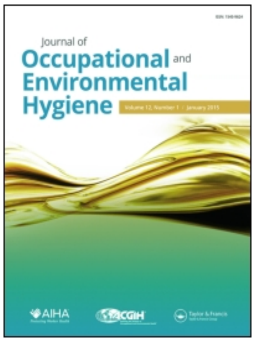

Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: http://www.tandfonline.com/loi/uoeh20

Respiratory Protection from Isocyanate Exposure in the Autobody Repair and Refinishing Industry

Youcheng Liu , Meredith H. Stowe , Dhimiter Bello , Susan R. Woskie , Judy Sparer , Rebecca Gore , Fred Youngs , Mark R. Cullen & Carrie A. Redlich

To cite this article: Youcheng Liu , Meredith H. Stowe , Dhimiter Bello , Susan R. Woskie , Judy Sparer , Rebecca Gore , Fred Youngs , Mark R. Cullen & Carrie A. Redlich (2006) Respiratory Protection from Isocyanate Exposure in the Autobody Repair and Refinishing Industry, Journal of Occupational and Environmental Hygiene, 3:5, 234-249, DOI: 10.1080/15459620600628704

To link to this article: https://doi.org/10.1080/15459620600628704

Published online: 23 Oct 2007.

Journal of Occupational and Environmental Hygiene, 3: 234–249
ISSN: 1545-9624 print / 1545-9632 online

DOI: 10.1080/15459620600628704

Respiratory Protection from Isocyanate Exposure in the Autobody Repair and Refinishing Industry

Youcheng Liu,[1] Meredith H. Stowe,[1] Dhimiter Bello,[2] Susan R. Woskie,[2] Judy Sparer,[1] Rebecca Gore,[2] Fred Youngs,[2] Mark R. Cullen,[1] and Carrie A. Redlich[1]

[1]Occupational and Environmental Medicine Program, Department of Internal Medicine, Yale University School of Medicine, New Haven, Connecticut
[2]Department of Work Environment, University of Massachusetts Lowell, Lowell, Massachusetts

This study, part of the Survey of Painters and Repairers of Auto bodies by Yale (SPRAY), evaluated the effectiveness of respiratory protection against exposure to aliphatic polyisocyanates. A total of 36 shops were assessed for respiratory protection program completeness; 142 workers were measured for respirator fit factor (FF) using PortaCount Plus respirator fit tester. Twenty-two painters from 21 shops were sampled using NIOSH method 5525 to determine the workplace protection factor (WPF) of negative pressure, air-purifying half-facepiece respirators equipped with organic vapor cartridges and paint prefilters during spray-painting and priming activities. Only 11 shops (30%) had written respiratory protection programs. Eighty percent of all fit tested workers passed the test on the first try with FF $\geq$ 100, and 92% passed the second test after respirator use training. Overall geometric mean (GM) FF was 1012 for all fit tested workers. Significant differences on pass rate (92% vs. 72%) and on FF (1990 vs. 736) were found between previously fit tested workers vs. nontested workers. Twenty-nine WPF samples were collected. The outside facepiece GM concentration of total isocyanate group (NCO) was 378.4 μg NCO/m^3 with 96% concentrations exceeding the U.K. short-term exposure limit, 70 μg NCO/m^3, but no in-facepiece concentrations exceeded the limit. The GM WPF of total NCO was 319 (GSD 4) and the 5th percentile was 54. WPF of total NCO was positively correlated with the duration of painting task. FF positively correlated with WPF when FF was $\leq$450 but negatively correlated with WPF when FF was >450. We conclude that negative pressure, air-purifying half-facepiece respirators equipped with organic vapor cartridges and paint prefilters provide effective protection against isocyanate exposure in spray and priming operations if workers are properly trained and fitted.

Keywords aliphatic polyisocyanates, hexamethylene diisocyanates (HDI), quantitative fit test, respiratory protection, survey of painters and repairers of auto bodies by Yale (SPRAY), workplace protection factor

Address correspondence to: Youcheng Liu, Occupational and Environmental Medicine Program, Yale University School of Medicine, 135 College Street, Room 366, New Haven, CT 06510; e-mail: youcheng.liu@yale.edu.

Autobody shops (collision industry or autobody repair and refinishing industry) are small businesses that are typically privately owned and geographically dispersed, with nonuniform work structures and practices.(1) They often lack resources for adequate engineering controls and complete respiratory protection programs.(2) In the United States, there are about 35,569 autobody facilities that are scattered throughout population centers, employing an estimated 168,000 to 205,000 workers.(3,4) Workers in this industry are exposed to a variety of respiratory hazards, including particles from sanding and body filling (bondo work); metals from cutting, grinding, and welding during body frame repair; volatile organic compounds from paints; and isocyanate vapor and aerosols from spray painting and priming operations.(2,5,6)

Isocyanates used in autobody shops are aliphatic or alicyclic polyisocyanates based most often on hexamethylene diisocyanate (HDI), and less commonly on isophorone-diisocyanate (IPDI) or occasionally dicyclohexylmethane 4,4-diisocyanate (HMDI), (7) all of which also contain small amounts (typically <1%) of the respective monomers.(7,8) Although mixtures are common during spray painting, the monomer is expected to be largely in the vapor phase whereas polyisocyanates are predominantly in the aerosol phase.(9) In the filtration process of a negative pressure, air-purifying half-facepiece respirator, aerosol particles/droplets in the inspired airstream are removed by the paint prefilters in front of the respirator. The vapors are removed primarily by packed activated carbon bed in the cartridges. The extent of aerosol vaporization after collection on respirator prefilters is unknown.

HDI, IPDI, and other diisocyanates are highly reactive chemicals that can cause occupational asthma in various settings including autobody shops.(10−17) Isocyanate asthma can persist even after removal from workplace exposure.(18,19) Therefore, control of isocyanate exposure through engineering measures and the use of respiratory protective equipment are important preventive measures. In the United States, the Occupational Safety and Health Administration (OSHA) requires small businesses like autobody shops to provide respirators to reduce employee exposure to respiratory hazards when engineering and administrative controls are not feasible or effective.[20] Fit testing before the use of a respirator and at least annually thereafter is an integral part of such a respiratory protection program.[21]

For a respiratory protection program to be effective, appropriate types of respirators must be selected based on the evaluation of hazards in the workplace and the identification of relevant workplace and user factors.[21] Factors to consider in the autobody repair industry include (a) the type of spray booth used that may affect exposure levels, or (b) the presence of facial hair at the edge of the respirator face seal that may interfere with the respirator fit. An important criterion in selecting respirators is the assigned protection factor (APF) established by the National Institute for Occupational Safety and Health (NIOSH) in its respirator decision logic.[22] However, the NIOSH AFP is mostly based on fit factor (FF) results from quantitative laboratory fit testing,[23] whereas in the workplace, many factors may affect actual effectiveness. Thus it is important to evaluate the performance of respirators in the work environment to determine the actual workplace protection factor (WPF).[24] Depending on the type of work environment and hazards, the WPF can vary considerably within and between workers[23] or among respirator types.[25]

Workplace performance testing with negative pressure, air-purifying half-facepiece respirators has been conducted in various work environments,[26−31] but few studies have been carried out to evaluate the performance of respirators in autobody shops against exposures to HDI vapor and aerosol.[32] Laboratory simulation testing with organic vapor respirator cartridges has suggested that no breakthrough would occur after 25 to 40 hours of cartridge exposure to challenge concentrations of HDI below 50[33] or 105 ppb[34] in the presence of organic solvents. Field testing in autobody shops is needed. In addition, little has been reported on the fit testing pass rate and fit factors for autobody shop workers, although limited testing from earlier NIOSH studies indicated poor fit and inappropriate respirator usage.[2,35]

In recent years, the U.S. Environmental Protection Agency (EPA) has been actively regulating polyisocyanate components of automotive refinishing paints and coatings through the New Chemicals Program,[35] and the OSHA regional office in Bridgeport, Connecticut, established a local emphasis program, including required respiratory protection, to reduce workplace health hazards associated with autobody shop work.[36] Additionally, a voluntary program called Product Stewardship Partnership was initiated by members of paint manufacturers, EPA, OSHA, NIOSH, and automotive repair associations to help autobody shops formulate a control strategy matrix that guides the selection of specific respiratory protection to be used with particular spray-painting booths.[35] It is not clear what impact these initiatives have had on respiratory protection in this industry.

Our group has conducted a cross-sectional study, Survey of Painters and Repairers of Auto bodies by Yale (SPRAY). Comprehensive strategies were utilized to evaluate airborne exposure to HDI polyisocyanates[37] assess the effect of shop factors, painting activities, engineering controls, and other determinants on airborne exposure[38] and determine the dermal contribution to total isocyanate exposures.[7] A final risk analysis is being conducted using personal isocyanate exposure indices modeled on exposure determinants. Respirator use, in theory, will modify individuals' airborne exposure to a significant extent and its effectiveness needs to be evaluated.

This study was therefore part of the overall SPRAY exposure assessment protocol with specific objectives to: (a) assess the respiratory protection programs in use in this industry, (b) evaluate respirator fit and identify its determinants, and (c) measure workplace performance of negative pressure, air-purifying half-facepiece respirators, and (d) evaluate the relationship of FF from PortaCount Plus respirator fit tester and WPF from isocyanate exposure measurements. The WPF developed in this study can be used both to model daily personal exposures to isocyanates, and to facilitate exposure control in this industry.

MATERIALS AND METHODS

Shop and Worker Selection

Details on shop and worker selection have been described elsewhere.[1,37,38] All workers in selected shops in the New Haven, Conn., vicinity, including painters, body repair technicians, and office workers were eligible to participate in the SPRAY health evaluation and overall exposure assessment. The Human Investigation Committee at Yale University approved the study. Written informed consent was obtained from all subjects and shop owners.

