

# Skin Exposure to Aliphatic Polyisocyanates in the Auto Body Repair and Refinishing Industry: A Qualitative Assessment

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Received 20 January 2007; in final form 27 March 2007; published online 30 June 2007

**Objectives:** Although respiratory exposures have been the primary concern with isocyanates, skin exposure also can occur and may contribute to sensitization and asthma. Methodologies to assess isocyanate skin exposure in the workplace are limited and skin exposure data scarce. The goals of this study were (i) to evaluate and validate the isocyanate colorimetric indicators against a quantitative assay, (ii) to evaluate the extent of isocyanate surface contamination and skin exposure among auto body shop workers and (iii) to evaluate isocyanate skin exposure determinants.

**Methods:** The colorimetric indicators were compared with a high-performance liquid chromatography (HPLC) quantitative assay based on the National Institute for Occupational Safety and Health Method 5525 using paired laboratory sampling. The colorimetric indicators were then used to assess surface contamination and skin exposure to aliphatic isocyanates in 35 auto body shops and 124 workers as part of an epidemiologic study. The positive sample rate was calculated for various surfaces, body parts and tasks. The color intensity of the colorimetric indicators was rated on a scale 0 (yellow color) to 5 (deep red). Side-by-side comparisons of the qualitative method with the quantitative HPLC assay were also performed in the field using paired samples.

**Results:** Laboratory and field evaluation validated use of the colorimetric indicators. The rate of positive surface samples for isocyanates was 46% ( $n = 145/313$ ). Thirty-four percent (73/216) of samples were positive for unprotected skin and 20% ( $n = 22/111$ ) for skin under latex gloves. The highest positive rate observed on skin samples was obtained after paint mixing and spraying tasks. The colorimetric indicators were highly specific for isocyanates, but false negatives occurred when compared with the more sensitive HPLC quantitative assay. The presence of surface contamination and the performance of paint-related tasks were the major determinants of isocyanate skin exposure.

**Conclusions:** This study documents extensive surface contamination and skin exposure, including under gloves, to aliphatic polyisocyanates during painting and paint mixing tasks in auto body shop workers. Contaminated surfaces and aerosol deposition during spray painting may both contribute to skin exposure. The colorimetric indicator is a quick, practical and low-cost, but not highly sensitive, industrial hygiene tool to detect isocyanate surface contamination and skin exposures following the use of isocyanate-containing products.

**Keywords:** auto body refinishing; exposure assessment; hexamethylene diisocyanate (HDI); isocyanates; PPE; skin exposure; surface contamination; Survey of Painters and Repairers of Autobodies by Yale (SPRAY)

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## INTRODUCTION

Auto body shop painters and repair technicians use polyurethane paints for spray refinishing work. The hardener component of such paints consists largely of low volatility oligomeric species of hexamethylene diisocyanate (HDI) and isophorone diisocyanate (IPDI), which contribute >99% of the total isocyanate functional groups (NCO). The remainder 1% comes from HDI and/or IPDI monomer (Bello *et al.*, 2004; Sparer *et al.*, 2004; Pronk *et al.*, 2006a). The term 'polymeric' will be used to denote all higher oligomers and partially polymerized species (resulting from the reaction of an isocyanate with the polyol), containing free isocyanate groups. Monomeric and polymeric isocyanates can cause sensitization and occupational asthma in exposed workers (Vandenplas *et al.*, 1993; Redlich *et al.*, 2006). Spray painters in the auto body industry are at greater risk of developing isocyanate asthma than other occupations (Di Stefano *et al.*, 2004). The auto body industry in the US employs >205 000 workers in ~35 500 auto body shops (US Bureau of Census, 2002).

Traditionally, isocyanate exposure assessment and preventive strategies have focused on inhalation exposures, likely related to isocyanate asthma being the primary health outcome of concern, as well as the historic tendency to overlook skin exposure. However, animal and human studies suggest a role for isocyanate skin exposure in developing sensitization, with subsequent inhalation exposures leading to asthma (Bello *et al.*, 2007a). Additionally, isocyanates can be skin irritants and contact allergens (Goossens *et al.*, 2002; Redlich *et al.*, 2006).

Methods to measure isocyanate skin exposure are limited and little has been done to evaluate skin exposures to isocyanates in occupational settings. As part of a cross-sectional epidemiologic study, the Survey of Painters and Repairers of Autobodies by Yale (SPRAY), airborne exposures to aliphatic polyisocyanates were quantified for different tasks and exposure determinants identified (Sparer *et al.*, 2004; Woskie *et al.*, 2004; Liu *et al.*, 2006). A pilot study demonstrated the feasibility of assessing surface contamination and skin exposure to isocyanates using the SWYPE™ colorimetric indicators (CLI, Des Plaines, IL) (Liu *et al.*, 2000). This technique is inexpensive, gives immediate results and is easy to use, making it feasible to detect isocyanate contamination on work surfaces and assess potential skin exposure in the workplace. Some laboratory validation has been done to investigate interferences and sensitivity of the surface SWYPE™ in contact with aromatic isocyanates (OSHA, 1997), but peer-reviewed laboratory and field data of these colorimetric indicators with aliphatic isocyanates are lacking. Evaluation of colorimetric indicators is especially needed to assess

their performance and utility under realistic work conditions.

This study was undertaken to (i) evaluate and validate the isocyanate colorimetric indicators in the laboratory and in the field against a quantitative assay, (ii) evaluate the extent of isocyanate surface contamination in the auto body shops and skin exposure among auto body shop workers and (iii) evaluate isocyanate skin exposure determinants. This article reports results of our exposure assessment obtained with the qualitative colorimetric indicator. Quantitative assessment of skin exposures was also conducted and will be presented in a companion publication. These findings will further the development of task-based models to estimate isocyanate skin exposures among auto body shop workers.

