies that are effective yet remain economically feasible are greatly desired. Changes in worker orientation within the spray paint booth can be a feasible and effective method for reducing exposure. Additionally, methods for increasing transfer efficiency are potentially effective at controlling exposure while also reducing the quantity of paint used.

Controlling spray distance has the potential to increase transfer efficiency, thus decreasing aerosol paint exposure.[18]

SPECIFIC AIMS

The primary goal of this research was to conduct an experimental assessment of how worker orientation and spray distance in relation to the painting of aircraft parts affected paint aerosol exposure, as a surrogate of CrVI exposure. To describe the association between paint aerosol exposure, worker orientation and spray distance in aerospace spray paint employees utilizing an experimental study design, the following aims were conducted;

1. To quantify paint aerosol exposure as a surrogate of CrVI exposure based on a worker orientation of 0^o, 45^o, 90^o, and 180^o at a fixed spray distance with respect to the aircraft part and the ventilation airflow.
    a. Null Hypothesis: There is no difference in CrVI exposure between worker orientations of 0^o, 45^o, 90^o, and 180^o;
2. To quantify paint aerosol exposure as a surrogate of CrVI exposure in relation to spray distance from the spray paint gun and aircraft part using a spray paint gun laser guide.
    a. Null Hypothesis: There is no difference in CrVI exposures between workers utilizing an industry recommended distance of 6 inches from the spray paint gun and the aircraft part (defined by manufacturer specifications) and workers not utilizing an optimal spray distance.

These aims yielded knowledge of how worker orientation and spray technique affect potential CrVI exposures resulting from spray painting. Results of this experimental study could prove useful in providing guidance in reducing particulate and CrVI exposures from spray painting. The results can be utilized by both the aerospace industry and health and safety professionals with the common goals of reducing spray paint-related particulate exposures by means of best practices and reducing the amount of paint used through increased transfer efficiency.

METHODS

This experimental study was conducted over the course of one day at one aerospace facility that specializes in aluminum finishing, including various surface treatments, chemical processing, and anticorrosive paint finishes. Monitoring was conducted in a commercial back-draft spray painting booth used primarily for anti-corrosive primer application. All condition scenarios were conducted in a randomized order for each subject. Nine spray painters were recruited on-site, in accordance with human subject approval, based on the requirement that they could paint in accordance to industry specifications and that they were employed at the facility. Six of the nine actually participated in the study as a result of one employee ending employment with the facility and two painters that were unable to complete the study due to spray paint equipment failure on the day they were sampled. Training was provided to each painter as to the purpose of the study, how the study-provided spray painting equipment worked, and the required spray painting parameters needed to effectively evaluate occupational exposures in accordance with the study design. Each employee completed a baseline scenario and all six conditions.

Aerosol exposures were measured using a factory calibrated Thermo Scientific pDR-1500 (Personal Data Ram) real-time aerosol monitor, set to measure total particulate matter mass concentrations (specified by the manufacturer as particles with a 1.0 to 10μm aerodynamic diameter) using a 1 second logging rate, internally calibrated 2.00 LPM flow rate and relative humidity correction. Using Tygon® tubing, the pDR inlet was placed in the breathing zone of the dominant hand side of the worker's lapel.

All subjects used the same Binks brand Mach 1 HVLP spray paint gun with specification BMS 10-11 (5-10% Strontium Chromate) AkzoNobel 10P8-10NF green fluid resistant epoxy primer, which was prepared prior to each sampling period using the same 1:1 ratio of solvent to primer. The solvent was AkzoNobel Fluid Resistant Epoxy Primer VOC Compliant EC-283 with the primary component being acetone. The spray duration of 2 minutes for each condition was based on the time needed to complete the coating of the aerospace parts according to industry specification. The spray paint gun parameters (paint flow volume rate, spray gun fan pattern, and air pressure) were set by the lead painter of the facility before and during the duration of the sampling period. Spray paint pressure was set to 10 psi. Paint pots were weighed before and after each experimental condition to measure the mass of primer used. For each condition, a series of representative aerospace parts were coated. Selection of these parts was made with the assistance of the painting facility (Figure 1). Two identical trays were produced, consisting of 25 small metal parts. The two trays of parts were switched between subjects and reused throughout the study.

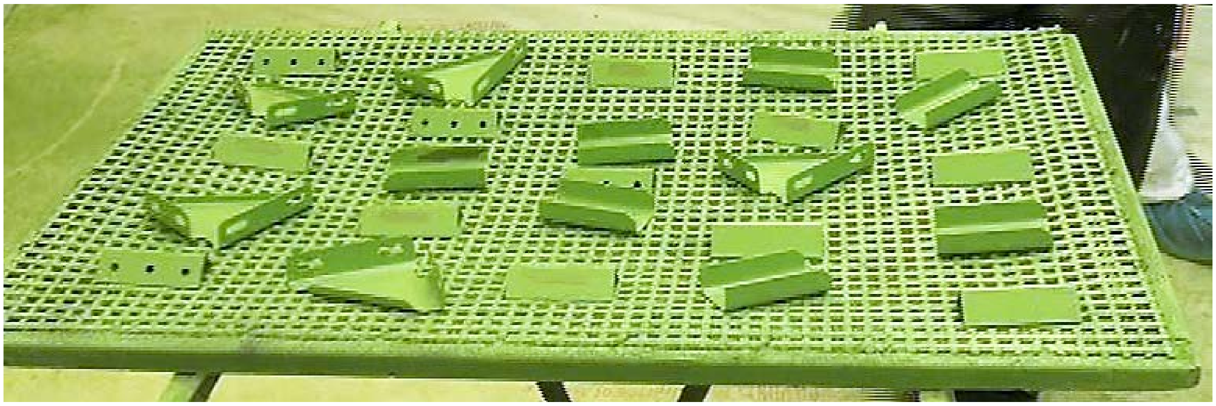

Figure 1. Representative aerospace parts used for all conditions

The evaluation, using airborne paint aerosol concentration (µg/m^3) as the continuous outcome, consisted of to two primary objectives:

- Effect of worker positional orientation on exposure; and
- The effect of spray distance on exposure.