Respiratory Protection Program Survey

Information from the owner/manager on annual gross income; total numbers of full-time and part-time employees; weekly number of cars or parts repaired; brands and quantities of paints and isocyanate hardeners used; type of spray booth and gun used; and type of personal protective equipment used, such as respirators, gloves, and paint suits was collected. Supplementary questions were addressed to painters if not answered by the manager. Questions pertaining to the respiratory protection program included whether a written program was established in the shop, if employees were trained to use respirators, if medical screening was provided for respirator users, and if any fit testing had been previously conducted. Information on the type, brand, coverage and cartridges of various respirators currently provided for spray painting, priming and body repairs, was collected both by interview and direct observation.

Respirator Selection and Fit Testing

Respirators selected for fit testing were the negative pressure, air-purifying half-facepiece respirators from Survivair

(SAS, Santa Ana, Calif.) and 3M Company (St. Paul, Minn.), equipped with organic vapor cartridges and paint prefilters (N95 from SAS; P95 from 3M), because these were the two major respirator types used in most shops for painting or priming. They were also used with P100 (or HEPA) filters for welding, sanding, and cutting tasks. In the selected shops, all participating workers who regularly used respirators in their work were fit tested. The testing was performed using the TSI PortaCount Plus respirator fit tester (model 8020, TSI Inc., Shoreview, Minn.); workers wore their own respirators. If a worker's own respirator was not available, a respirator of the same brand was provided by the study. The P100 (HEPA) filters and the respirator adaptors used for quantitative fit testing were purchased from the same manufacturers. Adaptors were placed in between the half facepieces and the P100 filters during quantitative fit testing. The brass probe from the adaptor was inserted through one of the inhalation valves and was placed in the approximate center of the respirator, above the exhalation valve and between the cartridge holders (see Figure 1).

The test protocol was based on those in the OSHA respiratory protection standard[21] and the American National Standard Institute (ANSI) method.[39] Since our protocol was selected before the new OSHA respirator standard was promulgated, FFs were measured when workers performed the following six (rather than current eight required) exercises: normal breathing (NB1), deep breathing (DB), moving head side to side (SS), moving head up and down (UD), talking (TK: reading the rainbow passage aloud or counting numbers backward if the subject did not read English), and normal breathing (NB2). The PortaCount Plus respirator fit tester automatically calculated a FF for each exercise and the overall testing using the following pre-determined equation:[40]

$$\text{Overall FF} = 6/[(1/\text{NB1}_{\text{FF}}) + (1/\text{DB}_{\text{FF}}) + (1/\text{SS}_{\text{FF}}) + (1/\text{UD}_{\text{FF}}) + (1/\text{TK}_{\text{FF}}) + (1/\text{NB2}_{\text{FF}})] \quad (1)$$

A level of 100 or above as the overall FF was considered passing consistent with the requirement in the OSHA Respiratory Protection Standard.[21] The first test was conducted without any training. If a worker failed the test on first try, training was provided on the proper use of respiratory protective devices. The worker was instructed to retighten the respirator or could select a different size respirator. The quantitative fit test was then repeated. This protocol was consistent with that used in earlier NIOSH investigations.[2] The goal was for all workers to achieve an adequate fit unless facial hair or other anatomic reasons prevented it. The actual FFs (each step and overall) and final pass/fail grade were recorded. Fit testing was conducted before respirator workplace performance samples were taken.

WPF Sample Collection

WPF testing was performed using workers' own half-facepiece respirators and N95 (or P95) prefilters if the facepieces were the reusable type that had detachable cartridges. Some workers also used the disposable type (exclusively from the 3M Company) in which the cartridges could not be detached from the facepiece. In-facepiece sampling was therefore not feasible for the disposable facepiece. In this case, we provided the reusable respirator facepiece of the same brand and size with organic vapor cartridges and paint prefilters for WPF testing.

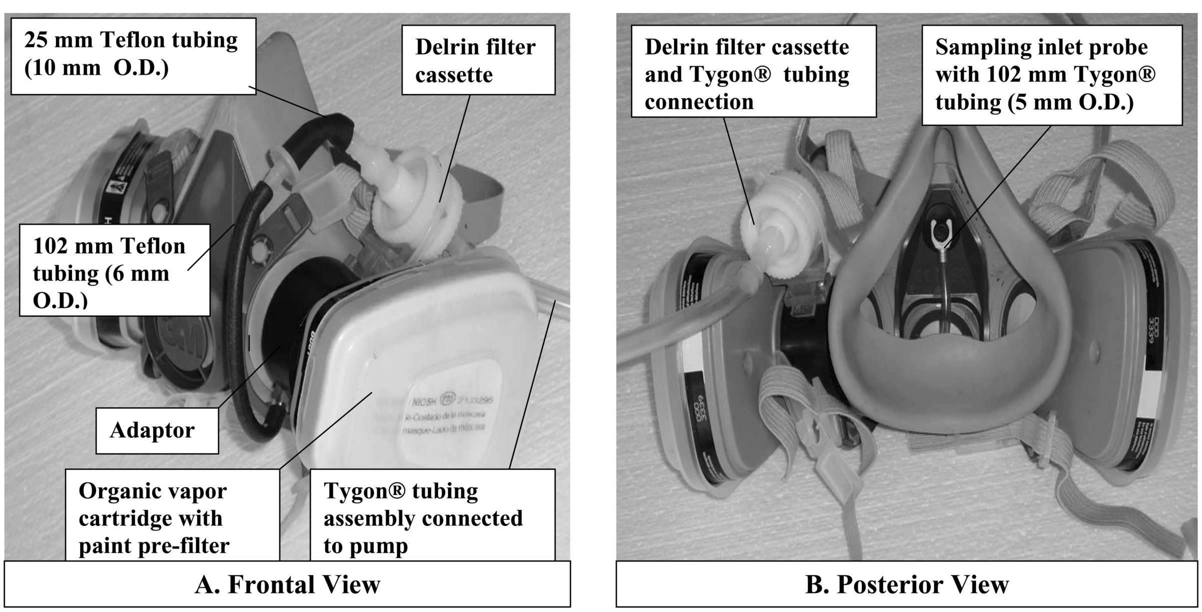

FIGURE 1. In-facepiece air sampling setup. The frontal view shows the mounting and connection of the respirator adaptor and Delrin cassette. The posterior view shows the location of in-facepiece sampling probe.

The sampling protocol to determine outside facepiece concentrations was based on the overall SPRAY exposure assessment strategy. Breathing zone air samples were collected at 2 L/min using an IOM inhalable sampler (SKC, Eighty Four, Pa.) attached on lapel and Gilian (Wayne, N.J.) personal sampling pumps calibrated before and after sampling with a DryCal DC-Lite primary flowmeter (Bios International Co., Pompton Plains, N.J.). IOM samplers with stainless steel cassettes were loaded with 25-mm quartz fiber filters impregnated with 500 μg of 1-(9-anthracenylmethyl)piperazine (MAP).[41] Filters still inside their stainless steel cassettes were transferred immediately after sampling to a jar containing 10 mL of a solution of 1×10^{-4} M MAP in acetonitrile. All samples were stored cold in the field and shipped in cooled containers to the laboratory for analysis. Additional details on sampling methods are provided in previous publications.[37,38]

The in-facepiece sampling was conducted using a 25-mm in-line polyacetal plastic Delrin cassette made by Dupont (SKC) that contained a single quartz fiber filter pretreated as described for the general air sampling.[37] The cassette was mounted to and connected with the respirator adaptor using two pieces of Teflon tubing with one piece 102 mm long and 6 mm O.D. and the other 25 mm long and 10 mm O.D. There was also a 76 to 102 mm long and 5 mm O.D. Tygon tubing as the sampling probe leading from the adaptor into the facepiece of the respirator as in fit testing (see Figure 1 for setup details). The Teflon tubing was preferred over Tygon tubing in sampling in an effort to minimize the loss of isocyanates. A sampling rate of 2 L/min was chosen based on the protocol from a similar study in aircraft spray painting.[31]

The WPF sample collection focused on tasks that had direct contact with isocyanate-containing products, namely, priming (or undercoat), sealer coating (to replace priming or cover the primer coat), and clear coating (top coat). Base coating (color coating or painting) was not sampled because no isocyanate-containing hardeners were used in most shops during our study. Priming was largely conducted on the shop floor outside the booth or inside a prep station (plastic curtain enclosures with mechanical ventilation) by body repair technicians, whereas painting was mostly done inside a spray booth by painters. Further description of autobody shop tasks is available from a previous publication.[38]

Once a worker was ready to paint inside a booth or to prime on the shop floor, both sampling pumps were turned on. Workers were asked to keep wearing the respirator between coats during their painting/priming tasks. If the worker had to take off the respirator for a break or to refill, the pumps were put on "hold" position. Sampling resumed after the respirator was put back on. Sampling duration covered the total spray time needed to finish a whole coating layer (1 coat for sealing, 1–5 coats for priming, and 2–3 coats for clear coating, all of which took from 3–38 min).

For each sample taken, information was also collected on the task activity (painting or priming), quantity of paints used, reducer and isocyanate hardeners added and their mixing ratios, painted (primed) area of the car, duration of the task and sampling, type of respirators used, and ventilation conditions in the booth or on the shop floor.

For logistic reasons, we were not able to collect in-facepiece samples for positive pressure half-face or full-face respirators, such as supplied-air respirators, and for N95 disposable dust masks. These respirator types were used less commonly than those reported here (see below). We were also not able to collect in-facepiece samples for the disposable type of facepieces in negative pressure, air-purifying respirators with organic vapor cartridges and paint prefilters, but we assumed their performance would be similar to the reusable facepieces.