## MATERIALS AND METHODS

### *Work process and potential for skin exposure*

Auto body shop work involves a number of different painting and non-painting tasks (Sparer *et al.*, 2004; Liu *et al.*, 2006). Painting tasks involve paint mixing, spray painting and cleaning equipment. Spray painting includes priming and/or sealer coating, base coating and finally clear coating. Skin exposure during mixing, spray painting and gun cleaning tasks may result from direct contact with the isocyanate bulk product, from contact with contaminated surfaces or from deposition of isocyanate vapor and aerosol on unprotected skin. Non-painting tasks such as dent repair have less potential for skin exposure. After priming, parts may be either dry or wet sanded. After the final clear coat, masking material is removed and the car may be compounded or buffed. These tasks may also provide opportunities for skin exposure to isocyanates, especially if the paints are not fully cured (Bello *et al.*, 2007b).

### *Study design and population*

This surface and isocyanate skin exposure assessment was an integral part of the SPRAY study (Redlich *et al.*, 2001; Sparer *et al.*, 2004; Woskie *et al.*, 2004). The qualitative evaluation was conducted in 35 shops, and a quantitative assessment targeted 22 of these shops due to financial and time constraints. Surface contamination and skin exposure, including exposure under gloves, coveralls and half-facepiece cartridge respirators, were evaluated based on guidelines from the US OSHA (1997) with modifications. The study protocol was approved by the Human Investigation Committee at Yale University. Informed written consent was obtained from each participant. Data on potential exposure determinants were collected from the shop owner/manager and workers, as previously described (Sparer *et al.*, 2004; Woskie *et al.*, 2004), including shop size,

paint types, shop ventilation and personal protective equipment.

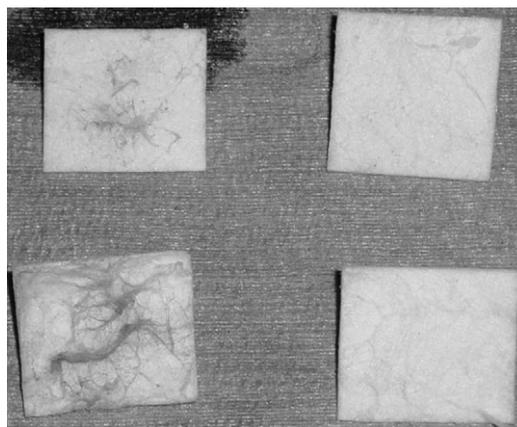
#### *Laboratory evaluation of SWYPE™ colorimetric indicators*

Prior to the field study, the qualitative SWYPE™ technique was compared with a high-performance liquid chromatography (HPLC) quantitative assay based on the National Institute for Occupational Safety and Health (NIOSH) Method 5525 for total aliphatic isocyanates in air (NIOSH 2003) with modifications (Bello *et al.*, 2002) to assess reproducibility of color intensity readings, determine detection limits and calibrate the SWYPE™ color rating with the amount of isocyanates recovered by the quantitative assay. Surface SWYPE™ pads, 2.5 × 2.5 cm in size from CLI (Fig. 1), were spiked by pipette with a known amount of an isocyanate blend (polymeric HDI and IPDI blend) in triplicates, at eight surface loadings covering the full range of SWYPE™ color intensity (<1–17 µg NCO per SWYPE™). The same volume of isocyanates was spiked in duplicates in a derivatizing solution of 1-(9-anthracenylmethyl)piperazine (MAP) in acetonitrile and analyzed by HPLC (Bello *et al.*, 2002). The SWYPE™ indicators were read by the same investigator who later read them in the field. The investigators involved with quantification and reading the SWYPE™ indicators were blinded of the amount of isocyanate spiked. The consistency of the SWYPE ratings by the investigator was assessed using replicate samples.

#### *Field assessment of surface contamination*

Surfaces likely to be in frequent contact with workers were evaluated including (i) those with possible high contamination by isocyanate-containing products and paints, such as hardener container, mixing tools and painting equipment, (ii) surfaces with possible contamination, such as body technicians' workbenches and tools (iii) surfaces with anticipated low or no contamination, such as office surfaces.

*Surface contamination assessment.* Same surface SWYPE™ indicators (Fig. 1.) as evaluated in the laboratory calibration testing, were used according to CLI's specifications and as previously described (Liu *et al.*, 2000). The investigator wore a pair of N-Dex powder-free nitrile gloves (Catalog # 9905PFL, Best Manufacturing Company, Menlo, GA) during sampling. A clean pair of gloves was used after each positive sample to avoid cross contamination. Selected surfaces were wiped with the SWYPE™ pad three times using the thumb, index and middle fingers holding the pad and pressed down firmly starting from outside moving toward inside concentrically. Areas wiped were standardized as 5 × 5 cm where possible, such as for the benchtop. Mixing rulers were wiped over an area of 2.5 ×



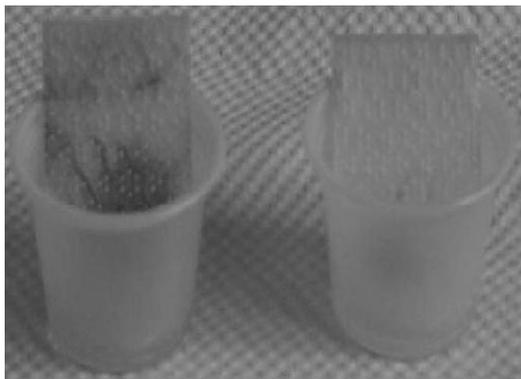
**Fig. 1.** Surface SWYPE™ indicators. The left column shows high isocyanate contamination (scores 3–4). The right column shows no/low contamination (scores 0–1).

