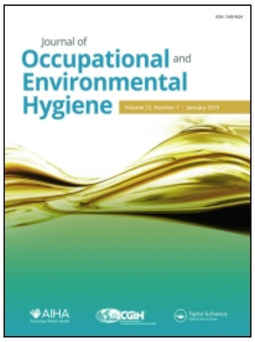

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Isocyanate Exposures in Autobody Shop Work: The SPRAY Study

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Isocyanates, known to cause respiratory sensitization and asthma, are widely used in automotive refinishing where exposures to aliphatic polyisocyanates occur by both inhalation and skin contact. The work reported here, the characterization of isocyanate exposure in the autobody industry, was part of an epidemiologic study of workers in 37 autobody shops in Connecticut. This article describes workplaces, tasks, and controls, and outlines the frequency, duration, and intensity of isocyanate exposures. Personal air samples taken outside of respirators had median concentrations of 66.5 μg NCO/m³ for primer, 134.4 μg (NCO)/m³ for sealer, and 358.5 μg NCO/m³ for clearcoat. Forty-eight percent of primer, 66% of sealer, and 92% of clearcoat samples exceeded the United Kingdom Health and Safety Executive guideline for isocyanate, though none exceeded the National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit for monomer. Nonisocyanate-containing primers and sealers are used in more than half the shops, but nonisocyanate clearcoats are rare. Eighty-two percent of personal samples taken within a spray booth exceeded the U.K. guideline: 81% of those in downdraft spray booths, 74% in semidowndraft booths, and 92% in crossdraft booths. Only 8% of shops reported that spraying is done exclusively in spray booths. All painters wore some type of respirator. In 30% of shops, painters used supplied air respirators; the rest relied on half face organic vapor cartridge respirators with N95 overspray pads. All shops provided some type of gloves, usually latex, not recommended for isocyanate protection. Despite improvements in autobody shop materials, practices, and controls, there are still opportunities for substantial exposures to isocyanates.

Keywords autobody shop, isocyanate, occupational exposures, small industry

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Asthma rates are rising throughout the world. Ambient, occupational, and other indoor environments are under scrutiny in the search for explanations. A small number of chemicals are among the known respiratory sensitizers, and prominent among them is the family of compounds known as isocyanates, widely cited as a cause of occupational asthma in the industrialized nations.[1,2] Although this effect has been widely cited, the role of monomer versus oligomer of isocyanates or the relative importance of intensity, duration, and frequency of exposure is not well understood. In the United States, the U.S. Occupational Safety and Health Administration (OSHA) has promulgated a ceiling standard for the volatile monomer of toluene diisocyanate (TDI) and extended that to the less volatile methylene bisphenyl diisocyanate (MDI) monomer, apparently aimed at controlling the short-term high level excursions rather than chronic low-level exposures.[3] Recent research has suggested that respiratory sensitization may be induced by skin exposure as well as by the inhalation route of exposure.[4] Many questions remain about what form of exposure is most harmful, and the biological mechanism of this harm.

Despite these acknowledged risks, the production of isocyanates continues to grow. A myriad of larger prepolymers has been developed to reduce the volatility of this useful and expanding family of compounds. Many industries have developed successful exposure control strategies, but widespread use of isocyanates in the paint systems used in the automotive refinishing industry still entails exposure. Nationwide, this is an industry of primarily small, family-owned repair shops (81%) with a median employment of five workers including the owner and an average revenue of about $550,000.[5] As currently performed, the repair and refinishing of cars entails the sprayed on application of isocyanate-containing coatings on almost every vehicle. In 1999, the U.S. Census reported about 35,500 automotive refinishing facilities scattered liberally throughout population centers in the U.S., employing a total of 205,000 people.[6] Significant exposure to isocyanates has been documented in this industry.[7–15] Previous work by a Yale study team showed there is respiratory disease among the workers (almost 20% reported symptoms), and that we could gain access to the shops and the workers for further study.[16]

In 1997, a cross-sectional epidemiologic study, the Study of Painters and Repairers of Autobodies by Yale (SPRAY), was initiated in collaboration with the University of Massachusetts at Lowell. The purpose of the study was to characterize the health effects of isocyanate exposures on actively employed autobody shop workers and to elucidate exposures.[17,18] Sorting the workers into broad categories by primary tasks was not difficult. Our earlier work, as well as the work of others in other geographic areas, has shown that among autobody shop workers painters have the highest potential exposures to isocyanates, body technicians have less risk of exposure, and office workers have the lowest potential exposure. This being generally acknowledged, painters' exposures have been modified to the greatest extent by a variety of controls including some strategies taken from each level of the industrial hygiene hierarchy of controls: substitution, engineering controls, administrative controls, and personal protective equipment.

Each autobody shop is a diverse and variable environment. The work environment resembles that of a group of craftsmen working under supervision of a manager, each working on his own project, some of them specialized in certain phases of the work. Each car that comes in requires a different amount of labor and different volume of coating to complete. Each shop is different from the others in its work practices and engineering controls and no two days are the same. Thus, the goal of the exposure assessment became to develop a model for exposure based on job title modified by shop factors and by control measures. In this article the tasks generating isocyanate exposures are explored, as are the variables that could modify the form, frequency, duration, and the intensity of the exposure.

METHODOLOGY

We identified shops within 35 miles of our base in New Haven, Conn., by using the telephone book and by referral from other participating shops. Of the 112 shops contacted, 31 were ineligible either because they did not paint or did not use paints containing any hexamethylene diisocyanate-based product, 20 refused, and the first 37 who agreed to participate were enrolled. Two-hundred sixty-six workers in those 37 shops agreed to participate. The first three shops were used to validate sampling method;[19] we were not able to obtain samples of spraying in two shops. Thirty-two shops were included in the analysis of air sampling of spray applications presented here. The 4-day diaries used to allocate workers' time were obtained for 233 workers in 35 shops.

Data Obtained from Participants

Owner/Manager Questionnaire

Information was collected by interview with the manager concerning the size of the business, the size of the facility, the number of employees, work practices, engineering controls, amount of isocyanate containing coatings used, and personal protective equipment provided for workers.