Sample Analysis

Isocyanate concentrations were quantified as HDI monomer (HDI), HDI polyisocyanates (pHDI), and IPDI polyisocyanates (pIPDI) from the same sample using NIOSH method 5525[41] and an Agilent HP1100 HPLC system with Agilent Chemstation software as described previously.[42,43] Exposure units were expressed as reactive isocyanate group mass, from hereon referred to as the NCO mass (μg). The μg NCO was used for HDI, pHDI, and pIPDI. The total μg NCO was the sum of HDI, pHDI, and pIPDI. The advantages for using this unit and factors for converting from NCO to the bulk product mass or the monomer mass have been discussed previously.[8] The assigned limit of detection (LOD) for the method was 4 ng NCO for HDI and 5 ng NCO for pHDI and pIPDI. For samples reported as at or below LOD, the actual assigned LOD values were used and divided by the sample air volumes to obtain the concentrations, which were then used in the statistical analysis. The LOD rather than ½ LOD was used to provide the most conservative estimates of protection factor, since most LOD values were inside the respirators. Because pIPDI was not used in 40% paints sampled, WPF for pIPDI was calculated only for those samples when pIPDI was actually present in the paint being used. Also for the total NCO calculation, pIPDI LOD was used only if the paint contained pIPDI.

Statistical Analysis

An average FF was obtained from the PortaCount Plus respirator fit tester for each worker. Fit test pass rate (%) was calculated as the number of workers passing the minimal FF of 100 on any test divided by total number of workers tested times 100. WPF was calculated as the outside-facepiece concentration (Co) divided by in-facepiece concentration (Ci). WPF was calculated separately for HDI, pHDI, pIPDI, and total NCO. Samples from the same worker were treated as independent samples as was the common practice in WPF studies.[23]

Statistical analysis was performed using Statistical Analysis System (SAS) software (version 8.12, SAS Institute). Descriptive statistics were obtained and Co, Ci, FF, and WPF data checked for normality using Shapiro-Wilk test and log probability plots. Outside and in-facepiece isocyanate concentrations, FF and WPF were normally distributed after log transformation. Therefore, statistical testing was performed on log-transformed data.

Fit test pass rates were assessed by the Chi-Square test and FFs evaluated by the analysis of variance (ANOVA) among personal characteristics, such as job category, gender, race, smoking status, education, and years working in autobody repair industry. The two-sample t-test was used to compare isocyanate concentrations and WPFs between clear coating and priming/sealer coating tasks, and between 3M and SAS respirator brands. A Pearson's correlation analysis was performed among the WPFs of all isocyanate types, and between the WPF of total NCO and the duration of painting. A random effects model was used to analyze the WPF variability within and between workers (respirator wearers).

To see if FF was a significant predictor of WPF, we matched FF measurements on 22 wearers with 28 WPF estimates from these workers, and conducted a regression analysis. One WPF sample (Worker 36 in Shop 5) did not have the FF and was excluded from this analysis. A visual inspection of the data indicated that a linear fit would be unsatisfactory as the log WPF increases and then decreases with increasing log FF. The broken stick regression was used instead, which is an example of a regression spline. A spline fit permits a more flexible fit to the data than allowed by regular regression by letting the slope vary at certain points on the predictor scale called knots. A number of different models were fit as various values of the break point were investigated. A knot of 450 [log (450) approximately = 6.1] was selected as giving the best fit using R^2 (about 34%) as a fit criterion. Once the knot was determined, a repeated measures regression was used to adjust for the repeat WPFs for 7 wearers. The SAS PROC REG was used as the first pass to obtain the "approximate" R^2, and to look at p-values for a standard regression. The SAS GENMOD procedure was then used to take into account nonindependent replicates. A repeated-measure adjustment was made for the fact that the fit factors were used repeatedly. This gave a better estimate of standard error for the regression estimates. The intercept was set at 0.

RESULTS

Respirator Use and Protection Program in Autobody Shops

As briefly reported in a previous article,[38] 37 autobody shops participated in the SPRAY study; one shop did not use the isocyanate hardeners during the survey week, therefore, the respirator data from this shop was excluded. Table I presents the details of respirator types provided and protection programs in place from 36 shops. A total of 32 shops provided workers with negative pressure air purifying, half-facepiece respirators for some task or tasks. The percentages do not add up to 100% because more than one brand of respirators was provided in some shops. For the 3M brand, more disposable-facepiece respirators (28 shops, 78%) were provided than reusable ones (10 shops, 28%). For the SAS brand, more reusable facepieces (24 shops, 67%) were provided than disposable ones (3 shops, 8%). However, SAS disposable facepieces were not used during our study; only disposable half-facepiece respirators with organic vapor cartridges and paint prefilters from 3M were used. Out of 36 shops, 23 (64%) also had one or more other respirator brands in their shops for painting and priming. These brands included MSA, Wilson, North, Binks, AO Safety, Gerson, and Sata. Although these respirators were available in the shops, most were rarely used. By report, shops selected specific respirator brands largely based on individual shop preference and manufacturers' representative (supplier) recommendations.

TABLE I. Respirators Used and Respiratory Protection Program in Autobody Shops (N = 36)

	Number of Shops (%)
Painting and priming respirator	
3M OV/P95[A] reusable	10 (28)
3M OV/P95 disposable	28 (78)
SAS[B] OV/N95[C] reusable	24 (67)
SAS OV/N95 disposable	3 (8)
Other brands[D]	23 (64)
Supplied-air respirator usage for painting and priming	
3M	14 (39)
SAS	2 (6)
Other	7 (19)
Non-painting-task respirator	
3M reusable OV/P100[E]	3 (8)
3M disposable OV/P100	1 (3)
SAS reusable OV/P100	1 (3)
3M N95 dust mask	11 (30)
Written respirator protection program	11 (30)
Employees trained to use respirator	19 (53)
Fit testing ever conducted	15 (42)

[A]OV/P95: Organic vapor cartridges and P95 oil-proof particle prefilter.
[B]SAS: Survivair System.
[C]OV/N95: Organic vapor cartridges and N95 nonresistant to oil particle prefilter.
[D]Other brands: Including MSA, Binks, etc. (refer to text for more details).
[E]OV/P100: Organic vapor cartridges and oilproof, high-efficiency particulate air prefilter.

For nonpainting tasks, such as sanding, grinding and welding, only 5 shops (14%) provided negative pressure, air-purifying half-facepiece respirators equipped with P100 (HEPA) filters. N95 dust masks were provided in 11 shops (31%). These masks were exclusively manufactured by 3M Company.

The type of supplied-air respirators (SAR) provided in shops is also presented in Table I. Of 36 shops, 23 shops (64%) provided SAR for painting (20 shops, 56%) and priming (3 shops, 8%). 3M was the major supplier of SAR. Actual use of SAR, however, was observed only in 11 (30%) shops during our survey time.[38] The most common stated reason that painters did not use SAR was that the airline hoses were cumbersome.

A written respiratory protection program was reported in 11 shops (30%); 19 shops (53%) had their employees trained to use respirators; and 15 shops (42%) had previously conducted fit testing for their employees. No medical screening or respirator maintenance program was provided in any of these shops.

Demographics of Study Subjects

A total of 266 workers participated in the SPRAY study, of which 142 reported routinely using a negative pressure, air-purifying half-facepiece respirator in their work. These workers were selected for fit testing. The other 124 workers were either office workers or those who did not use respirators for their work, such as workers doing detailing or tow truck driving. Twenty-two of the 142 workers with fit testing also participated in the WPF testing. Table II shows that the two subsets of the total population (FF testing and WPF testing) were comparable with regard to age, race, educational background, smoking status, and years working in the autobody repair and refinishing industry, similar to our prior findings.[1] However, unlike fit testing, WPF testing was conducted primarily with painters (95%) with only one body technician whose priming task was evaluated.

Fit Factors (FF)

Pass rate and FF of negative pressure, air-purifying half-facepiece respirators are presented in Table III. Out of 142 workers tested, 113 (80%) passed the test on the first try and 29 (20%) failed. Reasons for failing were: inappropriate donning and loose fitting facepiece (N = 17, 59%); thick beard and facial hair at the facepiece sealing edge (N = 9, 31%); and wrong respirator size (N = 3, 10%). Of those who failed on the first try, 23 (including 3 of the 9 failed with facial hair) were retested after training, redonning, and tightening of the respirator, or the choice of another respirator size. Eighteen workers (78%) passed the second test. Of the five failing the second test, three were those with facial hair who failed the first time. The other two still had a loose fit on the second try. Overall, 92% of workers passed after the first and second tests. The pass rate on first try was significantly higher ($p = 0.04$) for workers who reported to have been fit tested on a previous occasion (92%, N = 53) vs. those without previous testing (72%, N = 86). No statistically significant difference in pass rate was observed with other characteristics such as job category, gender, race, smoking status, education level, years employed in the industry, or respirator brand.

TABLE II. Demographics of Workers with Respirator Fit Testing and WPF Testing

	Fit Testing N = 142[A]		WPF Testing N = 22	
	n[B]	(%)	n[B]	(%)
Age				
Mean (SD)[C]	37.1 (10.8)		35.8 (7.1)	
Race				
Caucasian	108	77	18	82
Hispanic-American	24	17	4	18
African-American	8	6	0	0
Education (years)				
Less than 12 years	30	21	4	18
Graduated high school	74	52	14	64
Technical/associate or some college	32	23	3	14
College degree or more	6	4	1	4
Smoking				
Yes	60	42	9	41
No	82	58	13	59
Job category				
Painter	44	31	21	95
Technician	87	61	1	5
Office worker	11	8	0	0
Years in industry				
Mean (SD)	17.9 (10.4)		19.0 (7.3)	

[A] N = number of total workers in each testing type.
[B] n = number of workers in each category.
[C] SD = standard deviation.