7.6 cm on each side. For smaller and irregular surfaces, such as hardener container cap, the whole area was wiped and measured. Pads were then inspected for any color change. An orange to red color indicated the presence of aliphatic isocyanates (Fig. 1). Color intensity was semiquantitatively rated on a 0–5 scale (recorded as ‘–’ to ‘+++++’ in the field) with ‘0’ (–) as no color change (pale yellow, the patch's original color), ‘1’ (+) as light orange, ‘2’ (++) as orange, ‘3’ (+++) as deep orange, ‘4’ (++++) as red orange and ‘5’ (+++++) as the highest color intensity (deep red). All color ratings were performed by the same investigator. Twenty qualitative surface samples were targeted in each shop.

#### *Field assessment of skin exposure*

*Subject and task selection.* All shop-designated painters or body technicians who painted or primed with an isocyanate-containing paint during the survey week and one to two body technicians and office workers/managers who did not paint or prime were selected from each shop. Skin wipe sampling for exposure assessment was task based, similar to the air sampling strategy (Woskie *et al.*, 2004). Painting tasks included paint mixing, spray painting, spray gun cleaning and miscellaneous related tasks (untaping masking materials, dry or wet sanding of freshly painted parts and compounding). Non-painting tasks included masking the car, mechanical work, grinding and welding, dent repair, in-shop supervising and office work.

*Exposure of unprotected skin.* The skin SWYPE™ indicator was used as previously described (Liu *et al.*, 2000) and according to CLI's directions. The skin SWYPE™ is comprised of two portions: a 2.5- × 5.0-cm cloth sampling pad attached to a proprietary reagent-coated strip (Fig. 2). After the worker completed a task, exposed skin areas were



**Fig. 2.** Skin SWYPE™ indicators. The left cup (top piece) shows high isocyanate contamination (score 3). The right cup shows no contamination (score 0).

wiped twice with the cloth portion of the skin SWYPE™ pad. Both sides of a hand or the whole unprotected forearm were wiped. For the forehead, the exposed areas outside head covering were wiped; for face or neck outside the half-facepiece cartridge respirator, a 5.0 × 5.0-cm area was wiped. After sampling, the skin SWYPE™ pad was placed in a plastic cup, pad side down, and a developing solution of mineral oil was poured into the cup, reaching ~0.6 cm high. The solution migrated upward toward the reagent-impregnated strip, bringing with it isocyanates collected on the pad. Reaction of isocyanates with the reagent would result in an orange/red color, typically after ~5 min. The color intensity was similarly rated as in surface sampling by the same investigator. Twenty qualitative skin wipe samples were targeted for each shop.

*Skin exposure under personal protective equipment.* The presence of isocyanates under gloves and protective clothing was evaluated during mixing and painting tasks using the Permea-Tec™ indicators from CLI, as previously described (Liu *et al.*, 2000) and as per CLI instructions. Face areas covered by the half cartridge respirator facepiece were also wiped using the skin SWYPE™ sampling pad and measured. Permea-Tec™ indicators (2.2 × 2.2 cm) look similar to a band-aid adhesive strip and contain a proprietary reagent-coated yellowish pad that changes to orange or red color when in contact with aliphatic isocyanates (Fig. 3). Before each task was performed, the sampling pads (pad side out) were attached to the palm side of the thumb, index and middle fingers and the palm center of the dominant hand, or the pant leg under the coverall. The worker then donned the gloves and coverall. After finishing the task, the worker took off the gloves and coverall, and the pads were inspected for color changes. The color intensity was rated on the same scale as above. About 20 qualitative samples under personal protective equipment (PPE) were targeted for various tasks in each shop.



**Fig. 3.** Permea-Tec™ indicators. It shows contamination on glove finger patches. In this case, another layer of glove to be evaluated was worn over the patches.

#### *Sample information*

For each surface, skin or PPE sample taken, information was collected about the individual shop and subject, surface type and location, surface and skin areas wiped, type of PPE, painting information (task location and duration, quantity of paint, number of coats, hardener brand and painted surface areas) and ventilation (booth type and local exhaust). These variables were used in regression analysis to evaluate major skin exposure determinants.

#### *Quantitative assessment of surface and skin contamination*

Cloth wipe patches (5 × 5 cm) impregnated lightly with polypropylene glycol (PPG) were supplied by CLI. PPG-impregnated wipes provide good recovery of unbound isocyanates from the surface (Bello *et al.*, 2005). The investigator wore a clean pair of N-Dex nitrile gloves during sampling. After a surface or skin area was wiped, the sampling pad was placed into a jar containing a solution of MAP in methylene chloride for immediate extraction and derivatization. Samples were stored cold in the field and shipped in cooled containers to the laboratory for quantitative analysis as described above.

#### *Field evaluation of SWYPE™ colorimetric indicators*

A total of 151 paired qualitative surface SWYPE™ and quantitative samples and 98 paired skin SWYPE™ and quantitative samples were taken side by side to evaluate the relationship between the two methods on the limit of detection (LOD), sensitivity (ability to detect contamination when it is present) and specificity (ability to detect no contamination when it is not present), false positives or negatives (non-detectable values) of SWYPE™ indicators, and to assign an approximate isocyanate concentration

value to each color intensity score. Matched samples were collected on equal, side-by-side bench surfaces where isocyanate bulk product appeared more evenly spread, and on forearm and face skin areas where contamination from overspray aerosol deposition was considered more uniform. Half of the surface or skin area (half hand or forearm) was wiped for qualitative assessment and the other half for quantitative measurement.

#### Data analysis

**Laboratory evaluation of SWYPE™ indicators.** Color intensity readings for each isocyanate spike on the SWYPE™ indicator were plotted against the quantified amount of isocyanates to compare the two methods. Reproducibility in SWYPE™ color intensity rating was evaluated qualitatively by looking at the variation of scores within replicates and the average score between sets of replicates at similar loads. The LOD was determined as the lowest concentration where no color intensity was scored.