Diaries

The daily diary was used to record participants' activities by task every half hour for the whole workday during the study week (Monday–Thursday). A trained observer recorded the tasks and number of events performed and the personal protective equipment worn by each worker during each half hour, in consultation with that worker. Field industrial hygienists, based on their observations and experience with autobody shops, assigned an average task duration (in minutes) for each task.

For each worker for each day, daily percentages were calculated by summing up the time spent doing tasks in a particular task group and dividing that time by the total time spent in all task groups listed during the day. Lunch/break categories were not included. Once the daily percentages were obtained, they were averaged over a particular individual resulting in that person's average percentages over all the days for which diary information was available. Medians and quartiles by job category were then obtained.

Data on Sources and Controls

Isocyanate-Containing Products

Bulk samples of hardeners used during the study week were collected. Samples were poured directly from the opened manufacturer's container into a glass vial with a Teflon® cap liner. Chemical analysis of the bulk products was conducted using U.S. National Institute of Occupational Safety and Health (NIOSH) Method 5525 modified as described in a companion article.[20] To characterize chemical composition, bulk samples were empirically classified using Bayer's (Pittsburgh, Pa.) pure Desmodur® products, biuret (N100), isocyanurate (N3300), hexamethylene diisocyanate (HDI)-based polyisocyanate with high uretidinedione content (N3400), polymeric isophorone diisocyanate (IPDI) (Z4470), and combinations thereof.[21] Material safety data sheets (MSDSs) were obtained for 24 shops, excluding duplicates.

Airborne Isocyanate Sampling

A task-based personal sampling approach was employed for determination of isocyanate exposure. Type and formulation of coating, location in which task was performed, and controls in use were recorded for each sample. Personal samples were sometimes taken over the duration of a task from beginning to end, as the worker would describe the time he spent on a task. Others were taken for brief periods, so as not to dilute the intensity of exposure with time not actually performing the task. Personal air sampling for airborne isocyanates was conducted using a stainless steel inhalable sampler (IOM) by SKC

(Eighty Four, Pa.) with Gilian GilAir (Gilian Instrument Corp., West Caldwell, N.J.) personal air sampling pumps calibrated before and after each shift at 2 L/min. The IOM cassette was loaded in the laboratory with a 25-mm quartz fiber filter impregnated with 500 μg of 1-(9-anthracenylmethyl)piperazine (MAP). Immediately after sampling was stopped, the entire stainless steel IOM filter assembly was transferred into a jar containing 10 mL of 1×10^{-4} molar MAP in acetonitrile. Samples were stored and shipped in cooled containers. Samples were processed and analyzed using a modified version of NIOSH Method 5525. A detailed description of sampling and analysis is provided elsewhere. Concentrations obtained during spray application of isocyanate containing coatings are presented in this paper. Sampling done during other tasks included bystander exposures to shop floor spraying, mixing, gun cleaning, sanding and office areas. Those results are described in a companion article.[19,20] In addition, sampling was done in areas of the shop other than spray operations. These included bystander exposures to shop floor spraying, mixing, gun cleaning, sanding, and office areas. Results are described in a companion article.[22]

The metric used throughout this article is the total isocyanate functional group (nitrogen/carbon/oxygen—N=C=O or NCO), also commonly called the total reactive isocyanate group (TRIG). This metric uses mass of the NCO functional group of the molecule in calculating the NCO concentration (μg NCO/m^3). For full discussion of this metric and conversions to other commonly used units, see Bello.[21]

Spray Booths

Paint spray booths are a primary engineering control in this industry. In this study a spray booth was defined as any room or enclosed space used for the purpose of painting vehicles and having an exhaust fan. Booths were classified as either downdraft (air entering through the ceiling and exhausting through a plenum covered by filters in the floor), semidowndraft (usually air entering through the ceiling and exhausting at the back but also air entering through filters in the door and exhausting through a floor plenum), or crossdraft (usually air coming in through filters in the door and exhausted at the back, but could be any lateral configuration). Prep stations (free standing supply and exhaust ventilation systems that can be used to filter and recycle air or to exhaust it outside, and are enclosed by plastic curtains rather than wall) can be either downdraft or semidowndraft. They are treated as a subset of booths, used for smaller coating jobs as well as dust-generating jobs.

Booths were further classified as to whether they were purchased as a prefabricated unit or constructed in the shop, "homemade." A typical homemade booth is of crossdraft design, a cinderblock room within the shop, with an exhaust system consisting of a fan drawing air through dry filters into a plenum at the back of the booth and exhausting it outdoors. Many have filters in the doors for cleaning incoming air. Floors are hosed down for more dust control, and portable heat lamps are used to speed drying. Lacking make-up air, homemade booths operate at negative pressure relative to the rest of the shop. By contrast, booths bought as a unit from a supplier, designated as "prefabricated" booths, are sheetmetal rooms, often with a heater and programmable heat cure cycle of downdraft, semidowndraft, or crossdraft design. The downdraft and semidowndraft designs have supply air fans and operate at slight positive pressure to prevent the infiltration of dust from the shop.

Data collected on spray booths included: booth type, size, make, manufacturer specified airflow (cfm), filter condition, date of most recent filter change, and the presence or lack of a pressure gauge across exhaust filters. The actual flowrate (cfm) was determined using a TSI VelociCalc® Plus (St. Paul, Minn.) hot wire anemometer to measure average air velocity along the exhaust filter face. Average velocity was multiplied by filter area to obtain flowrate, which was divided by booth volume to calculate airchanges per minute.

Statistics

All analyses were performed using SAS V8 (SAS Institute, Cary, N.C.) and standard statistical procedures. Sampling results were skewed to the right and truncated on the left due to the presence of limit of detection values. Hence, exposures levels were described by the median and the 25th and 75th percentiles. To address the skewed distribution of the data, statistical testing was done using the natural log of the exposure concentration.