WORKER ORIENTATION

Worker positional orientation was evaluated at four different angles with respect to the worker, parts being painted, and flow of ventilation air in the spray paint booth: 0°, 45°, 90°, and 180° (Figure 2). Worker orientation was maintained by keeping the paint rack/parts at a specific location centered between the two side walls and seven feet from the filter bank. Painters remained stationary by rotating the paint rack in order to paint all sides of the parts. Variables other than orientation, such as work-piece height, were determined based on industry standards and practices and were made constant for the duration of the study. Aerosol exposures measured at 0°, 45°, and 180° were compared to the recommended best practice orientation of 90° to determine the effect of worker positional orientation on exposure. Spray distance (from gun to work-piece) was held constant at 6 inches using a commercially unavailable battery powered spray paint laser guide formerly made by LaserPaint (Figure 3). Six inches is the manufacturer recommended spray distance for a HVLP spray gun.

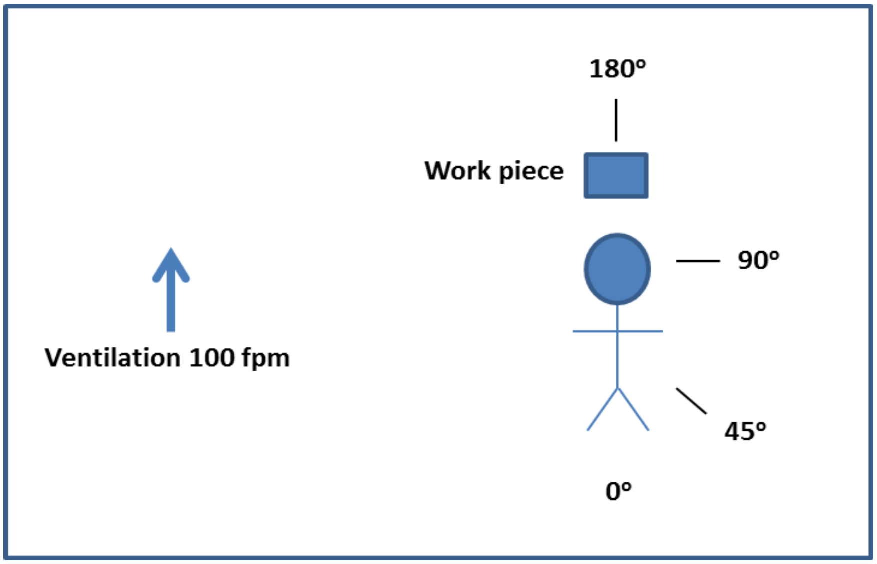

Figure 2. Worker positional orientation in relation to the work-piece and air flow of the spray paint booth

Figure 3. High Volume Low Pressure (HVLP) Spray Paint Gun (blue) with Laser Guide (black)

SPRAY DISTANCE

The effects of spray distance were measured utilizing three spray distances: 3 inches, 6 inches, and 12 inches. Six inches is the recommended spray distance for HVLP spray guns. The other two distances represent realistic high and low deviations from the optimum spray distance. Spray distance was determined using a spray paint laser guide that can be adjusted to varying distances. The laser guide attaches to the HVLP spray gun and desired distances are achieved by triangulating one laser beam in reference to a fixed laser beam built into the guide. All distance conditions were conducted at the 90^o worker orientation. Aerosol exposures measured at 3 inches and 12 inches were compared to the exposure measured at 6 inches to determine the effect of spray distance on exposure.

VENTILATION

The paint booth ventilation system was characterized by conducting a face velocity traverse across the filter bank at the beginning and end of the experiment using a TSI 9535-A thermal anemometry probe. In addition, capture velocities were recorded at the point of work (i.e. the rack) at the beginning and end of the experiment. On the day of the study, all stages of the spray paint booth filter system were replaced with new filters to optimize air flow. The height of the spray paint rack was held constant at 38 inches from the booth floor. The distance from the rack to the air filters was 7 feet.

The spray paint booth was a large enclosed booth, capable of coating small aircraft parts, measuring roughly 21’ x 8’ x 18’ (Figure 4). The ventilation air supply was located on the far ceiling near the entrance with baffles directing air flow towards the disposable particulate filters. Spray paint booth parameters were controlled as effectively as possible (Table 1). Spray paint gun pressure was held constant at 10 psi. Spray paint volume flow rate and fan pattern were made constant by having the lead painter adjust these parameters throughout the test period to meet industry standards. Capture velocity was 35-50 fpm, which is below the recommended velocity of 100 feet per minute (fpm), and variability was observed. The average cross sectional volumetric flow was below the recommended ACGIH volumetric flow rate of 100 cfm/ft^2 (or Q= 14810 cfm based on the dimension of the spray paint booth).[17] At the time of the study, adjustments to the ventilation system were not permitted by facility management.