**Field SWYPE™ validation and sampling.** Field data were entered into a Microsoft Access dataset and analyzed using SAS® (Statistical Analysis Software, version 8.12, SAS Institute, Cary, NC).

The rate of positive samples was calculated as the ratio of positive samples (scores 1–5) to total samples for each surface type, task, color intensity category, skin area (hands, forearms, neck and face) and PPE type (under glove, respirator or coverall). Color intensity scores were grouped as low (scores 1–2, marginal but definitive color change) and high (scores 3–5, intense color change) based on significant color intensity difference between the negative category and these two categories.

Results from the quantitative analysis were calculated as nanograms of total isocyanate groups (NCO) per square centimeter ( $\text{ng NCO cm}^{-2}$ ) of surface or skin area wiped. Data were log transformed and geometric mean (GM) and geometric standard deviation (GSD) were calculated for comparison with results from qualitative assessment.

Results on paired surface and skin wipe samples were cross tabulated for the low- and high-intensity score groups. The GM, GSD and percentage of samples above LOD were calculated for each group and the relationship between the two methods was compared and the sensitivity, specificity and false positive and negative rates were assessed. The GM levels of isocyanates among the three score categories were compared with each other using analysis of variance (ANOVA) and a significance level of  $P < 0.05$  was selected.

The positive rate for skin exposure was calculated using samples collected from tasks that involved the use of or direct contact with isocyanate paints only. Samples from non-paint tasks such as detailing, mechanical and body repair work, shop supervising and

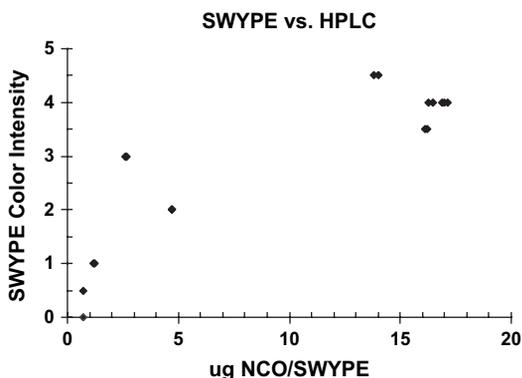
office work were not included. The positive rate was zero for these tasks and not listed in the skin exposure table.

**Evaluation of skin exposure determinants.** Log-binomial single-predictor regression modeling with a log link was performed on positive surface and skin sampling results to evaluate significant exposure determinants from task variables recorded in the sampling form, such as for a spray painting task, type of paints and quantities used and the painted area, ventilation conditions (booth type and shop general ventilation), climate parameters (temperature and relative humidity) and from shop variables, such as shop size and annual income. This analysis produces prevalence ratio (PR) estimates, the appropriate measure for non-rare events (Thompson *et al.*, 1998). When the PR is larger than one, the factor is identified as a risk factor for the PR.

## RESULTS

#### Laboratory evaluation of SWYPE™ indicators

The laboratory calibration of the SWYPE™ indicator against the quantitative HPLC assay shows a good quantitative relationship between the two methods (Fig. 4). Over a wide range of NCO loads spiked on the SWYPE™ pads, the higher the load the greater the SWYPE™ color intensity score. The relationship is reasonably linear at small NCO loads ( $<5 \mu\text{g NCO per SWYPE}^{\text{TM}}$ ), but flattens out at higher loads ( $>13 \mu\text{g NCO per SWYPE}^{\text{TM}}$ ). The SWYPE™ color intensity rating was highly reproducible under laboratory conditions with scores for replicates varying by not more than 0.5 across the whole range of isocyanate loads (overlapping replicates in Fig. 4). The variability at loads 0–5  $\mu\text{g}$  was negligible at comparable NCO loads; each data point



**Fig. 4.** Calibration of SWYPE™ color intensity score against the quantitative HPLC assay in a laboratory investigation. The apparent single data points in the 0–5  $\mu\text{g NCO per SWYPE}^{\text{TM}}$  range are in fact overlapping triplicates.

is a replicate. At the upper loads, slight variability is noticed by the overlapping data points (Fig. 4).

An estimate of the LOD for SWYPE™ indicators based on the regression line of the data points was  $\sim 0.7 \mu\text{g NCO}$  per SWYPE™ ( $17 \text{ nmol NCO}$ ). This is  $\sim 3.2 \mu\text{g HDI polyisocyanates}$  per SWYPE™, since polymeric HDI contains  $\sim 22\%$  free NCO ( $\mu\text{g NCO}/0.22 = 3.2 \mu\text{g HDI polyisocyanates}$ ). Expressed as square centimeter (based on SWYPE™ surface size of  $2.5 \times 2.5 \text{ cm}$ ) the estimated LOD was  $0.1 \mu\text{g NCO cm}^{-2}$  or  $0.5 \mu\text{g HDI polyisocyanates cm}^{-2}$ . The quantitative HPLC assay had an LOD (based on the main HDI polyisocyanate peak) of  $\sim 5 \text{ ng NCO per sample}$  ( $119 \text{ pmol per sample}$ ) with  $3.6 \text{ pmol NCO}$  injected.

### Surface contamination

Table 1 shows the results on surface contamination. A total of 313 surface samples were collected in 35 shops, of which 46% ( $n = 145$ ) were positive with some color intensity. The average positive rate of total samples was 22% ( $n = 68$ ) for the 'low' (scores 1–2) and 25% ( $n = 77$ ) for the 'high' (scores 3–5) intensity levels. The overall positive sample rates and rates under intensity categories (low versus high) for different surface types were variable (Table 1). The hardener mixing cup, hardener container cap

and painted car surfaces were at high positive rates and moderate intensity levels (73–80%; 1.5–2.5). Most painting and mixing surfaces had medium positive rates and intensity levels (41–67%; 0.5–2.0) including hardener mixing tools and bench and gun cup and handle after hardener coating and solvent washing. Several other surfaces (e.g. booth door handle) had low positive rates and low intensity levels (12–30%;  $\sim 0.5$ ). Non-painting surfaces such as body repair workbench and surfaces in the office had close to zero positive rates and intensities.