TABLE III. Fit Test Pass Rate and Fit Factor of Negative Pressure, Half-Facepiece Respirators by Personal Characteristics

	Fit Test Pass Rate			Quantitative Fit Factor[A]	
	N[B]	n[C]	(%)	GM[D]	GSD[E]
Total	142	113	80	1012[F]	10.6
Job Category					
Painter	44	37	84	1033	9.2
Technician	87	67	77	988	11.5
Office worker	11	9	82	1128	10.8
Gender					
Male	141	112	79	996	10.6
Female	1	1	100	10100	—
Race					
Caucasian	108	89	82	1033	9.8
Hispanic-American	24	16	67	884	15.4
African-American	8	7	88	1422	8.2
Current Smoking					
Yes	60	49	82	1037	10.0
No	82	64	78	995	11.0
Education					
Less than 12 years	30	24	80	1279	15.6
Graduated high school	74	60	81	1011	10.0
Technical/associate or some college	32	24	75	764	8.7
College degree or more	6	5	83	1431	10.7
Years in Industry					
<2	10	6	60	848	16.5
≥2	132	107	81	1026	10.3
Respirator Brand					
3M	70	55	78	1093	9.7
Survivair	71	57	80	934	11.8
Previous Training					
Yes	88	72	82	1145	10.6
No	45	34	76	989	10.3
Previous Fit Testing					
Yes	53	49	92*	1990*	7.3
No	86	62	72	736	11.8

Note: Dash represents not applicable.
[A] Fit factor from TSI PortaCount respirator fit tester: 100 or above indicated a pass and below 100 indicated a failure.
[B] N = total number of workers tested.
[C] n = number of workers passing the first test.
[D] GM = geometric mean.
[E] GSD = geometric standard deviation.
[F] GM FF for all workers tested.
*$p < 0.05$ comparing FFs between those previously fit tested and those never tested.

Overall geometric mean (GM) FF for all workers tested was 1012. Previously fit tested workers had significantly higher FF than workers who had never been tested before (1990 vs. 736, $p = 0.015$). No other characteristics were found to significantly affect the FF.

It is worth noting, however, that Hispanic workers; workers new in the industry (<2 years); and those with technical school, associate, or some college education showed a lower (but nonsignificant) pass rate and FF. Also noted were the high geometric standard deviations (GSDs) of FF for all categories, especially for those workers new to the industry and with less than 12 years of education, which was due to the high variability of FF between workers.

Outside-Facepiece Exposures

A total of 22 workers from 21 shops contributed 29 pairs of WPF samples using the reusable negative pressure, air-purifying half-facepiece respirator with organic vapor cartridges and paint prefilters. All workers in the WPF testing passed the fit test.

The outside-facepiece air samples were a subset of the total 380 air measurements conducted for the SPRAY study. Individual concentrations of HDI, pHDI, pIPDI, and total NCO are presented in Table IV. The locations of the sampling were mostly inside spray booths except for two samples from Worker 64 and Worker 134 that were taken on the shop floor during priming operations. Individual concentrations of isocyanate species and the total μg NCO/m^3 were generally in similar ranges to those found from the overall SPRAY study.[37] The full range was from 0.3 to 22.4 μg NCO/m^3 for HDI, 50.8 to 3135.0 μg NCO/m^3 for pHDI, 31.5 to 2392.7 μg NCO/m^3 for pIPDI, and 51.7 to 5550.0 μg NCO/m^3 for total NCO.

Table V further summarizes the isocyanate species and their respective outside-facepiece concentrations in comparison with relevant standards or guideline values. Average levels (GMs) were much higher than those (medians) reported earlier from the overall SPRAY study.[37] The GM(GSD) concentration of HDI was only 2.4(3.0) μg NCO/m^3, whereas GMs(GSDs) for pHDI and pIPDI were 302.8(2.8) μg NCO/m^3 and 135.5(2.9) μg NCO/m^3, two orders of magnitude higher, which indicates that pHDI and pIPDI contributed the most to the total NCO exposure, 378.4(3.0) μg NCO/m^3.

Although U.S. OSHA does not have a permissible exposure limit for aliphatic isocyanates,[44−45] occupational exposure limits (OELs) have been promulgated from other organizations or governments. The NIOSH ceiling limit (10 min) for HDI monomer, equivalent to 70 μg NCO/m^3, was used for comparison with HDI in Table V. NIOSH does not have a recommended exposure limit (REL) for pHDI, but the state of Oregon and Bayer Corporation have promulgated a short-term exposure limit (STEL, 15 min) for HDI-based polyisocyanates (biuret and isocyanurate) equivalent to 220 μg NCO/m^3. This was used for comparison with pHDI in Table V and in the SPRAY study.[37] For pIPDI and total NCO, the United Kingdom Health and Safety Executive (UK-HSE) STEL (10 min) of 70 μg NCO/m^3 for any isocyanate was used. Table V shows that no outside-facepiece HDI concentrations were above the NIOSH HDI monomer ceiling limit; 59% of pHDI concentrations exceeded the very high Oregon/Bayer STEL 220 μg NCO /m^3, whereas 72% pIPDI and 96% of total NCO concentrations were above the UK-HSE STEL for any isocyanate.

Outside facepiece concentrations (GM and GSD) were higher during clear coating tasks than in priming and sealer coating tasks with 350.7 (2.8) vs. 149.9 (2.6) μg NCO/m^3 for pHDI and 431.4 (2.9) vs. 175.7 (2.5) μg NCO/m^3 for total NCO. However, due to the small sample size in priming and sealer coating (N = 5), this difference was not statistically significant. Concentrations of HDI were similar during both operations: 2.3 (3.3) vs. 2.5 (2.4) μg NCO/m^3. No comparison was made for pIPDI because some of the clear coating and most primer paints sampled did not contain any IPDI component.

In-Facepiece Exposures

The in-facepiece concentrations of HDI, pHDI, pIPDI, and total NCOs from negative pressure, air-purifying half-facepiece respirators with organic vapor cartridges and paint prefilters are also presented in Tables IV and V. Overall, in-facepiece concentrations differ from the outside-facepiece concentrations by several orders of magnitude. In-facepiece samples at or below the LOD were 83% for HDI, 31% for pHDI, and 50% for pIPDI. No in-facepiece concentrations were above their respective OELs or STELs.

Workplace Protection Factor (WPF)

A total of 29 outside- and in-facepiece respirator sample pairs were collected to calculate WPFs for HDI, pHDI, pIPDI, and total NCO. Results appear in Tables IV and VI. WPFs ranged from 1 to 204 with a GM(GSD) of 17(4) for HDI, from 7 to 9777 with a GM(GSD) of 388(4) for pHDI, from 20 to 1489 with GM(GSD) of 358(3) for pIPDI, and from 9 to 5335 with GM(GSD) of 319(4) for total NCOs.

A comparison of WPF between primer/sealer coating and clear coating showed no statistically significant difference ($p > 0.05$), although WPFs [GM(GSD)] were higher in priming and sealer coating tasks than in clear coating tasks [HDI: 32(3) vs. 15(5); pHDI: 519(6) vs. 365(4); and total NCO: 404(4) vs. 304(4)].

Table VI summarizes the WPFs of HDI, pHDI, pIPDI, and total NCOs between two major respirator brands, SAS and 3M. No statistically significant difference in WPFs was found for pHDI, pIPDI, and total NCO. A statistically significant ($p < 0.05$) difference was only found for the WPF HDI with a higher value for 3M brand than the SAS brand [33(3) vs. 8(4)]. Table VI also presents the 5th, 10th, and 50th percentile estimates of WPFs for the two respirator brands based on total NCO concentrations. The 5th percentile of WPF estimate was 45 for SAS and 73 for 3M, both of which are greater than the ANSI assigned protection factor of 10 for negative pressure, air-purifying half-facepiece respirators with organic vapor cartridges. The overall GM WPF for all respirators was 319 (GSD = 4) and the 5th percentile 54.

To determine if facepiece leakage vs. incomplete collection via respirator cartridges was the cause for respirator breakthrough, we examined whether the WPF HDI and WPF pHDI changed proportionally. If so, leakage was suggested. The result from the Pearson's correlation analysis showed that WPF HDI increased positively with the increase of WPF pHDI with a correlation coefficient of 0.55 (N = 29, $p = 0.0019$). The Pearson correlation analysis also showed a positive correlation between the painting duration (min) and the WPF total NCO with correlation coefficient at 0.42 (N = 29, $p = 0.023$).

TABLE IV. Outside- (Co) and In-Facepiece (Ci) Concentrations (in μg NCO/m^3) of Isocyanates and WPF