RESULTS

Tasks and Exposures

Autobody Tasks

Task delineation varies from shop to shop and from car to car, but most work includes the tasks listed in Table I. Since SPRAY focused exclusively on isocyanate exposures, tasks that generate these are described more fully. Exposures to other respiratory irritants and their source tasks are noted. Heat, noise, cold, repetitive motion, or strenuous work in awkward positions, often present, are not discussed here.

The initial tasks of removal of damaged parts, frame straightening, reassembly, welding, grinding, bondo, and masking prior to applying primer or sealer do not entail direct exposure to isocyanate. Welding, usually done on a clean metal surface, is of fairly short duration, not an everyday task. Grinding is used to clean surfaces of rust or other degradation. Bondo, widely used as filler material, is a two-part polyester styrene resin paste used with a benzoyl peroxide hardener. Building up the surface with bondo is an iterative process of application with a spatula and sanding, generating copious dust. Some shops actually do no bondo work, using only replacement parts to reconstruct the surface.

Isocyanate is found in the hardener, which is mixed with a polyol/solvent base of primer, sealer, or clearcoat just before application. Primer, usually the first sprayed paint application, often contains isocyanate hardener. The primer layer, used over bondo, may be part of reshaping the contour of the vehicle

TABLE I. Auto Body Shop Tasks, Task Groups, and Associated Exposures (in Sequence)

Task	Isocyanate Exposure-Generating	Task Group	Hazard	Shop Factors Affecting Potential for Isocyanate Exposure
Removal of damage, frame straightening, assembly, welding, grinding	No	Mechanical work	Potential injury, welding fume, metal (lead, chromium, cadmium) dust, filler dust	Background levels and specific actions of other workers in the same room, such as painting outside a spray booth or sanding on isocyanate layers
Bondo application, sanding	No	Bondo work	Styrene, polyester, lead dust	Same as above
Mixing primer/sealer	Yes	Prep spray	Solvent, isocyanate	Number of jobs, mixing area ventilation, cleanliness of bench, containers, tools, hand washing facilities, and practices
Priming/sealing	Yes	Spray	Solvent, isocyanate	Primer/sealer may or may not contain isocyanate, work may be done inside or outside a booth, type, maintenance, and effectiveness of booth, general ventilation, PPE, proximity of other workers for bystander exposure
Sanding primer	Yes	Sanding primer	Isocyanate, metals dust	Use of isocyanate-containing primer, time since application, wet or dry sanding method, general ventilation, potential for bystander exposure
Masking/taping	No	Prep/finishing	None	Background levels
Mixing basecoat (color)	No	Prep spray	Solvent	Overall cleanliness of area, tool, containers may be contaminated
Spraying basecoat	No[A]	Spray	Solvent	Effectiveness of booth in clearing previous painting episodes
Mixing clearcoat	Yes	Prep spray	Solvent, isocyanate	Mixing area ventilation, cleanliness of area, hand washing
Spraying clearcoat	Yes	Spray	Solvent, isocyanate	Use of booth, type, maintenance, and effectiveness of booth, respirator, coveralls, gloves, spray technique, general ventilation, potential for bystander exposure
Gun cleaning	Yes	Prep spray	Solvent, isocyanate	Work practices, cleaning system, general cleanliness, local exhaust ventilation for gun cleaning area, frequency of changing of cleaning solvent, potential for bystander exposure
Untaping	Yes	Prep/finishing	Isocyanate-skin	Gloves, background levels
Compounding	Yes	Prep/finishing	Isocyanate-skin	Gloves, background levels
Washing, detailing	No	Prep/finishing	None	Background levels as above, often done outdoors

[A] In only one shop, a small amount of isocyanate-containing hardener was used in the basecoat formulation.

and is usually applied by the body technician, often outside the spray booth. Two to five coats of primer are typically applied, with each coat often applied in a few minutes. Wet or dry sanding is done on recently applied primer as well as old primer. Dry sanding can be manual or mechanical. Wet sanding is done by hand with a wet sponge and sandpaper.

Once shaping is complete, the vehicle is prepared for painting by masking and taping. Masking of small areas for priming takes a minute or two, but taping areas for color and clearcoat application can take more than an hour of carefully wrapping mirrors, key holes, lights, and trim in masking tape. Mixing two-part polyurethane primers, sealers, and clearcoats is done by the person who will apply the coating. It takes a few minutes to pour from the original containers of a gallon or less to a plastic measuring container, stir, and pour the mixture through a filter into the gun cup. Mixing the color-containing layer, called paint or basecoat, takes longer due to difficulties in matching the complex colors formed of many tints, metallics, and pearl. This layer rarely contains isocyanate.

All layers—primer, sealer, basecoat, and clearcoat—were applied using a high-volume low-pressure (HVLP) spray gun in the shops during this study. Sealer, used to cover and seal, is applied as a single coat instead of primer or over primer, usually by the painter in a spray booth. Basecoating or "painting" typically requires two to five coats of color for coverage. Clearcoat or topcoat is the final hard protective layer. Basecoating and clearcoating always use more paint, and take more time. Typically, application of the clearcoat layer, depending on the area to be covered, takes less than half an hour including interim drying time required between the two to three coats. Gun cleaning is usually done near the mixing area. The gun is rinsed with solvent, disassembled, and parts are placed in the enclosed gun cleaning system, taking a couple of minutes in all.

The final tasks of removing the tape (unmasking), compounding, and detailing may involve skin contact with dry-to-the-touch, but incompletely cured, clearcoat. Compounding is buffing the clearcoat with polishing compound to remove flaws caused by dust specks. Washing and detailing of cars is done outside when weather permits.