### Exposure of unprotected skin

The results of skin exposure to isocyanates during various painting and paint-related tasks are shown in Table 2. A total of 216 samples were collected from 124 workers, of which 34% were positive ( $n = 73$ ). Most positive samples, 26% ( $n = 55$ ), were at low intensity levels with only 8% ( $n = 18$ ) at high intensity levels. The highest rate and intensity of skin contamination were found for paint mixing and spray painting of primers and clear coats. For example, the rate of positive skin SWYPE™ samples during mixing of primer and clear coats was 75% (3/4) and 64% (7/11), respectively, and the positive rate for clear coating was 45% (38/84), of which 11% (9/84) were of high color intensity. Skin exposure

Table 1. Surface contamination by aliphatic isocyanates in SPRAY auto body shops by surface type ( $n = 313$ ) based on surface SWYPE™ colorimetric indicators

Surface	$n^b$	$n$ (%) <sup>a</sup>		
		Positive samples	Low color intensity <sup>c</sup> , scores 1–2	High color intensity <sup>c</sup> , scores 3–5
<b>Mixing surfaces</b>				
Cup for hardener mixing	25	20 (80)	13 (52)	7 (28)
Hardener container cap	30	22 (73)	5 (17)	17 (57)
Hardener mixing bench	33	20 (61)	4 (12)	16 (48)
Ruler for hardener mixing	18	9 (50)	3 (17)	6 (33)
Thinner container handle	17	7 (41)	5 (29)	2 (12)
Paint mixing scale	24	3 (12)	1 (4)	2 (8)
<b>Painting surfaces</b>				
Painted car surface	13	10 (77)	6 (46)	4 (31)
Masking tape and paper	18	12 (67)	5 (28)	7 (39)
Gun cup after coating	30	18 (60)	11 (37)	7 (23)
Gun cup after washing	10	6 (60)	3 (30)	3 (30)
Gun handle after coating	14	8 (57)	4 (28)	4 (28)
Booth door handle	20	6 (30)	5 (25)	1 (5)
Gun washer handle	14	3 (21)	2 (14)	1 (7)
<b>Non-painting surfaces</b>				
Body repair bench	20	0 (0)	0	0
Office desk and telephone	27	1 (4)	1 (4)	0
<b>Total</b>	<b>313</b>	<b>145 (46)</b>	<b>68 (22)</b>	<b>77 (25)</b>

<sup>a</sup>Number and rate of positive samples.

<sup>b</sup>Number of total samples.

<sup>c</sup>SWYPE™ color intensity score ranked from 0 to 5: 0, No color change; 1–2, Low, definitive color change, but of weak color intensity (light orange); 3–5, High, intense color change (deep orange to deep red). See text for more details.

to isocyanates was found for both wet sanding (42%, 8/19) and dry sanding (23%, 3/13) of paints. In general, no or very little contamination was found for tasks that did not involve the direct use of isocyanate bulks or close contact with painted surfaces.

Skin exposure to isocyanates on different body parts after painting tasks only are shown in Table 3. Equal sampling of different body parts was attempted with painting tasks, but some skin areas were not available for sampling (covered by sleeve or glove). Exposure of face and neck to isocyanates after painting was found in 39% (21/54) of samples, and was of comparable frequency to that of either hand (42%, 25/60) or forearm (27%, 6/22). For non-painting tasks, skin sampling was performed primarily on hands, based on observed work practices and pilot data indicating little exposure to other skin sites during these tasks. For mixing, 44% (10/23) of hand samples were positive for skin exposure (Table 2).

Table 2. Skin exposure to aliphatic isocyanates in SPRAY auto body shops for tasks of direct contact with isocyanates ( $n = 216$ ) based on skin SWYPE™ colorimetric indicators

Task	$n^b$	$n$ (%) <sup>a</sup>		
		Positive samples	Low color intensity <sup>c</sup> , scores 1–2	High color intensity <sup>c</sup> , scores 3–5
<b>Spray painting</b>				
Priming	29	7 (24)	4 (14)	3 (10)
Sealing	22	7 (32)	7 (32)	0 (0)
Base coating	1	0 (0)	0 (0)	0 (0)
Clear coating	84	38 (45)	29 (34)	9 (11)
<b>Paint mixing</b>				
Priming	4	3 (75)	2 (50)	1 (25)
Sealing	8	0 (0)	0 (0)	0 (0)
Base coating	0	0 (0)	0 (0)	0 (0)
Clear coating	11	7 (64)	5 (46)	2 (18)
<b>Paint related</b>				
Compounding	7	0 (0)	0 (0)	0 (0)
Untaping	18	0 (0)	0 (0)	0 (0)
Dry sanding	13	3 (23)	1 (8)	2 (15)
Wet sanding	19	8 (42)	7 (37)	1 (5)
Total	216	73 (34)	55 (26)	18 (8)

<sup>a</sup>Number and rate of positive samples.

<sup>b</sup>Number of total samples.

<sup>c</sup>The color intensity ranking and grouping is the same as in Table 1.