Shop ID	Worker ID	Resp. Type^A	Co-HDI^B	Ci-HDI	Co-pHDI^C	Ci-pHDI	Co-pIPDI^D	Ci-pIPDI	Co-Total^E	Ci-Total	WPF-HDI	WPF-pHDI	WPF-pIPDI	WPF-Total^F	Painting Task	Fit Factor
5	36	3M	1.14	0.03*	75.13	1.33	38.79	0.03*	115.06	1.38	43	57	1463	84	Primer	—
6	44	3M	6.50	0.04*	147.65	0.05*	—	—	154.15	0.08	178	3281	—	1891	Primer	6080
8	54	3M	2.80	0.03*	293.31	0.03*	—	—	296.11	0.06	110	9777	—	5335	Clear	1400
10	64	3M	5.59	0.13*	530.07	0.16*	—	—	535.66	0.28	45	3420	—	1913	Primer	446
12	74	SAS	4.56	0.08*	625.62	0.10*	—	—	630.17	0.17	59	6585	—	3664	Clear	453
14	84	SAS	0.41	0.13*	65.63	9.63	42.21	2.16	108.24	11.91	3	7	20	9	Clear	76432
14	84	SAS	0.86	1.00*	169.25	1.25*	107.26	0.95*	277.37	3.20	1	135	113	87	Clear	76432
15	89	SAS	0.33*	0.33*	117.09	0.42*	—	—	117.42	0.75	1	282	—	157	Clear	5483
17	121	SAS	1.95	0.29	709.84	1.48	253.78	0.17	965.56	1.93	7	481	1489	500	Clear	768
18	134	SAS	0.93	0.14*	50.82	0.18*	—	—	51.75	0.32	6	282	—	160	Primer	2051
25	178	3M	0.33	0.03*	125.81	0.60	31.54	0.03*	157.67	0.66	10	211	925	238	Clear	155
27	193	3M	2.05	0.07*	205.49	0.09*	—	—	207.54	0.15	30	2418	—	1348	Clear	12100
28	195	SAS	2.50	0.17**	253.29	1.21	85.32	0.16*	341.1	1.5	15	209	536	222	Sealer	22800
28	195	SAS	20.40	0.10*	2016.00	3.88	—	—	2036.40	3.98	204	2016	—	512	Clear	22800
29	197	SAS	1.15	0.05**	198.66	0.44	59.50	0.43	259.31	0.92	22	457	139	283	Clear	5130
31	205	SAS	0.75	0.33*	74.17	0.84	—	—	74.92	1.17	2	89	—	64	Clear	1880
32	209	3M	2.25	0.83	326.84	3.50	324.94	0.31*	654.02	4.65	3	93	1034	141	Clear	14700
32	209	3M	13.78	0.20	687.73	11.19	379.70	11.43	1081.21	22.82	69	62	33	47	Clear	14700
33	221	SAS	4.25	0.28	1184.55	3.28	283.66	1.10	1472.46	4.65	16	362	258	317	Clear	2480
33	226	SAS	0.65	0.20*	106.30	0.90	32.84	0.19**	139.79	1.29	3	118	173	108	Clear	219
34	233	3M	1.44	0.20	224.50	1.00	96.21	0.38	322.15	1.58	7	224	254	204	Clear	212
34	233	3M	7.27	0.09*	638.00	1.50	209.47	0.38	854.74	1.97	83	425	553	435	Clear	212
35	245	SAS	1.53	0.18**	137.00	0.50*	—	—	138.53	0.68	8	274	—	204	Clear	1440
35	245	SAS	3.61	0.21*	397.50	0.50	—	—	401.11	0.71	17	795	—	567	Clear	1440
36	250	3M	22.35	0.50**	3134.98	7.52	2392.69	6.32	5550.03	14.33	45	417	379	387	Clear	8860
37	256	3M	2.10	0.13**	478.35	0.72	124.84	0.13*	605.29	0.98	16	665	978	617	Clear	347
37	256	3M	5.37	0.13**	526.21	0.49	139.92	0.12*	671.49	0.75	40	1064	1188	899	Clear	347
38	261	3M	6.37	0.03*	1076.63	1.85	256.91	0.42	1339.90	2.30	190	581	614	582	Clear	9620
38	261	3M	2.70	0.29*	490.63	1.17	134.06	0.27*	627.38	1.72	10	421	497	364	Clear	9620

Notes: Concentrations have been rounded to nearest two decimal places for presentation. WPFs were calculated from nonrounded concentrations; therefore, they may not be the same as those calculated directly from the table. Dashes indicate pIPDI not present in bulk products.

^{A}SAS = Survivair.

^{B}HDI = HDI monomer.

^{C}pHDI = HDI polyisocyanate.

^{D}pIPDI = IPDI polyisocyanate.

^{E}Total = total NCO, sum of all isocyanate species.

^{F}WPF Total = Co-Total/Ci-Total.

*Concentrations at the LOD.

**Concentrations below the LOD.

TABLE V. Outside- and In-Facepiece Concentrations (μg NCO/m^3) of Aliphatic Isocyanates by Isocyanate Species

	Isocyanate Species	N^A	GM^B	GSD^C	25–75th Percentile	LOD^D (%)	OEL^E (μg NCO/m^3)	>OEL^F (%)
Co^G	HDI	29	2.36	3.1	1.14–5.36	3	70 (NIOSH)	0
	pHDI	29	302.78	2.8	137.00–625.78	0	220 (Oregon)	59
	pIPDI	18	135.50	2.9	65.10–254.68	0	70 (UK-HSE)	72
	Total	29	378.42	3.0	154.16–671.83	0	70 (UK-HSE)	96
Ci^H	HDI	29	0.14	2.6	0.08–0.27	83	70 (NIOSH)	0
	pHDI	29	0.78	4.4	0.44–1.50	31	220 (Oregon)	0
	pIPDI	18	0.38	4.8	0.16–0.52	50	70 (UK-HSE)	0
	Total	29	1.19	4.2	0.68–2.30	0	70 (UK-HSE)	0

^{A}N = number of samples.
^{B}GM = geometric mean.
^{C}GSD = geometric standard deviation.
^{D}LOD (%) = the percentage of samples at or below the assigned limit of detection.
^{E}OEL = occupational exposure limit. The concentrations in NCO were the equivalents of original product mass concentrations.
^{F}Percentage of samples above OEL. For HDI (monomer), the ceiling limit (10 min) of 70 μg NCO/m^3 from NIOSH was used; for HDI-based polyisocyanates (pHDI: biuret and isocyanurate), the short-term exposure limit (STEL, 15 min) of 220 μg NCO/m^3 from the state of Oregon and Bayer Corporation was used; for IPDI polyisocyanates (pIPDI) and total NCO, the STEL (10 min) of 70 μg NCO/m^3 for any isocyanate from the U.K. Health and Safety Executive (UK-HSE) was used.
^{G}Co = outside-facepiece concentration.
^{H}Ci = in-facepiece concentration.

Relationship Between FF and WPF

Figure 2 shows the relationship between FF measurements from 22 workers and 28 WPF estimates. Up to 6.11 (FF = 450), as the log FF increased, the log WPF also increased. At around 6.11, however, further increases in log FF were associated with a decline in log WPF. Both regression coefficients were statistically significant ($p < 0.0001$). The resulting regression equations are:

$$\ln\text{WPF} = 1.1272 \times \ln\text{FF}_1 \quad (2)$$

$$\ln\text{WPF} = -1.6012 \times \ln\text{FF}_2 \quad (3)$$

DISCUSSION

In this study, we assessed the respiratory protection programs in the autobody repair and refinishing industry in the greater New Haven, Connecticut, area. We evaluated respirator fit and measured the effectiveness of negative pressure, air-purifying half-facepiece respirators with organic vapor cartridges and paint prefilters against exposures to isocyanates during spray painting and priming operations. A major strength of our study is the large number of shops and high worker participation rate. To our knowledge, this is the largest published study

TABLE VI. Workplace Protection Factors of Negative Pressure, Air-Purifying Half-Facepiece Respirators with Organic Vapor Cartridges and Paint Prefilters by Isocyanate Type and Respirator Brand

					Total NCO^E			
Respirator	N^A	HDI^B GM^F (GSD)^G	pHDI^C GM (GSD)	pIPDI^D GM (GSD)	GM (GSD)	5th Percentile	10th Percentile	50th Percentile
SAS^H	14	8 (4)	268 (4)	196 (4)	208 (4)	45	71	213
3M	15	33* (3)	550 (4)	528 (3)	473 (4)	73	106	435
Combined	29	17 (4)	388 (4)	358 (3)	319 (4)	54	80	317

^{A}N = number of samples: for pIPDI, N = 7 for SAS, N =11 for 3M, total = 18.
^{B}HDI = HDI monomer.
^{C}pHDI = HDI polyisocyanates.
^{D}pIPDI = IPDI polyisocyanates.
^{E}Total NCO = total reactive isocyanate group mass.
^{F}GM = geometric mean.
^{G}GSD = geometric standard deviation.
^{H}SAS = Survivair.
*$p < 0.05$ comparing two brands by two-sample t test.

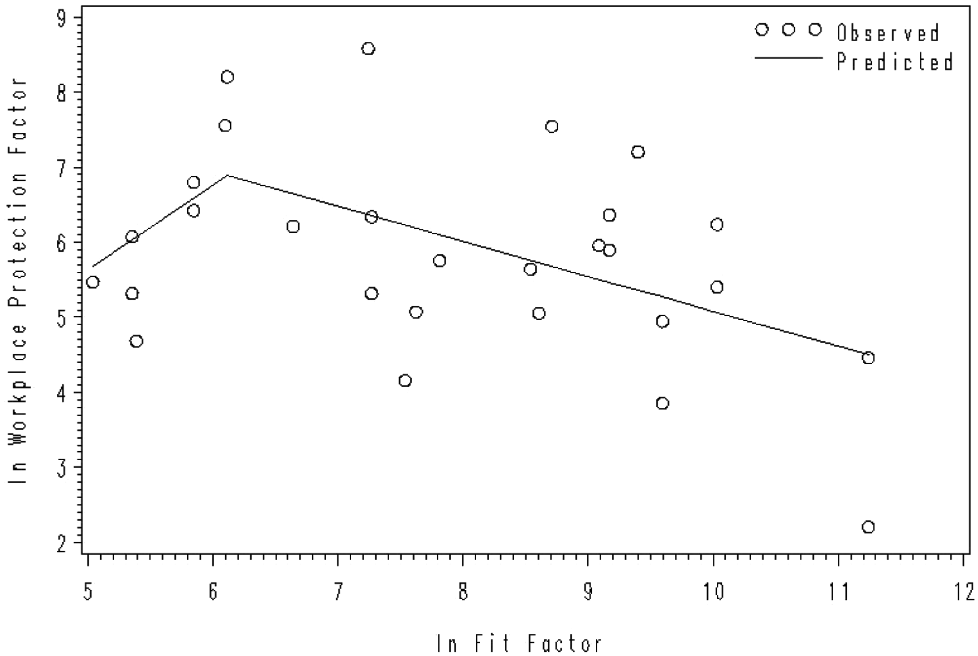

FIGURE 2. Correlation between log fit factor (lnFF) and log workplace protection factor (lnWPF). The circles indicate the observed values of lnFF and lnWPF and the solid line is the predicted values from the regression spline. Spline fit allows a flexible fit and the identification of a breakpoint (lnFF = 6.11, FF = 450). With increasing lnFF, lnWPF increases up to the point of lnFF = 6.11, and then decreases.

to date to evaluate respiratory protection in this setting. The shops surveyed appear representative of the types in the area in terms of size, productivity, type of engineering control measures in place and the respiratory protective equipment used.