Airborne Isocyanate During Spraying Operations

Table II shows airborne isocyanate concentrations taken outside of respirators for spraying primer, sealer, and clearcoat, in μg NCO/m^3. The highest airborne concentrations were measured in personal samples during applications of clearcoat. Sealer application samples were lower and primer samples were lowest of all. OSHA has ceiling standards for the aromatic isocyanate monomers, TDI and MDI, as its only regulations of isocyanate.[3] NIOSH has recommended a 10-min ceiling exposure limit for HDI monomer of 140 μg/m^3 that translates to 70 μg NCO/m^3, and a time-weighted average (TWA) that translates to 18 μg NCO/m^3.[23] The American Conference of Governmental Industrial Hygienists (ACGIH®) has TWA (but not short-term exposure limit [STEL] or ceiling) guidelines for both HDI and IPDI monomers that translate to 17 μg NCO/m^3.[24] In air samples from spraying operations, monomer comprised a median of 0.9% of the total isocyanate exposure. None of the samples had monomer levels exceeding the NIOSH-recommended level for HDI monomer of 70 μg NCO/m^3.

The Bayer Corporation has established as manufacturer's guidelines a 15-min STEL that translates to 220 μg NCO/m^3 for the HDI-based polyisocyanates biuret and isocyanurate, excluding monomers.[15] This level was later promulgated as a regulation by the state of Oregon OSHA.[7] The guidelines established in the United Kingdom specify a total NCO standard of 70 μg NCO/m^3 for a 15-min STEL for any isocyanate that includes both monomer and polymer contributions to total NCO groups.[8,9,25] In Table II our results are compared with these oligomer guidelines, the Bayer/Oregon guideline of 220 μg NCO/m^3, and the stricter U.K. Health and Safety Executive guideline of 70 μg NCO/m^3. For clearcoat applications, 66% of SPRAY samples exceeded the Bayer/Oregon polyisocyanate standard and 92% of samples exceeded the U.K. standard. Sealer applications were substantially lower with 34% of samples over the Bayer/Oregon standard and 66% of samples over the U.K. standard. Primer samples were lowest of all but nearly half of those were over the U.K. standard.

The quantity of isocyanate applied during the sample is given in Table II, as the amount of time to apply that quantity and/or the amount of time the sample was averaged were not standardized. This was primarily due to the realities of this complex and highly variable workplace. For example, some samples reflect as closely as possible actual spraying time, while others include a variable drying period between sprayed coats. In some cases sampling periods were influenced by

TABLE II. Airborne Isocyanate Concentrations During Spray Painting Tasks

		Air Concentration (μg Total NCO/m^3)					Bulk Hardener	
Coating Type	n	Median	25th Percentile	75th Percentile	Percent of Samples >70 μg/m^3 (%)	Percent of Samples >220 μg/m^3 (%)	Median Percent NCO (%)	Median mL of Hardener Applied
Primer	31	66.5	16.9	165	48	13	8	68
Sealer	29	134	48.4	296	66	34	11	53
Clear	93	358	157	855	92	66	10	138

concerns about reaching the limit of detection for the isocyanate analysis method. Sealing sample times, with the single coat application of sealer using the least material as shown in Table II, ranged from 2 to 36 min with a median of 6 min. Primers were applied in several coats though typically covering less area; sampling times for priming ranged from 3–37 min with a median of 15 min. Clearcoats typically involved applying a much greater volume of material than other isocyanate-containing layers. Clearcoating samples ranged from 1 to 49 min, with a median of 11 min. The median NCO content found in the hardeners used in the various layers (before mixing) were similar although primer hardeners appeared to be slightly more dilute. Mixing dilutions vary and the percentages in final formulations are not presented here.

Personnel and Business Factors

The SPRAY study included 37 shops of variable size and business activity (Table III). The smallest shop reported working on 8 cars (or jobs) per month, the largest 160 cars. The smallest had only the owner working, the largest shop had 20 full-time production workers. Shop area ranged from a 1500 ft^2 shop with two to three crowded bays and a small office, up to a 30,000 ft^2 cavernous building with numerous rooms, many of which were used for storing antique cars. The facilities in our study ranged in age from 1 month to 70 years old. Workers had a median work history of two shops in the last 10 years, with a range of 1 to 6 shops. Many (17%) reported moonlighting from 0.5 to 30 hours per week in another shop or at a residential garage painting motorcycles or doing noninsurance work on cars.

Business factors may impact exposures in many ways. Frequency of paint episodes is largely dependent on business volume. Small shops may have a job ready for paint only two or three times a week, whereas large shops may be painting more than twice that number of cars every day. Duration of painting sessions is determined by the quantity of surface to be covered, which is in turn determined by the extent of damage. For example, shops attached to dealerships might frequently repair small shipping dings. The actual size of the shop may allow workers to avoid bystander exposure more readily. The importance of these factors in predicting exposure level is examined in a companion article.[22]

Total clearcoat usage, based on figures provided to us by managers, ranged from 1–17 gallons per month with only three shops reporting more than 10. As would be expected, total volume of clearcoat used per month correlated strongly with business volume in number of jobs/month ($r_S = 0.77$, $p < 0.0001$). A clearcoat usage factor (ratio of the amount of clearcoat purchased per month in gallons, to the number of cars painted per month or clearcoat/car) reflects the size of jobs and ranged from 0.04 gal per car to 0.43 gal per car, with a median of 0.10. Two of the four dealerships in SPRAY fell into the lowest quartile in use of paint per car.

To explore differing levels of productivity we calculated a hustle factor (number of cars per month per full-time, nonoffice worker). This factor varied from 2.7 to 25 cars/month/FTE with a median of 7.4. The hustle factor correlated significantly with business volume indicating that larger shops were more productive ($r_S = 0.54$, $p = 0.0006$), implying a faster work pace and/or smaller jobs. A crowding factor was also calculated (nonoffice FTE per 1000 ft^2 of production area) to indicate spaciousness of work area. This factor ranged from a very cramped 3.3 workers per 1000 ft^2 to the palatial 0.2, with a median of 1.0.