Table 3. Task-based isocyanate skin exposure in different locations of the body for isocyanate painting tasks

Task	Number of positive SWYPE/total number of SWYPE (%)			
	Face and neck	Either hand	Either forearm	Total
Spray painting	21/54 (39)	25/60 (42)	6/22 (27)	52/136 (38)

### Skin exposure under PPE

To assess skin exposure under PPE (Table 4), a total of 194 samples from 23 shops were collected underneath gloves, coveralls and respirators. Twelve percent (23/194) of samples were positive with 9% (17/194) at low intensity and 3% (6/194) at high intensity. Skin exposure under gloves during various tasks was variable. The vast majority of shops (87%, 20/23) used latex gloves. The overall rate of positive Permea-Tec™ indicators underneath latex gloves was 20% (22/111) for all paint-related tasks (mixing, spraying and gun cleaning), of which 14% (16/111) and 5% (6/111) of samples were of low and high color intensity, respectively. The highest frequency of glove breakthrough (80%, 4/5) was found for spray gun cleaning, followed by clear coating (26%, 11/43), sealer coating (19%, 3/16) and priming (17%, 1/6). The sources of glove breakthrough were discussed later in this article. Samples taken from skin areas that were covered by half-facepiece cartridge respirators or coverall showed no or minimal skin contamination.

### Determinants of skin exposure

Shop, sample and task determinants of a positive skin SWYPE™ were identified using single-predictor regression modeling analysis (summarized in Table 5). Among the shop variables, the likelihood of one or

Table 4. Rate of positive Permea-Tec™ indicators for aliphatic isocyanates underneath gloves, half-facepiece respirators and coveralls in SPRAY auto body shops by isocyanate task

PPE type/task	$n^b$	$n$ (%) <sup>a</sup>		
		Positive samples	Low color intensity <sup>c</sup> , scores 1–2	High color intensity <sup>c</sup> , scores 3–5
<b>Under glove</b>				
All tasks	111	22 (20)	16 (14)	6 (5)
All spraying	65	15 (23)	10 (15)	5 (8)
Priming	6	1 (17)	1 (17)	0 (0)
Sealing	16	3 (19)	0 (0)	3 (19)
Clear coating	43	11 (26)	9 (21)	2 (5)
Mixing	41	3 (7)	3 (7)	0 (0)
Gun cleaning	5	4 (80)	3 (60)	1 (20)
<b>Under respirator</b>				
All spraying	27	0 (0)	0 (0)	0 (0)
<b>Under coverall</b>				
All tasks	56	1 (2)	1 (2)	0 (0)
All spraying	43	1 (2)	1 (2)	0 (0)
Mixing/gun cleaning	13	0 (0)	0 (0)	0 (0)
Total	194	23 (12)	17 (9)	6 (3)

<sup>a</sup>Number and rate of positive samples.

<sup>b</sup>Number of total samples.

<sup>c</sup>The color intensity ranking and grouping is the same as in Table 1.

more positive surface SWYPE™ samples identified in the shop was the most important determinant of a positive skin SWYPE™ [PR = 4.88,  $P = 0.01$ , 95% confidence interval (CI) = 1.5–16.1]. Several paint-related variables were also significant determinants of the positive skin SWYPE™ samples, such as coating type and location of painting tasks (Table 5). The use of an isocyanate hardener (PR = 5.9,  $P = 0.002$ , 95% CI = 1.9–17.8) and clear coat

painting (PR = 2.5,  $P = 0.0001$ , 95% CI = 1.6–3.8) were the most significant predictors.

#### Field evaluation of SWYPE™ indicators

The results from qualitative (SWYPE™) indicators and quantitative (HPLC) assay for both surface ( $n = 151$ ) and skin ( $n = 98$ ) sample pairs are presented in Table 6. The color intensity score, categorized into non-detectable, low (scores 1–2) and high (scores 3–5), were validated against the corresponding GM (ng NCO cm<sup>-2</sup>) isocyanate load. The field LOD for the SWYPE™ method was variable, characterized by a GM (GSD) of 2.2 (9.8) and 0.4 (8.0) ng NCO cm<sup>-2</sup> (area wiped) for paired 'negative' surface and skin SWYPE™ samples, respectively. The total NCO load for these HPLC quantitative skin wipes varied up to ~2 µg NCO per SWYPE™ (equivalent of 9 µg polyisocyanate per SWYPE™ or 1.4 µg polyisocyanate cm<sup>-2</sup> pad size), greater than the LOD of SWYPE™ estimated from the laboratory investigation.

The GM (GSD) low color intensity (scores 1–2) was estimated at 13.2 (6.4) and 3.5 (7.6) ng NCO cm<sup>-2</sup> for surface and skin samples, respectively, whereas for high color intensity (scores 3–5) the GM (GSD) was estimated as 41.9 (8.7) ng NCO cm<sup>-2</sup> for surface samples and 17.5 (2.6) ng NCO cm<sup>-2</sup> for skin samples. The levels of skin exposure were much lower than levels of surface contamination.

Results from ANOVA indicated that there is a significant difference ( $P < 0.0001$ ) in GM levels of isocyanates comparing the three score categories in both surface and skin samples: for surface samples, the negative category is significantly different from each of the two positive categories, but the low score category is not significantly different ( $P > 0.05$ ) from the high category; for skin samples, the negative category is significantly different ( $P < 0.05$ )

Table 5. Determinants of a positive skin SWYPE™ using single-predictor regression modeling

Determinant (variable name)	PR ( $P$ value)	95% CI
Shop characteristics <sup>a</sup>		
Surface positive test (1 or more positive surface SWYPE™ samples in shop)	4.88 (0.01)	1.48–16.09
Hustle (cars/month/full-time equivalent worker)	0.92 (0.03)	0.85–0.99
Sample characteristics		
Milliliters of NCO applied	1.00 (0.75)	1.00–1.00
Task performed in booth or mixing room versus elsewhere	2.29 (0.03)	1.07–4.91
Clear coating versus other types	2.46 (0.0001)	1.57–3.85
Area painted (ft <sup>2</sup> )	1.00 (0.06)	1.00–1.01
Painting time (min) <sup>b</sup>	0.99 (0.98)	0.97–1.03
Any use of hardener versus none	5.89 (0.002)	1.94–17.82
Windows in shop (closed versus open)	1.34 (0.32)	0.81–1.89
Body part sampled (face versus other) <sup>c</sup>	1.05 (0.85)	0.66–1.65

<sup>a</sup>Only two significant predictors out of 18 are presented. A full description of shop predictors for inhalation exposure can be found in Woskie *et al.* (2004).