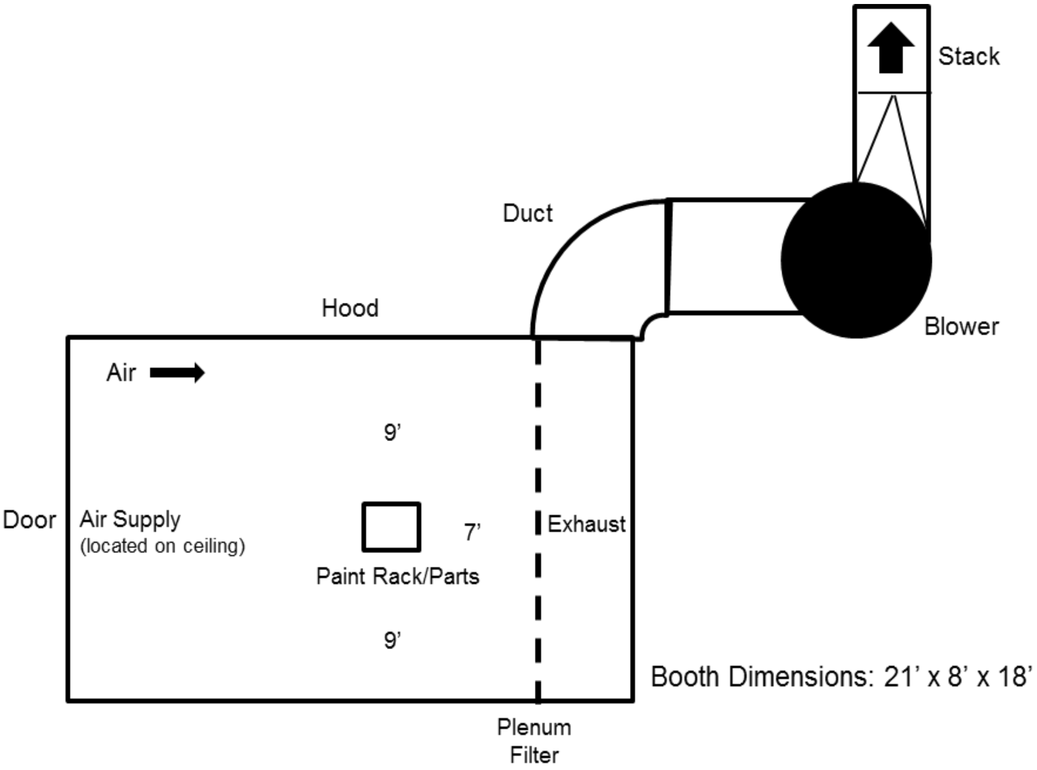

Figure 4. Paint booth configuration

Table 1. Environmental Parameter Settings

	Pre	**Post**
Gun Pressure (psi)	10	10
Gun Volume Flow Rate	standardized	
Fan Pattern	standardized	
Rack to Filter Distance (ft.)	7	
Rack Height (ft.)	3.17	
Capture Velocity (fpm)	35	50
Q (cfm)*	10585 (71.47 cfm/ft^2)	9962 (67.27 cfm/ft^2)
Booth Dimensions	L = 21.22; H = 8.16; W = 18.15	

**Based on filter traverse*

All spray painters and researchers potentially exposed to spray paint wore full Tyvek coveralls, booties, gloves, and a respirator with P100 and organic vapor cartridges.

DATA ANALYSIS

The data were analyzed with STATA Data Analysis Statistical Software version 14.2. Subject information, sample time periods, paint usage measurements, and booth condition data were recorded on field datasheets. Each condition test period was systematically standardized by the following steps:

1. Data were adjusted for negative values by test condition/subject by taking the lowest data point value and setting it to zero. All data were then adjusted by this offset. Negative value offset was contributed to the manufacturer's specified ±5% accuracy
2. Measurement periods for each condition were approximately 2 minutes in length. The relevant data for each test condition were identified by comparing start/stop times documented on field data sheets, and selecting 120 consecutive data points (120 seconds of exposure data) with the highest running average. This was done in an effort to only select data attributable to spray painting, while avoiding data from pre and post spraying activities.
3. The last 30 data points were removed because this time period represent post spraying exposures. The result was 90 data points for each test condition/subject.
4. The amount of paint used by each painter varied. As a result, the aerosol exposures varied based on the amount of paint used. To adjust for paint usage, data were standardized by dividing the aerosol concentration by the mass of paint used for each condition.

A categorical linear mixed model using a restricted maximum likelihood (REML) approach with “condition” (i.e. orientation or distance) as the categorical variable was developed to determine whether differences existed between the mean concentration for each condition compared to the reference conditions of 90° and 6 inches. The model combines the exposures of all subjects to create a universal mean for each condition for comparison. All conditions were included in the model rather than analyzing orientation and distance separately to increase the power of the model. Equal variance of the residuals was determined by plotting the residuals against the predicted fitted values.

RESULTS

Paint aerosol concentrations standardized for paint usage were used to determine the differences between the conditions. The mass of the paint used varied amongst painters with the mean paint usage ranging from 137.78 – 296.70 grams (Table 2). The mass of paint used by condition also varied with the mean paint use ranging from 168.35 – 221.17 grams (Table 3.)

Table 2. Subject paint usage

Subject	# Conditions	Mean Paint Consumption per condition (grams)	SD (grams)	Min (grams)	Max (grams)
1	6	175.4	27.7	153.4	209.5
5	6	137.8	10.6	152.8	183.7
6	6	166.2	23.0	152.2	216.9
7	6	150.5	86.8	70.6	339.3
8	6	268.8	89.5	123.6	358.9
9	6	296.7	40.2	280.8	388.7

Table 3. Mean paint consumption for each condition

Orientation	Distance (inches)	# Subjects	Mean Paint Consumption	SD (grams)	Min (grams)	Max (grams)
90^o	3	6	220.04	96.46	131.83	360.61
0^o	6	6	168.35	52.72	124.74	271.30
45^o		6	221.17	94.29	149.97	385.84
90^o		6	213.66	128.58	70.59	388.67
180^o		6	191.78	81.28	123.60	342.75
90^o	12	6	214.56	103.08	113.11	359.47

Summary statistics are presented in Table 4. Exposure data appeared to be log normally distributed based on the Q-Q plot (Figure 5). The geometric mean range of concentrations for the orientation conditions, corrected for paint usage, was 0.05 – 9.89 µg/m^3/gram. The orientation of 0^o had a geometric mean concentration of 0.05 µg/m^3/gram, following by 45^o (0.24 µg/m^3/gram), 90^o (1.5 µg/m^3/gram), and 180^o (9.89 µg/m^3/gram). The range of geometric mean concentrations for the distance conditions was 0.86 - 1.50 µg/m^3/gram. The spray distance of twelve inches had the lowest geometric mean concentration, followed by three and six inches.