Exposure depends on the tasks performed by the worker. Job titles have been consolidated into three major categories: body technician, painter, and office worker according to tasks performed (Table IV). Those who report spending more than half their time in the office, including the owners and managers,

TABLE III. Personnel and Business Factors Describing the Autobody Shops (N = 37)

	Mean	25th Percentile	Median	75th Percentile	Range
Cars/month[A]	45	20	30	60	8–160
Annual income[A] (in dollars)	788,225	300,000	500,000	1,200,000	100,000–3,500,000
Number of nonoffice employees[A] (FTEs)	5.4	3.0	5.0	7.0	1–20
Size (ft^2)	5580	2800	4800	6325	1500–30,000
Age of business[A] (years)	26	10.8	21	37	1 month–70 years
Years with same owner[A]	17	5.8	15	21	1 month–53 years
No. of different shops each employee has worked in over the last 10 years[B]		1	2	3	1–6
Total clearcoat usage (gallons/month)	4.6	1.8	4.0	6.0	1–17
Clearcoat usage factor (gallons/car)	0.12	0.07	0.10	0.14	0.04–0.43
Hustle factor (cars/month/FTE)	8.4	5.8	7.4	10.0	2.7–25
Crowding factor FTE/1000 ft^2	1.1	0.7	1.0	1.5	0.2–3.3

[A] As reported by owner.
[B] Work history forms collected by interview from individual workers. Employment of <3 months duration not counted.

TABLE IV. Distribution of Daily Task Activity by Job Title (Percent of Workday)

Task Group	Painters (n = 50) Median (25–75th Percentile)	Technicians (n = 110) Median (25–75th Percentile)	Office Workers (n = 63) Median (25–75th Percentile)
Spraying	9.8 (4.4–14.9)	0.4 (0–1.3)	0 (0–0)
Prep for spray (mixing, cleaning spray equipment)	5.0 (0.9–9.9)	0 (0–0.5)	0 (0–0)
Sanding primer (<24 hr old)	0 (0–1.8)	0 (0–0)	0 (0–0)
Sanding other (older paints)	0 (0–5.4)	0 (0–3.2)	0 (0–0)
Prep and finish (washing, taping, cleaning, compounding)	46.6 (21.0–58.2)	6.2 (1.0–25.5)	0 (0–0)
Mechanical work (disassembly and assembly, frame work, welding, grinding)	4.6 (0.8–18.7)	51.2 (17.4–72.4)	0 (0–1.7)
Bondo work (mixing, applying, sanding)	3.2 (0–8.3)	4.4 (0–16.4)	0 (0–0)
Office work	0 (0–0.3)	0 (0–0)	73.7 (27.0–96.4)
Miscellaneous (cleaning shop, moving cars, other)	9.4 (3.7–13.4)	7.1 (3.0–14.9)	24.0 (3.6–61.2)

are classified as office workers (27.5% of workers). Those who report spending more than half their time performing the painting tasks of masking, mixing, sealing, painting, gun cleaning, and clearcoating are classified as painters (22.9%). All others, including frame specialists, and miscellaneous helpers have been classified as body technicians (49.6%). The values in Table IV represent average daily percentages of working time spent in a particular task group. For example, the 9.8% median for painters means that half of the painters spent less than 9.8% of their working hours on spraying, while half spent more than 9.8% of their working time on spraying. For painters, the 75th percentile of 14.9% for painting means that 75% of the painters spent less than 14.9% of their workday spraying and conversely, 25% of the painters spent more than 14.9% of the workday spraying.

As expected, most painters spent the majority of their day on tasks directly related to painting, the technicians did mechanical work, and office workers did office work. Nevertheless, within a job title, workers do a number of tasks that overlap with other jobs. Thus it appears that job title is a reasonable descriptor of a worker's main tasks, but fails to include other auxiliary tasks that may contribute to exposure. For example, technicians were found to spray paint some of the time, and office workers do miscellaneous tasks in the shop that may result in their bystander exposure.

Control Factors

Substitution

Polyurethane paints containing isocyanate hardeners were introduced in the U.S. car refinishing market in the late 1960s and came into wide use in the 1980s. HDI-based hardeners were introduced first in the top or clearcoat to provide resistance to weather and sunlight. Aromatic isocyanates, particularly MDI, formerly popular in subsurface layers, have almost entirely disappeared from auto refinish paints. IPDI-based polyisocyanates, another group of saturated isocyanate, are being added increasingly to the HDI-based clearcoat hardeners.

Chemical information provided in MSDSs is limited and rarely describes the form of isocyanate in the product. Of MSDSs checked (for 24 shops, n = 65), over 80% describe all forms of polymeric HDI (any HDI-based prepolymer with more NCO groups than the monomeric HDI) with the same Chemical Abstract Service (CAS) #28182-81-2, "the homopolymer of HDI." In about 15% of MSDSs, the HDI oligomer is described more specifically as isocyanurate (CAS #3779-63-3), whereas in our analyses 79% of bulk samples contained some isocyanurate and 19% only isocyanurate. Only two MSDSs (3%) listed biuret at all (CAS #4035-89-6), whereas 35% of our bulk samples contained some biuret, and 12% contained only biuret as their isocyanate component of the hardener. However, the measured percentage of isocyanate in the bulk products agreed well with the percentage ranges specified in the MSDS. For more information, see Bello.[21]

Of the 74 hardeners used in the study shops (68 different hardeners, 6 duplicates reanalyzed) clearcoats were most likely to be formulated using a pure isocyanurate or mixtures of isocyanurate and polymeric IPDI hardener (Table V). Primers and sealers most commonly use pure biuret or a biuret/isocyanurate mixture in the hardener.

Out of 37 shops, the primer contained isocyanate in 21 shops (57%), sealer in 24 shops (65%), and clearcoat in all (though it was not used during our study week in one shop), whereas basecoat, except for one shop (3%), was isocyanate-free. Those primers and sealers that do not contain isocyanate hardeners most likely contain either two-part acrylic resins that are crosslinked using a blocked polyketimine or epoxies activated by polyamides or polyamines. It is not evident that this variation in use resulted from a conscious effort to reduce the potential for isocyanate exposure in all shops, but it is effectively a substitution.