Our study revealed that most shops relied heavily on the use of respirators. Although engineering controls, such as the use of advanced downdraft booths for painting and local exhaust ventilation for paint mixing, can significantly reduce exposures to isocyanates,[2,37,38] respiratory protection is still needed. In 92% of shops surveyed in this study, priming was performed outside spray booths with little engineering control. In small shops where there was no spray booth or shop floor areas were small, respirator use often provided the only line of protection. Therefore, full respiratory protection programs that include all OSHA-required components for respirator selection, training, annual fit testing, and respirator maintenance are currently needed in this industry.

Our results suggest that there have been some improvements in this industry in respiratory protection programs in recent years based on a comparison with results from earlier surveys conducted by NIOSH.[2,35] This is reflected in the higher rate of previous respirator training and fit testing reported by workers, provision of more than one type of respirator for different repair tasks, and higher average fit test pass rate and FFs than in NIOSH studies. Still, half of the shops had neither provided respiratory protection training to their workers nor conducted fit testing on their employees; two-thirds of the shops had no written respiratory protection program established. Though one-third of the shops reported a written program, implementation of the full respiratory protection program was not adequate. No medical screening, respirator maintenance (cleaning and disinfection), or evaluation of program effectiveness was observed in any of the shops. Schedules of cartridge and filter changes were not documented in shops. From our observation, such change was highly variable and random, and it appeared cartridges and paint filters from disposable facepieces were more frequently changed than cartridges of reusable facepieces. Although OSHA requires small businesses like autobody shops to comply with respiratory protection regulation, most shops were doing the protection based on the manufacturers' recommendations, or even individual workers' preferences, rather than based on mandatory requirements.

Our findings showed that proper training on respirator use and selection of a correct respirator size can significantly improve both fit test pass rate and FFs, highlighting the importance of establishing a full workplace respiratory protection program. The lower but not statistically significant pass rate and FF for Hispanic workers warrants further investigation. Language may be a barrier in training Hispanic workers in addition to possible difference in facial structure that may impact respirator fit.[46] Thick facial hair at the edge of the respirator seal was frequently found as a reason for test failure. The lower pass rate for new workers may suggest that young workers were less experienced in using a respirator properly, received less training in respirator use, or had different facial structure. Other personal characteristics such as smoking status or job category were not found to be significant predictors of fit test pass rate and FF.

Our fit test methods were consistent with those from a previous study using the portable TSI PortaCount Plus respirator fit tester.[40] Quantitative FFs obtained from this method have been shown to be highly correlated with those obtained by photometer quantitative fit test system.[40] The pass rate of 80% in our study is much higher than in NIOSH surveyed shops in the early 1990s where the pass rate was only 33%,[2,35] and than in another study in South Australia in the late 1980s where the pass rate was 32%.[47] Poor maintenance and defects in facepieces were found as main reasons for fit test failures in these studies. In our study, we provided different sizes of facepieces for fit testing when workers' own respirators did not fit, were not immediately available or they used the disposable type. Our respirator facepieces were in better condition, which might have helped increase the pass rate. However, it may also indicate an improvement in respirator use in this industry in recent years. Still, 20% of workers did not pass the first test largely because of inappropriate donning and loose fitting facepieces. After proper training and the choice of correct respirator sizes, the pass rate increased to 92%, suggesting training with proper fit testing is a good tool to improve respirator fit. This was further exemplified by a higher pass rate and FF of previously fit tested workers compared to workers who had never been tested before.

The WPF testing showed that negative pressure, air-purifying half-facepiece respirators with organic vapor cartridges and paint prefilters provided the 5th percentile protection factor of 54 for total NCO, which is above the ANSI assigned protection factor 10 for these respirators.[2,39] Ten of 29 samples for HDI monomer showed a WPF value less than 10. However, 83% of in-facepiece samples and 3% of outside samples were $<$LOD for HDI monomer, since in general the paint contained $<1\%$ HDI monomer, which had little impact on overall exposure to total NCO. The number of samples with WPF HDI < 10 would have been reduced by half if we had used $^1/_2$ LOD for those in-facepiece HDI concentrations that were at or below the LOD as is the common practice.[48] We did not do so in order to be more conservative on our WPF estimates. As described earlier, the recent paint manufacturers' stewardship program recommended that respirators with APF ≥ 25, such as supplied-air respirators, be used for sidedraft booths and negative pressure, air-purifying respirators with APF ≥ 10 used for downdraft booths.[35] In this study, we found the 5th percentile of WPF to be 72 for downdraft booths (N = 18) and 54 for crossdraft or homemade booths (N = 9), which suggests that negative pressure half-facepiece respirators can provide respiratory protection that meets the minimal APF requirements for booth types.

We found no significant difference in WPFs for pHDI, pIPDI, and total NCO between the two respirator brands. Only WPFs for HDI monomer, showed significantly higher values for 3M than SAS brand. Given the small sample size, practical limitations of the sampling and the various factors that can impact respiratory protection efficiency, caution is warranted in interpreting these findings. For example, since we were unable to sample from the disposable type of 3M facepieces, we had to substitute a reusable 3M facepiece to perform the WPF testing and fit testing. It is possible that the cartridge and paint prefilter efficiency of the reusable respirators we provided differed from the disposable ones the workers were actually using. In addition, given the extremely low HDI monomer exposure levels outside the facepieces, the very small contribution of HDI monomer to total NCO, and that over 80% of in-facepiece samples for HDI were at or below LOD for HDI, the practical importance of the respirator brand difference in WPF HDI noted is unclear.

The GM WPFs found in our study (total NCO = 319, HDI = 17, pHDI = 388, and pIPDI = 358) are difficult to compare with previously reported WPF values using negative pressure, air-purifying half-facepiece respirators, which are quite variable, and were determined from a range of exposure settings, with few studies investigating isocyanate exposures. They are higher than in a Finland study of autobody shop spray painters where the WPF (calculated from reported 6 pairs of inside/outside facepiece concentrations) was 6.4 for HDI and 6.0 for pHDI.[32] They are also higher than those reported by Spear et al.[27] (mean = 6.5, 5th percentile <0.5) in a lead smelter study, Weber and Mullins[29] (GM WPF = 39.7) in a styrene environment, and Wu[30] (mean = 2.5) for benzene soluble fraction of total particulate concentrations in a coke oven study. They are comparable to values reported by Lenhart and Campbell (GM WPF = 180, 5th percentile = 18).[49] However, they are much lower than those reported by Zhuang and Myers[31] in an aircraft spray painting study where GM WPF ranged from 770 to 10786, and 5th percentiles were at 171, 437, and 1121 for three half-facepiece respirator brands, based on the metal masses measured from titanium and chromium.

As discussed by Nelson,[25] variations of WPFs among different studies may reflect the differences in filter efficiency, face-seal leakage, and leakage through respirator defects such as faulty valves. A combined analysis on data from several studies by Nelson[25] revealed a GM of 290 and the best estimate of 5th percentile value as 13 for half-facepiece respirators.

The air samples for WPF evaluation were taken mainly during painting activities inside the spray booths with few outside spray booth priming tasks measured. This led to a higher overall GM (378.4 μg NCO/m^3) and greater percentage (96%) of total NCO concentrations exceeding the UK-HSE 10 min STEL standard 70 μg NCO/m^3 than in the SPRAY overall study (median = 205.5 μg NCO/m^3, 79% exceeding the UK-STEL standard).[37] However, none of the inside-facepiece concentrations of isocyanate species or total NCO was above the U.K. standard, further confirming the good protection achieved through the use of a negative pressure, air-purifying half-facepiece respirator with organic vapor cartridges and paint prefilters.

A factor that may have affected the estimation of WPF in our study is the particle size distribution of polyisocyanate aerosols, and the percentage of lung retention. If all the isocyanates inhaled were retained by the lungs, then when sampling during exhalation, little isocyanate would be collected, and the average in-facepiece concentrations would be significantly reduced. If none of the polyisocyanates were retained by the lungs (not likely) then the results would truly reflect facepiece (and/or filter) leakage. We were not able to take particle size samples in this study, but previous reports from other authors suggested that aerosols from spray painting could have a mass medium aerodynamic diameter (MMAD) from 2.9 μm to 9.7 μm.[50,51] These sizes of aerosols are in the range of thoracic particulate mass[52,53] suggesting isocyanate aerosol particles may deposit in the lungs when inhaled. A recent study reported that 61–90% of inhaled HDI vapor at concentrations varying from 5.1–15.2 ppb was retained within the airways and/or lung parenchyma.[54] The retention rate for pHDI or pIPDI aerosol is not clear and may impact on their estimated WPFs.

In this study we used different sampling strategies—IOM sampler for outside-facepiece concentrations and Delrin cassettes for in-facepiece concentrations. The IOM sampler efficiently samples particulate matter up to 100 μm in equivalent aerodynamic diameter that is deposited anywhere in the respiratory system. Because the Delrin cassettes have a smaller inlet, and might have collected a lower percentage of large particles, resulting in possible overestimation of WPF.

Our results on WPFs confirm earlier findings from other authors that WPFs can vary considerably within and between respirator wearers and were described by lognormal distribution parameters.[23] WPF values in our study (Table IV) showed large variations among participants, isocyanate species, and within workers for the seven subjects on which duplicate samples were obtained. In theory, if everything were due to facepiece leakage, one would expect the same WPF regardless of the type of outside contaminant. In fact, this is the basis of using WPF data in our exposure model for SPRAY study. The positive correlation between WPF HDI and WPF pHDI supports that the leakage was the main cause of breakthrough. However, WPF values still varied considerably even for the same isocyanate type. One reason was that the WPF values were positively correlated to outside-facepiece concentrations (for example, $r = 0.37$, $p = 0.0478$, $N = 29$ for WPF pHDI), which were affected by many workplace factors, such as amount of NCO used and the type of spray booth in place, as reported by Woskie et al.[37]

In this study, task duration was also found as a contributing factor. With increased task duration, WPF was also increased, which indicates a better respirator seal with longer task performance, possibly due to the sweat accumulation inside the facepiece. The age of cartridges at the time of sampling could also have affected the protection efficiency. Task type may also be a factor, but the small sample sizes of total WPF sample pairs for clear coating vs. priming/sealer coating limited our ability to detect a significant task effect.