Table 4. Condition aerosol exposure summary statistics corrected for amount of paint used (µg/m^3/gram)

Orientation Angle (degrees)	**Distance (inches)**	**N (subjects)**	**Data points**	**AM (SD)**	**GM (GSD)**	**95% CI**	
0	6	6	540	0.10 (0.24)	0.05 (2.51)	0.046	0.054
45	6	6	540	1.64 (4.49)	0.24 (6.38)	0.21	0.28
90	6	6	540	3.92 (7.45)	1.50 (3.86)	1.34	1.68
180	6	6	540	16.79 (17.89)	9.89 (2.97)	9.02	10.84
90	3	6	540	3.48 (6.72)	1.43 (3.83)	1.27	1.60
90	6	6	540	3.92 (7.45)	1.50 (3.86)	1.34	1.68
90	12	6	540	4.90 (9.76)	0.86 (7.06)	0.73	1.02

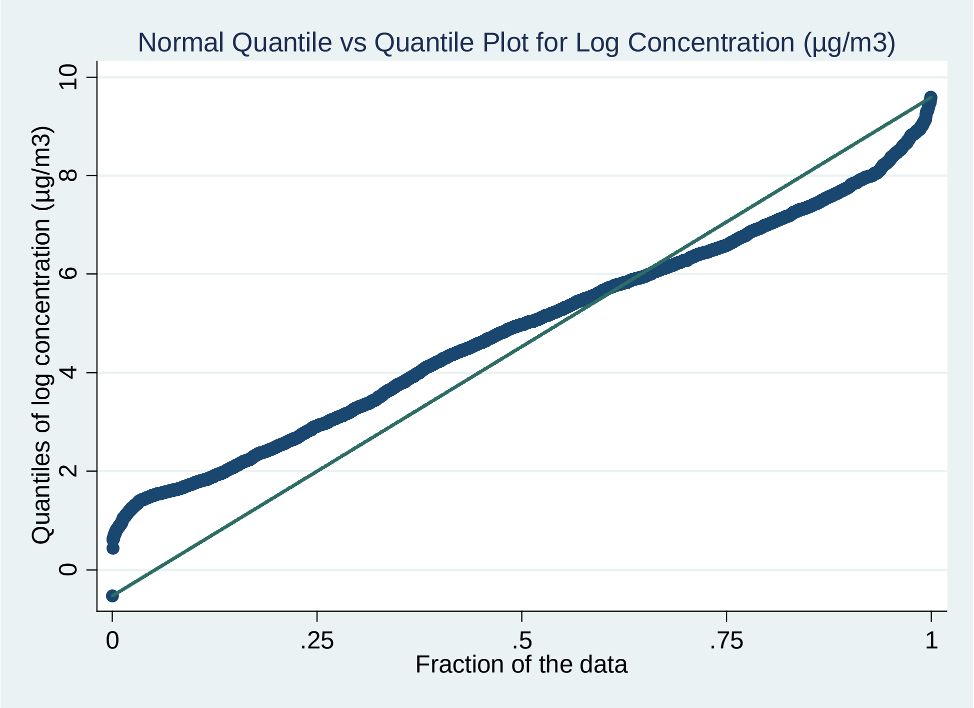

Figure 5. Q-Q plot for log concentration

The overall trend shows that the geometric mean of the paint consumption-corrected concentration increased as orientation moves from 0° toward 180° (Figure 6). In contrast, distance did not demonstrate an obvious trend (Figure 7). Boxplots for both orientation and distance by subject are shown in Figures 8 and 9. The distributions for all subjects except Subject 6 showed an increase in exposure as the orientation moves from 0^o to 180^o. However, no discernible trend was apparent for spray distance. While the distribution appears to be affected by outliers, they were left in the data set because no observable reason for removing these data points was witnessed and all values were within the range of previously observed exposure data for spray painting.[10]