TABLE V. Type of Isocyanates in Hardeners Used in Study Shops

		Percent (n) of Total Bulk Products Containing Listed Components (N = 74)				
Paint Type	n (%)	Biuret (N100)	Isocyanurate (N3300)	Biuret + Isocyanurate	Isocyanurate + IPDI Polymer	Percent Total (%)
	n	14	14	22	24	
Clear	39	0 (0)	15 (11)	12 (9)	26 (19)	53
Sealer	20	9 (7)	1 (1)	11 (8)	5 (4)	27
Primer	15	9 (7)	3 (2)	7 (5)	1 (1)	20
Percent total		19	20	30	32	100

Engineering Controls

Spray booths are the primary means of engineering control for airborne isocyanate exposure in this industry. Only 4 shops of the 37 had no booth at all, 20 had one booth, 10 had two, 2 shops had three, and 1 had four spray booths. Of those with no booth, two used a separate room to spray but lacked a fan. Most of the booths measured about $24 \times 15 \times 8.5$ ft^3 inside (mean 3900 ft^3); two were much larger truck booths (max 22,000 ft^3). Three shops (8%) had purchased prep stations as their second or third booth. Typically, shops with more than one booth had a mixture of types, keeping the old after the purchase of a new. Forty-six percent of shops had at least one downdraft booth, 41% a crossdraft booth, and 22% a semidowndraft booth.

Actual flowrates were measured in all but three of those shops having operable booths (Table VI). Air exchange rates for the booths, excluding the prep stations, ranged from less than 0.1 to 4.8 air changes per minute. Downdraft and semidowndraft booths together (excluding prep stations) had significantly higher flowrates than crossdraft booths (normal approximation of Wilcoxon rank sum = −6.17, $p < 0.0001$). Notably, one prep station without exhaust filters had an extremely high exchange rate (20.5 air changes per minute, based on the volume enclosed in its curtains); it served to clear the entire shop when it was on.

Airborne isocyanate concentrations (Table VI) tended to decrease with increasing air exchange rates. Concentrations in the crossdraft booths were significantly higher than those in the downdraft and semidowndraft booths ($F = 5.82$, $p = 0.02$ where the F-statistic is the ratio of the explained variability divided by the model degrees of freedom to the unexplained variability divided by the error degrees of freedom). The difference in isocyanate concentrations between semidowndraft and downdraft booths was not statistically significant. All of the downdraft booths were prefabricated units whereas 53% of the crossdraft booths were homemade. Isocyanate concentrations during spraying in the two types of crossdraft booths were not significantly different ($F = 0.08$, $p = 0.78$). Although these samples were taken in spray booths, 92% of personal isocyanate air samples in crossdraft booths, 74% in semidowndraft booths, and 81% in downdraft booths were above the HSE standard of 70 μg NCO/m^3. Almost half the spray samples in downdraft booths exceeded the less strict Bayer/Oregon standard of 220 μg NCO/m^3. These samples in booths are all of spray application and are all taken outside the painter's respirator; detailed results of nonspray task sampling are reported elsewhere.[22]

Two shops had extensive local exhaust ventilation systems throughout the shop for priming and sanding tasks. Most shops

TABLE VI. Air Exchanges (Air Changes Per Min) and Airborne Isocyanate Concentration (μg NCO/m^3) by Booth Type

	Booth Airflow			Air Concentration					
Booth Type	No. of Booths	Median (acm)	25–75th Percentile (acm)	No. of Samples	Median	25–75th Percentile	Percent >70 μg NCO/m^3 (%)	Percent >220 μg NCO/m^3 (%)	Median mL of Hardener Applied
Crossdraft (all)	15	0.5	0.3–1.6	36	346	184–705	92	69	For all inside booth samples 169
Crossdraft homemade	8	0.3	0.2–0.5	20	326	173–705	90	65	
Crossdraft prefabricated	7	1.4	0.9–2.3	16	383	224–1060	94	75	
Semidowndraft	8	2.0	1.6–2.6	27	271	61.2–563	74	52	
Downdraft	17	2.7	2.2–3.4	62	206	81.8–604	81	48	
Prep stations	3	3.0	3.0–11.8	5	185	134–302	80	40	
Outside booth				33	148	34.6–335	67	27	46

relied on natural ventilation—opening and closing the big bay doors to clear the air when weather permitted. A number of shops had wall-mounted louvered exhaust fans that were used only rarely and briefly after periods of intense sanding or grinding. Another strategy was to turn on the booth fan and open the spray booth door to clear shop air. Ceiling mixing fans were common, as were freestanding fans. Four shops had central air conditioning everywhere except in spray booths. The variety of layouts, the ever-shifting weather conditions, doors open and shut, and fans on and off made it difficult to characterize general ventilation in any meaningful way.

Few shops had local exhaust ventilation used for all paint mixing, which might be done in a single mixing room or in multiple locations. A separate primer mixing station lacking local exhaust ventilation was sometimes provided for the technicians. Another separate mixing station was often provided for computerized mixing of basecoat (color). These color mixing stations were typically small rooms (too small for all mixing work) with local exhaust ventilation, attached to a prefabricated spray booth.

HVLP guns were required by the Connecticut Department of Environmental Protection,[26] beginning in 1998, under the permitting process required for compliance with the Clean Air Act. Between our pilot study in 1992 and the current study, use of HVLP guns went from rare to universal, as did enclosed gun cleaning systems, also required under the same permit regulations.

Administrative Controls

Use of booths. In each shop, the booth with the best dust control was favored for applying basecoat and clearcoat. Priming and sealing were more often done in the older booth or prep station or with no control at all. Application of an isocyanate-containing primer on the open shop floor, outside a paint spray booth, and without local exhaust ventilation is a common practice that potentially exposes workers in other bays. These bystanders do not wear respirators, certainly not paint respirators. Although only four shops had no paint spray booth at all, in over 90% of shops there was occasional exposure of bystanders to primer and sealer applied by co-workers outside a booth. Thirty-five percent of those shops used coatings that did not contain any isocyanate but did, of course, contain solvents. Those personal air samples (Table VI) collected on workers spraying isocyanate primer or sealer outside the booth were small jobs and produced significantly lower concentrations than those done in any type of spray booth ($N = 158$, $F = 7.67$, $p = 0.006$).