<sup>b</sup>One outlier value removed.

<sup>c</sup>Painting only—mixing was almost entirely assessed for hand exposure.

Table 6. Relationship between the qualitative (SWYPE™ indicators) and quantitative (HPLC assay) assessments of contamination by aliphatic polyisocyanates in the SPRAY auto body shops for surface and skin

Qualitative score <sup>a</sup>	Quantitative results <sup>b</sup>			
	$n$ (%)	$n > \text{LOD}$ (%)	GM <sup>c</sup> (ng NCO cm <sup>-2</sup> )	GSD (ng NCO cm <sup>-2</sup> )
Surface, $n = 151$ pairs				
0 (negative)	79 (52)	54 (68)	2.20	9.78
1–2 (low)	26 (17)	25 (96)	13.17 <sup>d</sup>	6.43
3–5 (high)	46 (30)	42 (91)	41.89 <sup>d</sup>	8.69
Skin, $n = 98$ pairs				
0 (negative)	81 (83)	58 (72)	0.42	7.97
1–2 (low)	9 (9)	9 (100)	3.53	7.55
3–5 (high)	8 (8)	8 (100)	17.50 <sup>d</sup>	2.55

<sup>a</sup>Same as described in Table 1.

<sup>b</sup>Quantitative isocyanate surface concentration (ng NCO cm<sup>-2</sup>) was calculated as ng NCO on the wipe/sampled surface or skin area.

<sup>c</sup>ANOVA:  $P < 0.0001$  for overall comparison among the three score categories.

<sup>d</sup>ANOVA:  $P < 0.05$  comparing low and/or high score categories with the negative score category.

from the high, but no other significant difference was observed.

SWYPE™ indicators were highly specific, but considerably less sensitive for isocyanates, compared to the quantitative HPLC assay. The specificity of the SWYPE™ indicators was 100% (23/23) (0 false positives) for skin samples and 83% (25/30) for surface samples (7% false positives). The sensitivity of SWYPE™ indicators was 55% (67/121) for surface samples, and only 23% (17/75) for skin samples, compared to the quantitative HPLC assay. Thus, the fraction of 'false negatives' (or non-detectable values) for SWYPE™ were high: 68% (54/79) for surface samples and 72% (58/81) for skin samples compared to quantitative HPLC assay (Table 6).

## DISCUSSION

This investigation of skin exposure to aliphatic polyisocyanates in the auto body industry documents two key findings. First, it validates the colorimetric SWYPE™ indicator as a highly specific but not very sensitive qualitative method to detect isocyanate surface contamination and skin exposure, compared to the quantitative HPLC assay. Second, using this qualitative method we demonstrate that isocyanate surface contamination and skin exposures are common in this industry, and identify determinants of skin exposure to isocyanates. These findings should facilitate the development of personal skin exposure indices as well as focus future preventive interventions.

Although SWYPE™ indicators have been available commercially for >10 years, this is the first published study we are aware of that evaluates the utility of SWYPE™ indicators to detect surface contamination and skin exposure to aliphatic isocyanates, by comparing them with the paired quantitative sampling assay in both laboratory and workplace settings. The SWYPE™ indicators were first calibrated and validated by comparison with the quantitative HPLC assay in the laboratory investigation, and then further evaluated under work conditions. The findings enabled assignment of crude quantitative levels to qualitative SWYPE™ color intensity scores, and the determination of their LOD. The assigned LOD of  $\sim 3.2 \mu\text{g HDI polyisocyanates per SWYPE}^{\text{TM}} (0.5 \mu\text{g cm}^{-2})$  based on our laboratory study is consistent with available LOD estimates (3–5  $\mu\text{g}$  per SWYPE™ for aromatic isocyanates) reported by CLI and OSHA (1997). The higher LOD for SWYPE™ in the field (up to 9  $\mu\text{g}$  per SWYPE™ or 1.44  $\mu\text{g cm}^{-2}$  HDI polyisocyanate) likely was due to reduced recovery of isocyanates from skin and surfaces compared to that in laboratory testing.

A positive SWYPE™ sample in this work setting was a highly specific indicator of isocyanate on skin

or work surfaces as documented by no (for skin) or very few (surface) false positive SWYPE™ samples. Thus, colorimetric indicators provide a useful, quick and relatively inexpensive workplace tool to assess isocyanate skin or surface contamination shortly after use of isocyanate-containing products. This method can increase awareness and facilitate preventive measures such as change in work practices or use of appropriate PPE. Since isocyanate skin exposure data are so limited, and dose–response relationships are not defined, caution is warranted in labeling skin exposures as high, low or relevant.

However, our findings also highlight several limitations of SWYPE™ indicators as well as our study design. Most important was the low sensitivity (high rate of false negatives) in comparison to quantitative HPLC assay, not unexpected given the substantial time, cost and expertise needed for the sensitive HPLC assay (LOD  $\sim 5 \text{ ng NCO per sample for laboratory samples}$ ). Therefore, a negative SWYPE™ does not preclude the possibility that isocyanate may be present on the sampled surface or skin area.