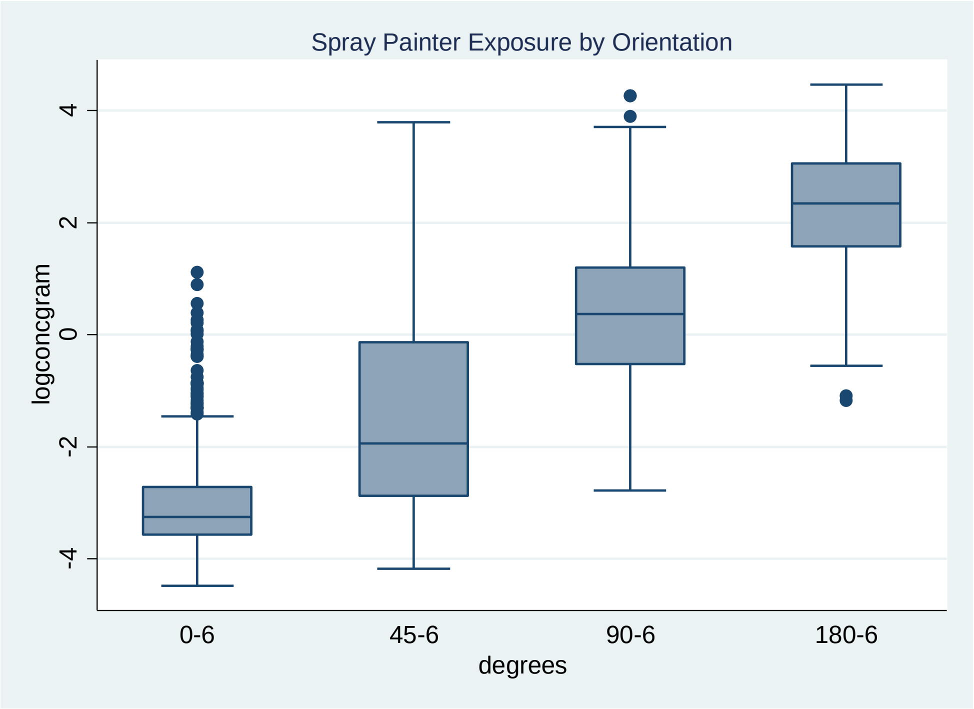

Figure 6. Overall paint aerosol log concentration by orientation

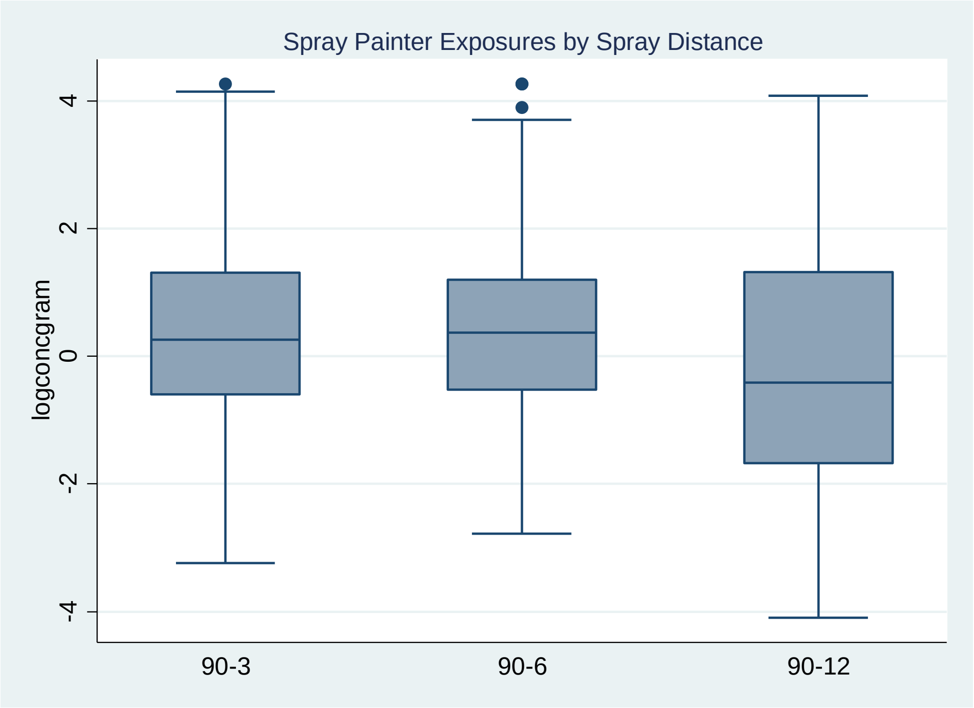

Figure 7. Overall paint aerosol log concentration by spray distance

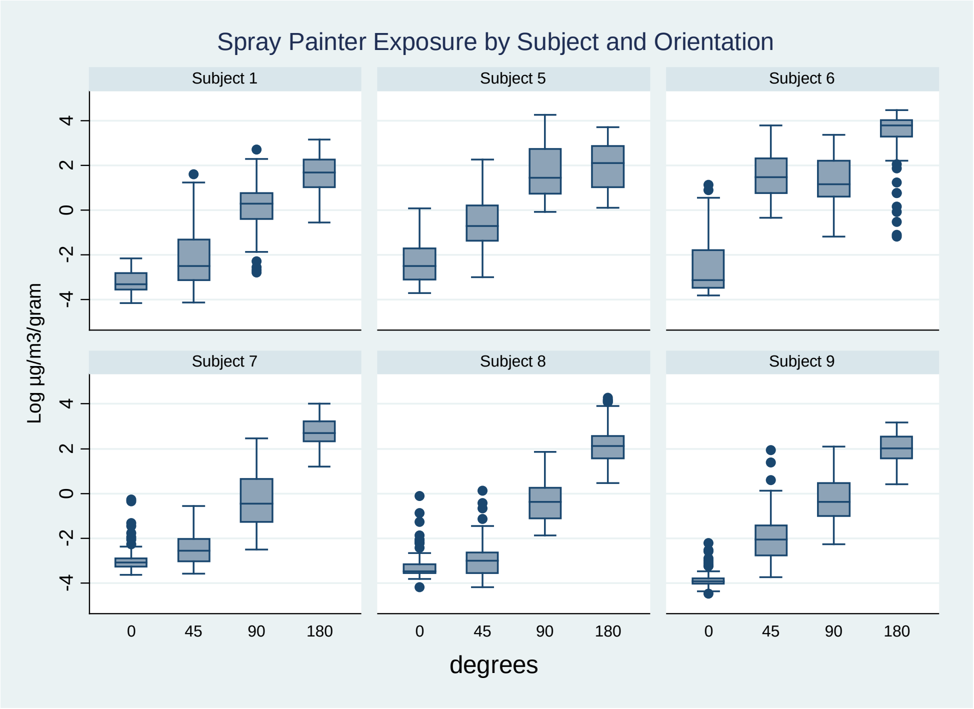

Figure 8. Paint aerosol log concentration by subject and orientation

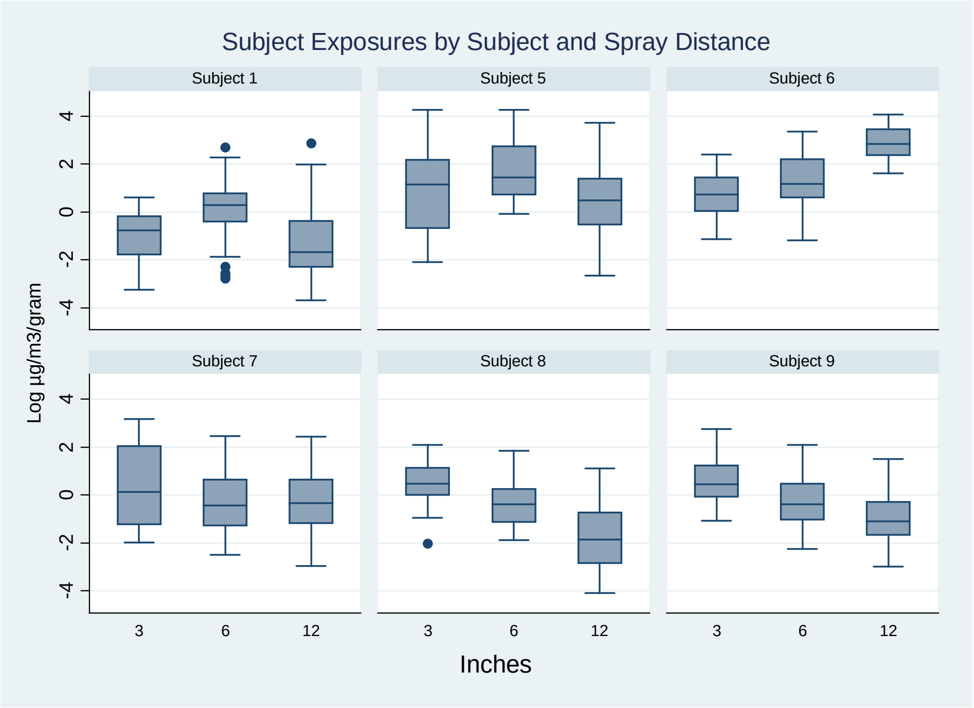

Figure 9. Paint aerosol log concentration by spray distance and subject

A categorical linear mixed model with restricted maximum likelihood (REML), using "condition" as a categorical variable, was used to test whether the log mean concentration/gram (µg/m^3/gram) for each worker positional orientation (or spray distance) was the same as the reference orientation of 90^o (6" in the case of spray distance). Results are shown in Table 5. The estimated within-subject and between-subject variances are shown in Table 6. Variance estimates show that the majority of the variance is between individuals. Equal variances were confirmed by plotting a residual plot based on a categorical linear mixed model with REML (Figure 10).