Maintenance and housekeeping. The actual flowrate was compared with booth design specification when possible (airflow design specifications could be obtained for only 13 booths from 12 shops). The measured flow ranged from 30% of the specified flowrate to 140% with a median of 70%. About half the shops had a gauge measuring pressure drop across the filter to indicate a need for a filter change. In about 34% of booths it was reported that filters had been changed within the last month, with another 20% having changed them within the last few months. These reports agreed fairly well with the subjectively rated appearance of the filters by the investigators.

In most shops brooms were used to sweep the floors. Sometimes areas were hosed down with water. Booth floors themselves, especially in homemade booths, were often hosed down for dust control prior to painting.

Training. OSHA regulations require that all workplaces inventory, label, and make available to workers information and training on the potential health effects and safe handling of all chemicals at the work site. A written program is required to specify how workers are to be trained, who is responsible for all aspects of the program, and where MSDSs are kept. Forty-seven percent of the shop owners/managers reported having a written hazard communication program.

Personal Protective Equipment

All shops relied on personal protective equipment (respirators, gloves, and coveralls or uniforms) to protect painters from airborne and skin contact with paints. Owners of small shops typically depend on suppliers and/or painters for information about personal protective equipment. Table VII presents types of respirators, coveralls, and gloves used by painters as reported by managers. Information on uniform use applies to all workers in the shop.

Respirators are the primary protection from airborne exposures for painters while spraying. Some shops reported providing as many as three different respirator options for their painters, but in all shops the painter wore some kind of respirator at least for clearcoating. Nineteen shops reported providing supplied air respirators (SAR) with breathing air compressors or proper filtration, but only in 11 shops were any painters observed using SARs (Table VII). Thirty-two shops reported providing either a reusable or a disposable half face

TABLE VII. Respirators and Personal Protective Equipment Provided for Spray Painting

PPE	No. of Shops (%)
Respirators	37/37 (100)
Supplied Air Respirators (SAR) owned by shop	19/37 (54)
SAR used by painter(s)	11/37 (30)
Cartridge HF (disposable or reusable) with charcoal filter and N95 prefilter	32/37 (86)
Gloves	35/36 (97)
Powdered latex	14/36 (39)
Nonpowdered latex	18/36 (50)
Nitrile	9/36 (25)
Coveralls	28/35 (80)
Disposable tyvek	10/35 (29)
Reusable nylon and other	18/35 (51)
Uniforms provided	18/33 (55)
Required	13/33 (39)
Laundered by employer	12/33 (36)

respirator with organic vapor cartridges and N or P95 prefilters for painters, who typically donned respirators at the mixing station just prior to entering the booth to spray and removed them as soon as they came out, before cleaning their guns. For sanding, grinding, and other dusty jobs, workers were observed using half face cartridge respirators with HEPAs, N95 disposable dust masks, or no protection at all. It appeared to be based on personal choice, with considerable variation among technicians even within a shop.

Eleven shops reported having a written respirator program. All employees who used respirators had one for their personal use, sometimes several for different uses. Proper storage and cleaning of respirators was rare. Fit testing and respirator field fit factors will be discussed in a future publication.

The most commonly reported glove worn was nonpowdered latex provided in 50% of shops, followed by powdered latex in 39%, nitrile in 25%, and neoprene in 3%. Only one of the 36 shops reported that they did not provide any sort of chemical protective glove for painting. Twelve shops provided more than one type of chemical protective glove. Most shops offer gloves for protection from heat when welding or abrasion for grinding and mechanical work. Results of skin wipe sampling and a discussion of skin exposures to isocyanates in autobody shops can be found in a companion article.(27)

Eighty percent of shops reported providing some kind of coveralls to painters. Reusable coveralls were more common than disposable Tyvek®, which were reused as long as possible. Eighteen out of 33 shops provided uniforms, but only 13 required that they be worn. One required uniforms but did not provide them.

DISCUSSION

Validity of Study

Autobody repair is an industry of small and varied shops presenting many challenges to study. Isocyanates, a growing group of compounds without standardized names, standardized measurement and analytical methods, a universal metric, or exposure limits, intensify the challenge. Every shop and every individual in those shops have their own combination of exposure control strategies. It is difficult to extract meaningful conclusions regarding patterns of exposure, illness, and effective control from this accumulation of nonconforming data. But with 78% of our samples of spray applications containing isocyanate exceeding the U.K. HSE 10-min ceiling standard of 70 μg NCO/m^3, the endeavor is crucial.

The SPRAY shops appear to be reasonably representative of the industry. The *U.S. BodyShop Business*,(5) an autobody trade magazine, reported in 2001 that the average shop does about 14 jobs per week, has almost 6000 ft^2 of production space (median 4000), has a median employment of 5 workers, has an average sales volume of about $550,000, and has been in business for almost 23 years. By these measures the shops in our sample are a little older, about the same size, a little less productive, but similar to those autobody shops surveyed by Enander and colleagues(28) in 1996 in nearby Rhode Island. In our study we divided the workforce into three broad exposure groups: painters, who spend the majority of their time in painting and related tasks; body technicians, who do almost everything else to repair the car and do some of the priming; and office workers, who spend the majority of their time in the front office. Our finding that painters spend about 10% of their time in spray booths are comparable with other reports.(9,10)

Control factors explored are likewise not unique to the automotive refinishing industry in Connecticut, but comparisons here, too, have not been consistently reported. Autobody paints are themselves moving targets; composition has changed over time with the transition from lacquers to polyurethane enamels occurring during the past two to three decades. Monomer content is universally very low and contributes little to the total airborne isocyanate. Jaycock and Levin(29) described an autobody enamel paint containing 4–9% total aliphatic polyisocyanate by weight in 1984. Pisianello(10) noted a proportion of total polyisocyanate in the final paint mixture between 5 and 15% by weight, translating to 1–3% NCO by weight. Goyer and colleagues(14) reported a range of HDI oligomer weight in hardeners from 9 to 49%.