Another limitation of the SWYPE™ indicators was their variability in the workplace setting. Although the laboratory testing showed reliable color readings with repeat isocyanate loads and the intensity score increased proportionally with greater amounts of isocyanates spiked on the SWYPE™ pads, the workplace validation testing showed much greater variability, as reflected in the high GSDs from the paired qualitative and quantitative field samples. Several factors, including variable areas and uneven distribution of isocyanates on skin and surfaces in the side-by-side sampling, uneven distribution on colorimetric pads and variable sampling efficiencies for the quantitative versus SWYPE™ indicators likely contributed to the observed variability between paired qualitative and quantitative samples. Although the surface and skin SWYPE™ and PPE Permea-Tec™ indicators all use the same propriety reagent to detect free NCO groups, there are differences, which also may have contributed to the variability between qualitative and quantitative results. For example, the surface SWYPE™ and Permea-Tec™ indicators react upon direct contact with isocyanate, whereas the skin SWYPE™ indicator utilizes a cloth pad that requires isocyanate transfer to the reagent strip, for which recovery rates are unknown. In addition, color intensity scoring of SWYPE™ is a subjective process and requires the consistency of persons reading the SWYPE™. A more objective color scheme (such as a color intensity standard or the use of a chromameter to process the intensity) may reduce variability in color intensity rating and should be developed for future studies. Controlled laboratory testing could have clarified some of these issues regarding surface evaluation, but ethical concerns limit human laboratory studies.

Another important consideration with evaluation of isocyanate skin exposure is the timing, which is crucial, since SWYPE™ indicators and the HPLC quantitative assay both depend on the detection of free NCO groups. Skin wipe sampling in this study was performed immediately after tasks involving uncured isocyanate-containing products, except for dry sanding with old paints. Isocyanates may be absorbed through the skin (Fent *et al.*, 2006) and/or may react with water, sweat and skin proteins (Wisniewski *et al.*, 2000), which could result in reduced detection of skin exposure. Thus, routine surveillance with SWYPE™ indicators could substantially underestimate skin exposure, especially if such exposure is sporadic and the sampling is not timed immediately after the exposure.

Despite these limitations, SWYPE™ indicators provide an immediate, easy, inexpensive and useful tool for employers and workers to detect workplace isocyanate surface contamination and skin exposures shortly after they occur. Such immediate detection should increase awareness of the potential for skin exposure as well as lead to improved prevention. SWYPE™ indicators can also serve as a valuable research tool in further investigating the health effects of isocyanate skin exposures.

The second key finding of this study was the extensive isocyanate skin exposure, including hands, face and forearms, during a variety of routine tasks, and including underneath PPE, based on >200 qualitative SWYPE™ skin samples taken from 124 auto body workers. Skin exposure was also documented during tasks considered lower risk for isocyanate exposure and where gloves typically are not worn, such as dry and wet sanding. Contamination was noted on most surfaces during painting and mixing tasks. Such surfaces provide opportunity for direct skin contact until fully cured, which can take days to weeks (Bello *et al.*, 2007b). Our findings of extensive isocyanate hand skin exposure are consistent with Pronk *et al.* (2006b) who recently reported quantitative hand skin exposures in auto body shop workers, using nitrile rubber gloves as collection media under normally worn gloves. Another recent report documented skin exposure to HDI on a single painter using a tape strip method to sample the stratum corneum and liquid chromatography–mass spectrometry analysis (Fent *et al.*, 2006).

Comparable frequencies of contamination of different body parts (face/neck, hands and forearms) and the significant association with isocyanate paint content point to deposition of overspray aerosol as a significant source for skin exposure. The relative contribution of overspray aerosol deposition to skin exposure is unknown. Our data on exposure determinant modeling suggest that contaminated surfaces, the use of isocyanate-containing hardeners and NCO content are an important source of skin exposure.

Surface contamination may serve as a major skin exposure source during mixing tasks where aerosol deposition is unlikely. Identified determinants of skin exposure should be targeted for exposure control.

Sampling under gloves indicated frequent isocyanate breakthrough and skin exposure during certain tasks. For example, skin exposure under latex gloves was found in ~23% of the samples during painting tasks, and up to 80% during spray gun cleaning. Our observations documenting skin exposure under gloves are consistent with recent findings from Pronk *et al.* (2006b). Compared with exposures of unprotected skin, however, the rate of positive samples was generally lower under latex gloves. Whether glove failure, especially during spray gun cleaning, is due to isocyanate breakthrough with/without solvent assistance, mechanical tears in gloves or polymer disintegration is not known and warrants further study, as do other glove types such as nitrile.

Testing under protective clothing and under half-facepiece organic vapor cartridge respirators, the dominant type in actual use in the U.S. (Liu *et al.*, 2006), indicated little or no breakthrough from isocyanates using the qualitative sampling. However, lower levels of isocyanate skin exposure cannot be ruled out given the greater sensitivity of the quantitative assay noted above. An intervention study to evaluate the effectiveness of different PPE and work practices is underway.

## CONCLUSION

This study has demonstrated the utility of qualitative SWYPE™ indicators as a reliable, immediate and low-cost, but not highly sensitive, detection tool for identifying isocyanate surface contamination and skin exposure in the workplace, immediately after use of isocyanate-containing products. Using SWYPE™ indicators we have documented widespread isocyanate surface and skin contamination associated with paint-related activities. Exposure of unprotected skin was common during some paint-related tasks, including tasks for which gloves are not routinely worn such as wet and dry sanding. Isocyanates were also detected underneath commonly used latex gloves. Contaminated surfaces and deposition of overspray aerosol both likely contribute to isocyanate skin exposure in these workers. Although the health effects of isocyanate skin exposure remain unclear and warrant further research, it is prudent to develop better strategies to reduce such exposures. Although qualitative indicators have limitations, they can facilitate awareness of, research on and prevention of isocyanate skin exposure.

*Acknowledgements*—This study was supported by the US National Heart, Lung and Blood Institute/National Institutes of Health grant 1R01-HL62932 and NIOSH/Centers for Disease

Control grant IR01OH03457. Dr Redlich was supported in part by National Institute of Environmental Health Sciences grant K24-ES00355. We thank Tom Klingner at CLI, Richard Lawrence and Dr Allan Hines at OSHA, Mark Boeniger and Dr Robert Streicher at NIOSH for technical support and invaluable suggestions. We are grateful to Frank Walsh for his dedicated fieldwork. We thank shop management and workers, whose participation and support made this study possible.

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