Table 5. Categorical linear mixed model with restricted maximum likelihood (REML) for worker positional orientation and spray distance compared to the reference orientation and distance of 90°, 6 inches (α = 0.05)

	Intercept	**0º 6”**	**45º 6”**	**180º 6”**	**90º 3”**	**90º 12”**
N	36					
Subjects	6					
Coefficient	0.98	-3.58	-1.74	1.65	-0.01	-0.36
SE	0.46	0.65	0.65	0.65	0.65	0.65
Z	2.13	-9.16	-4.46	4.22	-0.02	-0.91
p-value	0.033	<0.001	<0.001	<0.001	0.985	0.404
95% CI	0.08, 1.90	-4.41, -2.74	-2.58, -0.90	0.81, 2.49	-0.85, 0.83	-1.20, 0.48

Table 6. Variance components from mixed model using REML to estimate variances

Variance Components	**Coefficient (SE)**	**%**
Within-subject variance (SE)	0.549 (0.155)	43.1%
Between-subject variance (SE)	0.724 (0.516)	56.9%
Total Variance	1.27	

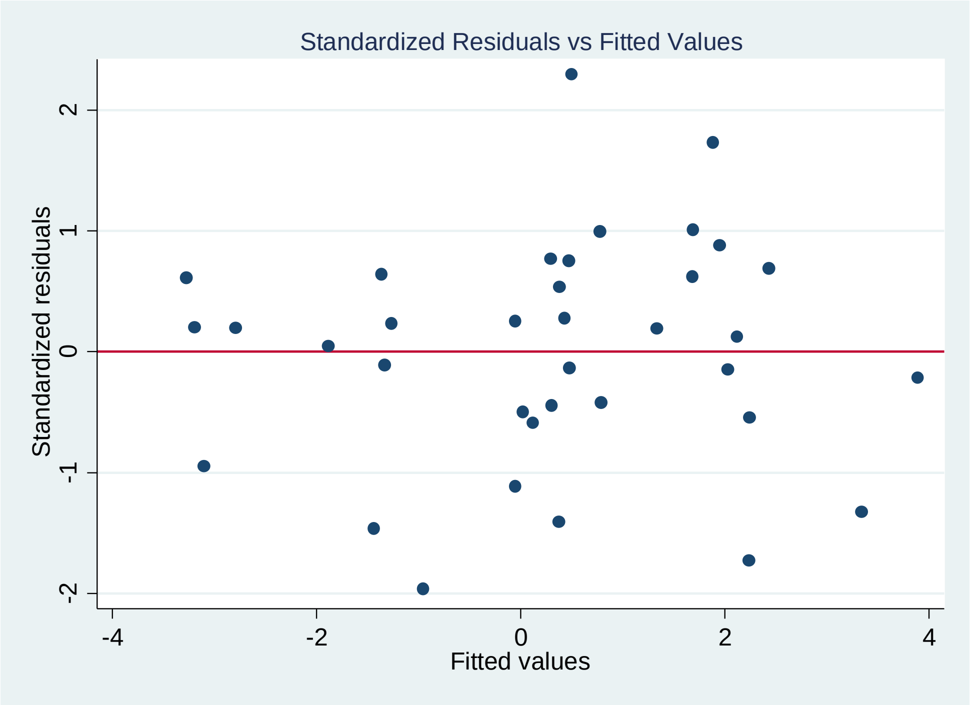

Figure 10. Residual plot based on a categorical linear mixed model with REML

Results indicate that there is an association between orientation and aerosol exposure. All orientation conditions were significant ($\alpha = 0.05$) with 0^o resulting in the greatest reduction in exposure with a geometric mean of 0.08 µg/m^3/gram followed by 45^o with a geometric mean of 0.47 µg/m^3/gram when compared to 90^o (Table 7). These results are in contrast to 180^o which had a geometric mean of 14.0 µg/m^3/gram. The geometric mean of the reference condition, 90^o, was 2.69 µg/m^3/gram. No distance conditions were statistically significant. These results were attained by assessing each variable individually while all other variables were set to zero. The geometric means were determined by adding the intercept and variable and then exponentiating the sum.

Table 7. Geometric mean concentration/gram for each orientation condition (µg/m3/gram)

Orientation	**N**	**Geometric Mean**	**95% Confidence Intervals**
0^o	6	0.08	0.1, 0.11
45^o	6	0.47	0.05, 0.66
90^o	6	2.69	1.04, 6.82
180^o	6	14.0	1.38, 19.69

Figure 11 shows the predicted geometric mean concentrations for each orientation. These predictions were determined by multiplying the geometric mean concentrations by the condition’s average mass paint use.