Our bulk samples, taken straight from the hardener container before addition of the polyol base, reducers, or additives, were between 4 and 18% NCO with a mean of 10% (excluding the single MDI-based isocyanate used on truck dollies at 27%). These will be diluted by as much as 8:1 or as little as 1:1, encompassing the reported ranges. Newer low-volatile, organic compound-high solids formulations are appearing, but none of the managers in our sample reported even considering switching to water-based paints until required to do so. Many, however, were aware of isocyanate-free primers and willing to explore that option as a control measure. As our knowledge of the mechanisms of induction of isocyanate asthma grows, we may be better able to develop safer substitutes.

In autobody shops, paint spray booths are the primary means of exposure control for tasks involving spraying. All but four shops in the SPRAY study had paint spray booths, 46% of them downdraft booths. All of the SPRAY downdraft, semidowndraft, and all but 4 of the crossdraft booths had more than 30 air changes per hour (0.5 air changes per min), the flow rate required by Oregon state regulations, intended to reflect an average face velocity of 100 ft/min.(7) Our findings of significantly lower exposures in downdraft and semidowndraft booths than in crossdraft booths, is consistent with previous findings of the superiority of downdraft booths.(30)

Our quantitative exposures with geometric means of 67 and 358 μg NCO/m^3 for priming and clearcoating, respectively, are roughly consistent with others' findings, but these comparisons are difficult as each study was designed for a different purpose, reflected different conditions, used different sampling and analysis methods, and is reported in different units. In Table VIII, quantitative data from some studies in autobody shops have been translated into μg NCO/m^3 with some of the accompanying sampling and shop characteristics.(7–11,13–15,31–34) Efforts were made to extract data taken under conditions most comparable with our own settings. Differences in sampling and

TABLE VIII. Airborne Concentrations of Isocyanates Reported in Autobody Shops (Translated to NCO μg NCO/m^3)

Publication	Airborne Isocyanate Levels Translated to (μg NCO/m^3)	Spray Gun, Ventilation	Sample Type, Sites (For Exposures Cited)
This study	Priming GM = 67 Clearcoating GM = 358	HVLP 50% of booths downdraft, 22% semidowndraft, 30% crossdraft	Personal 34 shops, Conn.
Maitre et al.[13] (1996)	Spray range 54–652	Conventional guns, downdraft, with velocity measurements	Personal 1 auto shop training center, France
McCammon and Sorensen[32] (1996)	Spray range ND–>109	HVLP and conventional guns inside booth and outside	Personal 1 shop, Colo.
Goyer et al.[14] (1995)	Spray range = 2–428	Downdraft booths, extensive ventilation evaluation	Personal 15 booths Montreal, Canada
McCammon[33] (1996)	Spray clearcoat range ND–105	Conventional and HVLP guns crossdraft booth	Personal 1 shop, Colo.
Cooper et al.[31] (1993)	Range—ND to 730	Non-HVLP, semidowndraft booths	Personal 1 shop, Ohio
Myer et al.[15] (1993)	Spraying GM = 593		Personal 7 shops repainting trains, aircraft, and autos, USA
Lesage et al.[11] (1992)	Spray range 304–413	Downdraft booths, extensive area sample, and booth information	Area samples at breathing zone height, 2 shops, Montréal, Canada
Janko et al.[7] (1992)	Priming GM = 13 Clearcoating GM = 350	Non-HVLP guns, 67% of booths had < 0.5 air changes per min	Personal 60 shops, Ore.
Tornling et al.[9] (1990)	Spray AM HDI-BT = 1090 Spray AM HDI-BT = 500 Spray AM HDI-BT = 260	Booths < 0.83 acm >0.83, <2.5 acm booths >2.5 acm	Personal 7 shops, Sweden
Pisaniello and Muriale[10] (1989)	Spray priming GM = 27 Spray clearcoat GM = 70 Spray single-stage GM = 202	Non-HVLP 71% of samples in downdraft booths	Personal 14 shops, Australia
Alexandersson et al.[8] (1987)	Spray AM HDI-BT = 25 Spray monomer AM = 500	— —	Personal samples 15 shops, Sweden
Rosenberg and Tuomi[34] (1984)	AM monomer = 25 AM oligomer = 313	Non-HVLP crossdraft > 20 air changes/hour	Personal 3 shops and 1 school, Finland

analytical methods are not included here. Despite the variety of conditions, most of the findings are in the same range.

Other commonly mentioned engineering controls, HVLP guns and enclosed and automated gun cleaning machines, were in almost universal use among SPRAY shops.

The practice of priming, even occasionally painting, outside the spray booth was widespread and noted by other investigators.[7,10,28,35] Booth maintenance practices were not studied specifically by others but were mentioned as factors contributing to poor booth performance. Nowhere were hygiene facilities and usage discussed.

In SPRAY, painters as well as body shop technicians wore respirators during spraying, most often using half face respirators with organic vapor cartridges and N95 overspray filters. Over half the shops had supplied air respirators available but they were used in only 30% of shops. Respirators were not used for mixing, gun cleaning, and bystander exposure to isocyanate spraying. Others have made similar observations.[7,10,31,35]

Gloves and protective clothing are frequently provided but usage is quite variable, as is consistent with other investigators' reports. However, the gloves provided most often (latex) were not protective for either solvents or isocyanates.

CONCLUSION

Although there have been many improvements in the autobody shops in this region over the last decade, there are still many opportunities for high-risk exposure. Associated health effects on the workers in this study will be reported shortly. Exposures (outside respirators) to polymeric isocyanates during spraying in autobody shops in this study were high with 48% of primer samples, 66% of sealer samples, and 92% of clearcoat samples exceeding the HSE ceiling standard of 70 μg NCO/m^3, despite the widespread use of spray booths as a primary means of exposure control. Nonisocyanate-containing primers and sealers are used in more than half the shops, but nonisocyanate clearcoats are not widely used in this industry in this region. Administrative controls are not universally enforced. Painters rely on respirators but issues of proper usage, maintenance, storage, and inspection remain. Skin protection lags behind that. The effects of interventions to mitigate exposures and effects are under current investigation by the team.

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