The total WPF variation could be partitioned into within- and between-worker variability, but few studies have tried to quantify the two variation components. Traditionally WPFs were aggregated and well described by a two-parameter lognormal distribution.[23] Nicas and Neuhaus[23] recently reanalyzed WPF data from seven studies of negative pressure, air-purifying half-facepiece respirators using a random effects model and found that *the within-wearer component dominated the between-wearer component*. A random effects model analysis was also performed in this study on the seven worker pairs of WPF samples. It revealed a larger between-wearer variability than that within wearers (variance: 0.9663 vs. 0.6391). Our results were limited by the small number of workers and measurements for each worker.

To estimate personal isocyanate exposures in the SPRAY epidemiologic study, individual external exposures should be adjusted for the effect of respirator use as measured by WPF. However, WPF was not measured for every worker who used a respirator. An alternative approach is to develop a regression model between FF and WPF and estimate each worker's WPF from their FF measurement. Our regression analysis showed the relationship was not strictly linear; rather, the WPF increased with FF to a point and then declined. This could be because to achieve a very high FF the respirator must be worn very tightly, and the worker cannot tolerate that tightness in the hot spray painting environment so he loosens it during the WPF testing, producing the downward slant of the WPF to FF relationship. In general, earlier studies found little or no correlations between FF and WPF measured in the workplace using the assumption of simple linearity.[23,55,56] It has been suggested that using FF of 100 or greater was part of the reason for the poor correlation because that limited the lower end of the regression line.[56] Later, Coffey et al.[57] used the end-exhaled air analysis of vapor (Freon-113) instead of aerosol to determine the WPF and found high correlations between Freon exposure in the lungs and the protection factor in three of six fit test methods in a simulated health care environment.

Zhuang et al.[56] recently re-evaluated the relationship between FF and WPF in a foundry environment and found a significant linear correlation between the two. The Coffey and Zhuang studies included poor FF ($FF < 100$) in the analysis. On the other hand, there is no particular reason to expect the relationship between FF and WPF to be linear, since fit testing is conducted in a short-term controlled situation and the WPF testing in a longer real-world application. The use of regression spline analysis in this study enabled us to identify a broken-stick relationship between FF and WPF, which needs further evaluation in future research.

Because diisocyanates have poor warning properties and exposure may cause serious respiratory ailments, NIOSH recommends powered air-purifying respirators or airline-supplied-air respirators for spray painting.[35] However, these respirators are expensive and cumbersome to use. As noted, supplied-air respirators were only used in a small number of shops. For technical reasons, we were not able to sample in-facepiece concentrations which precluded us from estimating the WPF for this respirator type. Recently, OSHA has clarified that employers may use air-purifying gas and vapor cartridge respirators (APRs) for hazardous chemicals, such as isocyanates, as long as appropriate precautions and cartridge change schedules are in place.[58] In this study, we demonstrate that if properly fitted, APRs with paint prefilters can reduce isocyanate exposures to values less than appropriate OELs, which further supports OSHA's clarification. A cartridge's replacement schedule, however, is dictated by its performance against the organic compounds/solvents within the coating system, not the isocyanate, because the organic vapors penetrate through the cartridge/filtering element far sooner than the isocyanates. This is based on the assumption of a good respirator fit and the retention of painters' acute sense of smell even after working in shops for a while. This needs to be considered when evaluating the performance of negative pressure, air-purifying half-facepiece respirators with organic vapor cartridges and paint prefilters against isocyanates and establishing cartridge change schedules in shops.

Our study demonstrates that prior fit testing with training can significantly increase the fit test pass rate and fit factor. Therefore, it is necessary for shops to provide respirator use training and fit testing to all workers. There is also a need to better educate shop owners/managers and workers on the proper use and necessary care of half-facepiece respirators and set up schedules for cartridge and paint pre-filter changes. The Product Stewardship Partnership program by paint manufacturers, EPA, OSHA, NIOSH, and automotive repair associations allow shops to select correct respirators based on the type of spray booths in use. To help shops improve their respiratory protection program and workers increase their respirator use in painting activities, we have recently initiated another study, Safe Methods for Autobody Shop Health (SMASH), in this industry. Various interventions such as educational training and work practice modification are being implemented and evaluated that may identify more effective measures for shops to protect their workers from exposure to isocyanates and other respiratory hazards.

CONCLUSION

The autobody repair and refinishing industry remains heavily reliant on respirator use as the main protection from isocyanate exposures. Although there has been a general improvement in this industry, the respiratory protection programs remain incomplete or missing in some shops. Negative pressure, air-purifying half-facepiece respirators with organic vapor cartridges and paint prefilters are the major type in use for spray painting and priming. About 20% of workers failed the first fit test on these respirators, due largely to loose fitting facepiece, wrong respirator sizes and facial hair. With adequate training and selection of correct respirator sizes, however, an improved fit test pass rate was achieved and good protection against isocyanate exposure was obtained. GM WPF for total NCO using negative pressure air-purifying half-facepiece respirators with organic vapor cartridges and paint pre-filters was 319 with GSD at 4 and 5th percentile value at 54. We conclude that if fit tested appropriately and worn properly, negative pressure, air-purifying half-facepiece respirators with organic vapor cartridges and paint prefilters can provide reasonably effective worker protection against the whole range of diisocyanate exposures in autobody spray painting activities.

ACKNOWLEDGMENT

We are indebted to Dr. Howard Cohen for providing invaluable comments on the manuscript. We appreciate the reviewers' comments, which significantly improved our presentation. We are thankful for technical support from Dr. Robert Streicher at NIOSH. We thank Frank Walsh for his dedicated fieldwork, and Karim Ibrahim for technical assistance. We are very grateful to all shop management and participating workers for making this study possible.

This study was supported by NIOSH/CDC Grants 1R01OH0 3457, 2R01OH034506, 5 R01OH004246, AAMC/NIOSH/CDC Cooperative Agreement Grant MM-0722-04/04, NHLBI/NIH Grant 1R01HL62932, and NIEHS Grant K24-ES00355.

REFERENCES

1. **Redlich, C.A., M.H. Stowe, A.V. Wisnewski, et al.:** Subclinical immunologic and physiologic responses in hexamethylene diisocyanate-exposed autobody shop workers. *Am. J. Ind. Med. 39*:587–597 (2001).
2. **Heitbrink, W.A., M.E. Wallace, C.J. Bryant, and W. Ruch:** Control of paint overspray in autobody repair shops. *Am. Ind. Hyg. Assoc. J. 56*:1023–1032 (1995).
3. **United States Census Bureau:** "Economic Census, North American Industry Classification System (NAICS) Code 811121." [Online] Available at http://www.census.gov/epcd/ec97/industry/E811121.HTM (Accessed August 8, 2005).
4. **U.S. Department of Labor Bureau of Labor Statistics:** "2001 National Occupational Employment and Wage Estimates: 49–3021 Automotive Body and Related Repairers." [Online] Available at http://www.bls.gov/oes/2001/oes493021.htm (Accessed August 8, 2005).
5. **Jayjock, M.A., and L. Levin:** Health hazards in a small automotive body repair shop. *Ann. Occup. Hyg.28*:19–29 (1984).
6. **Janko, M., K. McCarthy, M. Fajer, and J. van Raalte:** Occupational exposure to 1,6-hexamethylene diisocyanate-based polyisocyanates in the State of Oregon, 1980–1990. *Am. Ind. Hyg. Assoc. J.53*:331–338 (1992).
7. **Liu Y, J.A. Sparer, S.R. Woskie, et al.:** Qualitative assessment of isocyanate skin exposure in autobody shops: A pilot study. *Am. J. Ind. Med. 37*:265–274 (2000).
8. **Bello, D., S.R. Woskie, R.P. Streicher, et al.:** Polyisocyanates in occupational environments: A critical review of exposure metrics and standards. *Am. J. Ind. Med. 46*:480–491 (2004).
9. **Lesage, J., N. Goyer, F. Desjardines, J.Y. Vincent, and G. Perrault:** Workers' exposure to isocyanates. *Am. Ind. Hyg. Assoc. J. 53*:146–153 (1992).
10. **Randolph, B.W., U.G. Lalloo, E. Gouws, and M.S. Colvin:** An evaluation of the respiratory health status of automotive spray-painters exposed to paints containing hexamethylene di-isocyanates in the greater Durban area. *S. Afr. Med. J. 87*:318–323 (1997).
11. **Tarlo, S.M., and G.M. Liss:** Diisocyanate-induced asthma: diagnosis, prognosis, and effects of medical surveillance measures. *Appl. Occup. Environ. Hyg. 17*:902–908 (2002).
12. **Vandenplas, O., A. Cartier, J. Lesage, Y. Cloutier, G. Perreault, L.C. Grammer, et al.:** Prepolymers of hexamethylene diisocyanate as a cause of occupational asthma. *J. Allergy Clin. Immunol. 91*:850–861 (1993).