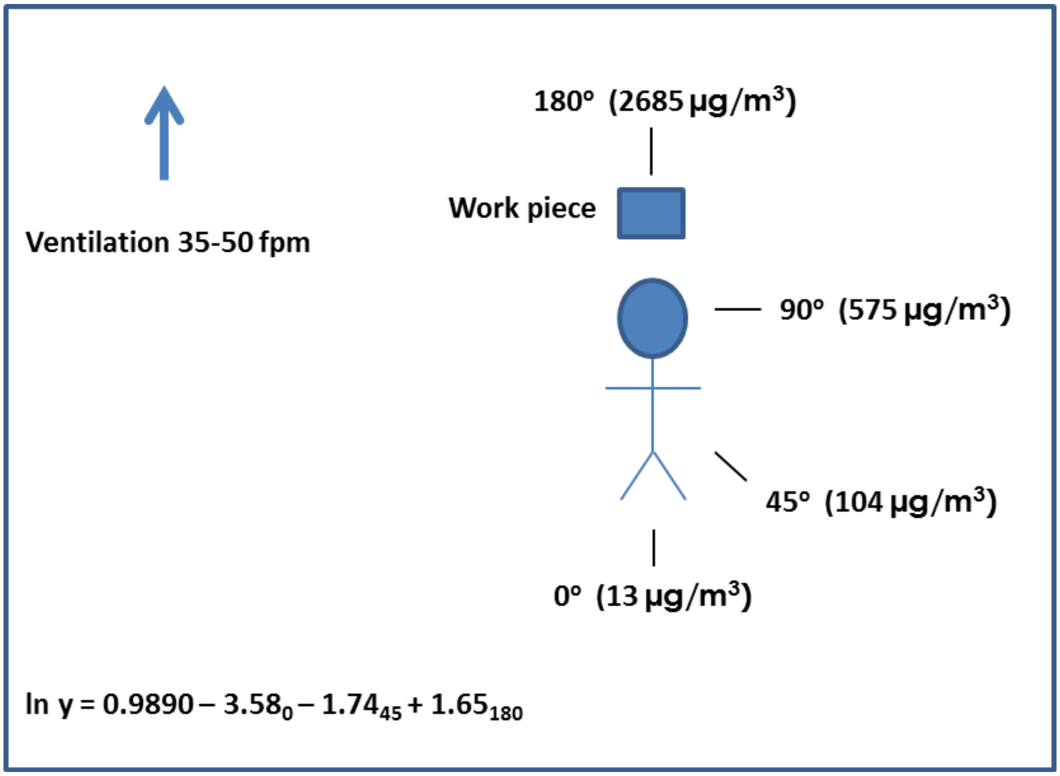

Figure 11. Predicted geometric mean paint aerosol exposures (µg/m3) based on linear mixed model with REML using the average paint mass of each condition.

DISCUSSION

The results of this study have implications for work practices on exposure to CrVI in the aerospace painting industry. CrVI exposures can be predicted based on the aerosol exposure shown in Figure 11 and the mass percentage of CrVI contained in the paint or primer provided by the Safety Data Sheet (SDS). Assuming that the specification BMS 10-11 primer used in the study contains approximately 10% Strontium Chromate (the high content range found on applicable safety data sheets), the predicted exposures to CrVI can be found in Table 8.

Table 8. Predicted CrVI exposure based on study aerosol exposures assuming 10% of paint as CrVI

Orientation Angle (degrees)	**Aerosol Exposure (μg/m^3)**	**CrVI Exposure (μg/m^3)**
0	13	1.3
45	104	10.4
90	575	57.5
180	2685	268.5

As shown in Table 8 the potential to reduce the CrVI exposure level below the OSHA PEL of 5 μg/m^3 and AL of 2.5 μg/m^3 is possible through changes in worker orientation in the spray paint booth and worth exploring further. The degree to which the changes in worker orientation can reduce CrVI exposures needs to be further studied and correlated with paint/primer aerosol exposures, as well as paint booth ventilation characteristics. However, the predicted CrVI exposures are based on short-term sampling and are likely an overestimate of exposure given that spray painters typically do not spray paint for the entirety of an 8-hour work day.

WORKER ORIENTATION

Results of this study show that painter orientation is associated with worker exposure to paint aerosols; therefore, orientation may affect exposure to CrVI when using CrVI based paints and primers. Study results indicate that under the conditions sampled, painting from the 0° and 45° orientations may significantly ($p<0.05$) reduce exposures compared to the reference orientation of 90°. In contrast, the orientation of 180° may significantly ($p<0.05$) increase exposure, which follows the evidence presented by past research.[20,22,24] These results are consistent with previous computational fluid dynamics models and worker exposure models that showed the position of 90° to have higher exposures than the position of 0°.[14,23] The assumption made prior to this research based on industry best practices was that the 90° orientation would yield the lowest exposure due to paint aerosol getting caught in an eddy between the painter and the parts at the 0° orientation. However, these results support that exposures may be a complex interaction between the body, ventilation rate, and the spray parameters (air pressure, air velocity, paint volume flow rate, and fan pattern), and that the position of 90° may not always be the most ideal position for minimizing exposure. In particular, booth airflow velocity was below recommended values, which may have impacted airflow patterns and the relationship between orientation and exposure. For example, the lower air velocity may produce less contaminant removal, while producing fewer eddies. In contrast, a higher air velocity may be more effective at capturing contaminants, but also result in more eddy formation at the worker that could increase exposure. Moreover, when painting in the 90° orientation the spray painters were observed to intermittently spray upwind of themselves as a result of a sweeping motion in their painting technique, which can result in directing paint aerosols to a painter's breathing zone. While the range of sweep may vary due to the part being painted and the skill of the painter, attention must be paid to the degree that paint is sprayed upwind given its potential contribution to exposure. In contrast, painting from the 0^{o} and 45^{o} orientations typically led painters to position the spray paint gun such that the spray was directed downwind toward the filter bank and away from the breathing zone. Further, the deflection of the aerosol off the part in the 90° position may also contribute to exposure because some particles are directed upwind upon impact; whereas, the deflection of particles in the 0^{o} and 45^{o} position may direct the particles downwind or allow the ventilation to better capture and move the particles downwind.[19]

Spray Distance

The study results showed that the distance from the spray paint gun to the aerospace part did not significantly ($p>0.05$) effect exposure for any of the distances tested. While spray distance may not affect worker exposures to aerosols, distance does affect the quality of the coating.[15]

The effect of spray distance may have been difficult to determine based on the study design. First, the same parts were used throughout the study. Two trays of parts were prepared prior to the sampling and were alternated between subjects. As a result, these parts received multiple coats, well beyond the desired coating for production purposes. This excessive coating may have altered the transfer efficiency compared to production scenarios. In addition, the parts used for the study only represent a particular type of part that is typically coated. Larger and geometrically more diverse parts may yield different exposure results with respect to spray distance

Emphasis on spray distance as a research interest may be limited by the need to maintain specific distances for production purposes. To better determine whether spray distance is a driver of exposure, the methods used for this study need to be modified to incorporate the use of new parts for each condition, as well as, a variety of different aerospace parts. In addition, further attention to coating quality should be incorporate to insure that sampling methods mimic that of production painting processes.

IMPLICATIONS AND LIMITATIONS

The results of this study show practical implications for industry. First, this study may assist training programs for painters to stress the importance of orientation in reducing exposure. Second, painting operations may be able to reduce exposure even when the paint booth ventilation is deficient through the use of the 0^o and 45^o spray orientations. Moreover, the use of a real-time aerosol monitor proved to be an effective exposure monitoring tool for comparing the relative differences between varying painting techniques without the costly use of CrVI analysis. However, additional research is needed to determine the association between aerosol paint and CrVI exposures.

The study did highlight several limitations. First, the sample size was small in both the number of subjects tested and the number of ventilation scenarios evaluated. Second, real-time aerosol monitoring does not replace regulatory approved sampling methods for CrVI; such as OSHA ID-215 version 2 or NIOSH 7600 analytical methods. However, real-time aerosol monitoring does provide an effective method for evaluating relative differences between spray painters and ventilation designs. The third major limitation was the variability of the ventilation. The lower air velocity of the paint booth ventilation used for the study may have resulted in different exposure results for each condition. For example, had the ventilation been operating at the recommended 100 fpm, the pattern of exposure reduction may have been different.

Moreover, the exposure results for the 0^o orientation may have been higher due to the potential for an eddy to develop downstream of the painter and paint aerosol becoming entrained and accumulating in the worker's breathing zone. The best way to address this deficiency is to evaluate conditions that incorporate average ventilation air velocities of 100 fpm and higher.

Of special concern were the parts used for the study. First, larger parts than those used for the study may prove more difficult in maintaining a particular orientation. Further, the parts were repeatedly coated, which may have affected the transfer efficiency by increasing the percentage of coated surface area and increasing the amount of paint aerosol that stuck to the parts or rack that under normal production painting conditions would have remained airborne.

Finally, this study assessed exposure for a short duration of time for each condition. This duration may not be representative of the exposure for a full shift. Painters may shift orientations and find it difficult to remain in a single orientation in order to reduce exposure. Further, production needs remain a contributing factor to exposure. The needs of production, whether it be the rate of production or specific requirements, may dictate the techniques used in painting rather than a desire to reduce exposure.

FUTURE RESEARCH

Future work to further model the effects of orientation could prove useful in developing production strategies that enable companies to reduce the exposure to CrVI below the action level and permissible exposure level. To achieve this refinement, the use of motion sensing infrared videography could prove useful by allowing researchers to establish 3-dimensional relationships between the painter's body, spray paint gun, and the part sprayed. Not only could this information prove beneficial in improving painting best practices, it could also be integrated into new spray equipment design. Moreover, any findings could be integrated with measurements of transfer efficiency, which may prove possible by measuring the amount of paint used, film thickness, and percentage of paint solids

Additional research should also be aimed at determining the practicality of painters maintaining optimal orientations when spraying larger and more geometrical diverse parts. If optimizing painter orientation is to be a means of controlling exposure, then research in collaboration with industry must show that its practical to either move the part within the spray paint booth or the painter in order to maintain the desired orientation. Further, research should be directed at evaluating different paint booth air velocities to determine how higher and lower air velocities compare with the results of this study. Lastly, this research suggests that a reduction in aerosol exposure is possible even when the ventilation is operating below the ACGIH recommended air velocity of 100fpm. Research focusing on the ability of companies to tailor work practices to reduce exposures with less than effective engineering controls is warranted given the usefulness of holistically integrating work practices and engineering controls as an exposure reduction regime.

CONCLUSIONS

Aerospace spray painters using anti-corrosive base paints and primers are at risk of overexposure to CrVI. The current controls employed by industry and manufacturing, while effective in controlling for some exposures brought about by these paints and primers, are often ineffective at reducing CrVI exposure below the OSHA action level of 2.5 µg/m^3 and the permissible exposure limit of 5 µg/m^3. Given the current state of controls in the industry, research was conducted to evaluate the effectiveness of worker orientation and spray distance (distance from the spray gun nozzle to the part) on reducing exposures. Research results showed that worker orientation has a statistically significant impact on painter exposure to primer aerosols, with the orientation of 0^o and 45^o resulting in lower exposures than the reference orientation of 90^o. Exposures in the orientation of 180^o were noticeably higher than the 90^o reference orientation. These results show that the painter's orientation is a factor in paint aerosol exposures, which includes CrVI. Specifically, the results indicate that under the conditions tested worker orientations upwind of the spray painting resulted in lower exposures compared to 90^o. This evidence suggests that control of exposures is possible when the ventilation is operating below the ACGIH guidance of 100 fpm. Further research is necessary to determine whether production constraints allow for a consistent painter orientation that yields reduced exposures, whether the reduction brought about by orientation is great enough to reduce CrVI exposure below regulatory levels, and how aerosol exposures respond to higher and lower paint booth air velocities. Lastly, the results are applicable to other spray painting operations (i.e. top-coat) that do not use CrVI given the similarities of the processes.

Results for the effect of spray distance on exposure reduction show that under the conditions produced during this study, the three distances evaluated were not different with respect to exposure. While the study design may have led to these results, the limited difference between the three distances may in fact be negligible with respect to exposure. Given the impact on spray distance on coating quality, varying the spray distance to reduce exposure is not supported by this research and should be maintained in accordance with manufacturer specifications.

The overall results of this study suggest that work practices can play an integral role in personal exposures to spray paint aerosols. Where health effects brought about by low level exposures to contaminants in the work place challenge the traditional approach of using engineering controls as a primary strategy in reducing exposures, the evaluation of work practices is warranted in ensuring that exposures are adequately reduced. The challenge remains in striking the balance between the responsibilities of the employer and employee. More research is required to further understand the social and occupational implications of such a strategy in reducing exposures to not only CrVI in paints and primers, but also other exposures that challenge the existing strategies for control.

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