13. **Hrncir, D.E.:** You are the flight surgeon: Isocyanates are the most common cause of occupational asthma. *Aviat. Space Environ. Med.61*:765–766 (1990).
14. **Cockcroft, D.W., and J.T. Mink:** Isocyanate-induced asthma in an automobile spray painter. *Can. Med. Assoc. J. 121*:602–604 (1979).
15. **Clarke, C.W., and P.M. Aldons:** Isophorone diisocyanate induced respiratory disease (IPDI). *Aust. N. Z. J. Med. 11*:290–292 (1981).
16. **Cullen, M.R., C.A. Redlich, W.S. Beckett, et al.:** Feasibility study of respiratory questionnaire and peak flow recordings in autobody shop workers exposed to isocyanate-containing spray paint: Observations and limitations. *Occup. Med. 46*:197–204 (1996).
17. **Seguin, P., A. Allard, A. Cartier, and J.L. Malo:** Prevalence of occupational asthma in spray painters exposed to several types of isocyanates, including polymethylene polyphenylisocyanates. *J. Occup. Med. 29*:340–344 (1987).
18. **Pisati, G., A. Baruffini, and S. Zedda:** Toluene diisocyanate induced asthma: Outcome according to persistence or cessation of exposure. *Brit. J. Ind. Med. 50*:60–64 (1993).
19. **Vandenplas, O., J.L. Malo, M. Saetta, C.E. Mapp, and L.M. Fabbri:** Occupational asthma and extrinsic alveolitis due to isocyanates: Current status and perspectives. *Br. J. Ind. Med. 50*:213–228 (1993).
20. **Occupational Safety and Health Administration (OSHA):** *Small Entity Compliance Guide for the Revised Respiratory Protection Standard.* Washington, DC:U.S. Department of Labor, 1998.
21. "1910.134 Respiratory Protection," *Federal Register 63:5* (8 January 1998), pp. 1270–1300.
22. **National Institute for Occupational Safety and Health (NIOSH):** *Respirator Decision Logic (DHHS/NIOSH Pub. No. 87-108).* Cincinnati, Ohio: NIOSH, 1987.
23. **Nicas, M., and J. Neuhaus:** Variability in respiratory protection and assigned protection factor. *J. Occup. Environ. Hyg. 1*:99–109 (2004).
24. **Johnston, A.R., W.R. Myers, C.E. Colton, J.S. Birkner, and C.E. Campbell:** Review of respiratory performance testing in the workplace: Issues and concerns. *Am. Ind. Hyg. Assoc. J. 53*:705–712 (1992).
25. **Nelson, T.J.:** The assigned protection factor of 10 for half-mask respirators. *Am. Ind. Hyg. Assoc. J. 56*:717–724 (1995).
26. **Morre, D.E., and T.J. Smith:** Measurement of protection factors of chemical cartridge, half-mask respirators under working conditions in a copper smelter. *Am. Ind. Hyg. Assoc. J. 37*:453–458 (1976).
27. **Spear, T.M., J. DuMond, C. Lloyd, and J.H. Vincent:** An effective protection factor study of respirators used by primary lead smelter workers. *Appl. Occup. Environ. Hyg. 15*:235–244 (2000).
28. **Gregory, S., G.S. Hewson, and M.I. Ralph:** Determination of program protection factors for half-mask respirators used at a mineral sands separation plant. *Am. Ind. Hyg. Assoc. J. 53*:713–720 (1992).
29. **Weber, R.A., and H.E. Mullins:** Measuring performance of a half-mask respirator in a styrene environment. *Am. Ind. Hyg. Assoc. J. 61*:415–241(2000).
30. **Wu, M.T.:** Assessment of the effectiveness of respirator usage in coke oven workers. *Am. Ind. Hyg. Assoc. J. 63*:72–75 (2002).
31. **Zhuang, Z.Q., and W.R. Myers:** Field performance measurements of half-facepiece respirators—Paint spraying operations. *Am. Ind. Hyg. Assoc. J. 57*:50–57 (1996).
32. **Rosenberg, C., and T. Tuomi:** Airborne isocyanates in polyurethane spray painting: determination and respirator efficiency. *Am. Ind. Hyg. Assoc. J. 45*:117–121 (1984).
33. **Vasta, J.F.:** Respirator cartridge evaluation for isocyanate containing Imron® and Centari® enamels. *Am. Ind. Hyg. Assoc. J. 46*:39–44 (1985).
34. **Dharmarajan, V., R.D. Lingg, and H.E. Myer:** Evaluation of organic-vapor respirator cartridge efficiency for hexamethylene diisocyanate vapor in the presence of organic solvents. *Appl. Occup. Environ. Hyg. 16*:397–404 (2001).
35. **Heitbrink, W.A.:** "A Control Matrix for Spray Painting at Autobody Repair Shops." [Online] Available at http://www.osha.gov/SLTC/autobody/docs/nioshctm/nioshctm.html (Accessed August 8, 2005).
36. **Phillips, J.T.:** *OSHA Regional Instruction-Local Emphasis Program of Autobody Shops (Directive Number CPL 2-2.2).* Bridgeport, Conn.: OSHA Bridgeport Area Office, 1998.
37. **Woskie, S., J. Sparer, D. Bello, et al.:** Determinants of isocyanate exposures in autobody repair and refinishing shops. *Ann. Occup. Hyg. 48*:211–221 (2004).
38. **Sparer, J.A., M.H. Stowe, D. Bello, et al.:** Isocyanate exposures in autobody shop work: The SPRAY study.*J. Occup. Environ. Hyg. 1*:570–581 (2004).
39. **American National Standard Institute (ANSI):** *American National Standard for Respirator Fit Testing Methods* (ANSI/AIHA Z88.10-2001). [Standard] Fairfax, VA: AIHA, 2001.
40. **Rose, J.C., R.K. Oestenstad, and V.E. Rose:** A comparison of respirator FFs determined by portable condensation nuclei counting and forward light-scattering photometric methods. *Appl. Occup. Environ. Hyg. 5*:792–797 (1990).
41. **National Institute for Occupational Safety and Health (NIOSH):** Isocyanates, total (MAP). Method 5525. In *NIOSH Manual of Analytical Methods (NNMAM),* 4th Edition. DHHS (NIOSH) Pub. No. 94-113, Supplement 3, P.C. Schlecht and P.F. O'Connor (eds.). Cincinnati, Ohio: U.S. Department of Health and Human Services, 2002.
42. **Bello, D., R.P. Streicher, and S.R. Woskie:** Evaluation of the NIOSH draft method 5525 for determination of the total reactive isocyanate group (trig) in air in autobody repair shops. *J. Environ. Monit. 4*:351–360 (2002).
43. **Bello, D., R.P. Streicher, Y. Liu, J. Sparer, F. Youngs, and S.R. Woskie:** Field comparison of impingers and treated filters for sampling of total aliphatic isocyanates using the MAP reagent.*Am. Ind. Hyg. Assoc. J. 63*:790–796 (2002).
44. **Streicher, R.P., C.M. Reh, R.J. Key-Schwartz, P.C. Schlecht, P.E. Cassinelli, and P.F. O'Connor:** Determination of airborne isocyanate exposure: considerations in method selection. *Am. Ind. Hyg. Assoc. J. 61*:544–556 (2000).
45. **Streicher, R.P., C.M. Reh, R.J. Key-Schwartz, P.C. Schlecht, P.E. Cassinelli, and P.F. O'Connor:** Analytical instrument performance criteria: selecting isocyanate sampling and analytical method. *Appl. Occup. Environ. Hyg. 17*:157–162 (2002).
46. **Oestenstad, R.K., and L.L. Perkins:** An assessment of critical anthropometric dimensions for predicting the fit of a half-mask respirator. *Am. Ind. Hyg. Assoc. J. 53*:639–644 (1992).
47. **Pisaniello, D., and I. Muriale:** The use of isocyanate paints in auto refinishing—A survey of isocyanate exposures and related work practices in South Australia. *Ann. Occup. Hyg. 33*:563–572 (1989).
48. **Hornung, R.W., and L.D. Reed:** Estimation of average concentration in the presence of nondetectable values. *Appl. Occup. Environ. Hyg. 5*:46–51 (1990).
49. **Lenhart, S.W., and D.I. Campbell:** Assigned protection factors for two respirator types based upon workplace performance testing. *Ann. Occup. Hyg. 28*:173–182 (1984).
50. **Chan, T.L., J.B. D'Arcy, and R.M. Schreck:** High-solids paint overspray aerosols in a spray painting booth: Particle size analysis and scrubber efficiency. *Am. Ind. Hyg. Assoc. J. 47*:411–417 (1986).
51. **D'Arcy, J.B., and T.L. Chan:** Chemical distribution in high-solids paint overspray aerosols. *Am. Ind. Hyg. Assoc. J. 51*:132–138 (1990).
52. **Herrick, R., and J. Dement:** Industrial hygiene. In *Textbook of Clinical Occupational and Environmental Medicine,* L. Rosenstock and M.C. Cullen (eds.). Philadelphia: W.B. Saunders Company, 1994. pp. 169–193.
53. **ACGIH®:** *TLVs and BEIs® Based on the Documentation of the Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices.* Cincinnati, Ohio: ACGIH, 2003.
54. **Monso, E., Y. Cloutier, J. Lesage, G. Perreault, and J.L. Malo:** What is the respiratory retention of inhaled hexamethylene di-isocyanate? *Eur. Respir. J. 16*:729–730 (2000).
55. **Lee, K.Y., A. Slavcev, and M. Nicas:** Respiratory protection against *Mycobacterium tuberculosis*: Quantitative fit test outcomes for five type N95 filtering-facepiece respirators. *J. Occup. Environ. Hyg. 1*:22–28 (2004).

56. **Zhuang, Z., C.C. Coffey, P.A. Jensen, D.L. Campbell, R.B. Lawrence, and W.B. Myers:** Correlation between quantitative fit factors and workplace protection factors measured in actual workplace environments at a steel foundry. *Am. Ind. Hyg. Assoc. J. 64*:730–738 (2003).
57. **Coffey, C.C., D.L. Campbell, W.B. Myers, and Z., Zhuang:** Comparison of six respirator fit-test methods with an actual measurement of exposure in a simulated health care environment: Part II—Method comparison testing. *Am. Ind. Hyg. Assoc. J. 59*:862–870 (1998).
58. **Fairfax, R.E.:** "07/18/2000—Selection of Air Purifying Respirators for Gases and Vapors with Poor Warning Properties (diisocyanates)." [Online] Available at http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=23425&p_text_version=FALSE (Accessed August 8, 2005).