Journal of Occupational and Environmental Hygiene
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713657996

Field Comparison of Air Sampling Methods for Monomeric and Polymeric 1,6-Hexamethylene Diisocyanate

Jennifer M. Thomasen[a]; Kenneth W. Fent[a]; Carolyn Reeb-Whitaker[b]; Stephen G. Whittaker[bc]; Leena A. Nylander-French[a]
[a] Department of Environmental Sciences and Engineering, Gillings School of Global Public Health, The University of North Carolina at Chapel Hill, Chapel Hill, North Carolina [b] Safety & Health Assessment & Research for Prevention (SHARP) Program, Washington State Department of Labor & Industries, Olympia, Washington [c] Local Hazardous Waste Management Program, Public Health-Seattle & King County, Seattle, Washington

First published on: 23 February 2011

To cite this Article Thomasen, Jennifer M. , Fent, Kenneth W. , Reeb-Whitaker, Carolyn , Whittaker, Stephen G. and Nylander-French, Leena A.(2011) 'Field Comparison of Air Sampling Methods for Monomeric and Polymeric 1,6-Hexamethylene Diisocyanate', Journal of Occupational and Environmental Hygiene, 8: 3, 161 — 178, First published on: 23 February 2011 (iFirst)

To link to this Article: DOI: 10.1080/15459624.2011.555711
URL: http://dx.doi.org/10.1080/15459624.2011.555711

Journal of Occupational and Environmental Hygiene, 8: 161–178
ISSN: 1545-9624 print / 1545-9632 online

DOI: 10.1080/15459624.2011.555711

Field Comparison of Air Sampling Methods for Monomeric and Polymeric 1,6-Hexamethylene Diisocyanate

Jennifer M. Thomasen,[1] Kenneth W. Fent,[1] Carolyn Reeb-Whitaker,[2] Stephen G. Whittaker,[2,3] and Leena A. Nylander-French[1]

[1]Department of Environmental Sciences and Engineering, Gillings School of Global Public Health, The University of North Carolina at Chapel Hill, Chapel Hill, North Carolina
[2]Safety & Health Assessment & Research for Prevention (SHARP) Program, Washington State Department of Labor & Industries, Olympia, Washington
[3]Local Hazardous Waste Management Program, Public Health-Seattle & King County, Seattle, Washington

This study was to critically compared 13 different air samplers for their ability to monitor air exposures to monomeric and polymeric 1,6-hexamethylene diisocyanate (HDI) in the automotive refinishing industry. Using both fast- and slow-drying clearcoat, we tested the following types of samplers: single- and dual-stage 37-mm polypropylene (PP) and polystyrene (PS) samplers (open- and closed-face), IOM (with plastic and stainless steel inserts), OSHA42, IsoChek, and WA-DOSH samplers. Midget impingers with frit were used as reference samplers. We observed the PP, PS, and IOM samplers to measure greater levels of HDI monomer and biuret when a fast-drying clearcoat was applied compared with a slow-drying clearcoat. When a slow-drying clearcoat was applied, the open-face PP and PS samplers measured significantly more monomeric and polymeric HDI (2-fold; $p < 0.003$) than the closed-face PP and PS samplers. We determined that significantly more monomeric and polymeric HDI were measured by impingers (1.3–1.9-fold) compared with single-stage PP/PS ($N = 59$), dual-stage PP/PS ($N = 59$), or IOM ($N = 24$) samplers. However, when stratified by cassette characteristics, the open-face single-stage PP and PS samplers performed equally to the impingers for HDI monomer when a fast-drying clearcoat was applied, and for all analytes when a slow-drying clearcoat was applied. Significantly higher HDI monomer concentrations (1.2–3.1-fold; $p = 0.001$) were measured with OSHA42 compared with the impinger. The IsoChek did not detect HDI monomer, and of the three samplers analyzed by laboratories other than UNC (i.e., OSHA42, IsoChek, and WA-DOSH), the WA-DOSH was in the best agreement with the impingers. The influence of clearcoat drying time on the sampler's ability to measure monomeric and polymeric HDI emphasizes the importance of the speciation of diisocyanates in chemical analysis and the careful consideration for the selection of the air sampler to be used when measuring exposures during automotive spray painting.

Keywords 1, 6-hexamethylene diisocyanate (HDI), air sampling, inhalation exposure, polyisocyanate, sampling method

Correspondence to: Leena A. Nylander-French, Department of Environmental Sciences and Engineering, Gillings School of Global Public Health, The University of North Carolina at Chapel Hill, CB #7431, Rosenau Hall, Chapel Hill, NC 27599-7431; e-mail: leena_french@unc.edu.

INTRODUCTION

Diisocyanates are a group of highly reactive, low-molecular-weight aromatic and aliphatic compounds, characterized by containing two isocyanate functional groups (N=C=O). Exposure to isocyanates may cause adverse effects in respiratory tract, skin, and eyes.[1,2] Occupational or environmental asthma may account for as much as one-third of the more than 10 million adult asthma cases,[3] with isocyanate-induced asthma accounting for between 5 to 30% of the occupational asthma cases.[4–9] A large number of these workers are employed in the automotive refinishing industry where polyurethane-based paints and coatings containing monomeric and polymeric 1,6-hexamethylene diisocyanate (HDI) are used. The most widely used isocyanates include HDI monomer as well as the HDI polyisocyanates uretdione, biuret, and isocyanurate.[10] Throughout the article we will refer to both diisocyanates and polyisocyanates as isocyanates.

The measurement of airborne isocyanate-containing compounds continues to be a challenge in the industrial hygiene field. Selection of the most appropriate sampling and analytical method for quantitative monitoring of isocyanate exposure in a specific workplace environment is difficult for the following reasons: (1) isocyanates may be in the form of vapors or aerosols of various particle sizes; (2) the species of interest are reactive and unstable; (3) commercially available pure analytical standards exist only for monomeric diisocyanates;

and (4) low limits of detection are needed.[11,12] Use of an appropriate sampling and/or analytical method is critical for accurate assessment of worker's exposure to isocyanates. Most of the exposure assessment studies evaluating airborne isocyanate exposure in the automotive refinishing industry have used a variety of air sampling devices and analytical methods, therefore making it challenging to compare the results.[13–18]

In the spray painting environment, monomeric and polymeric HDI are present in both aerosol and vapor phases.[19] Several sampling devices and analytical chemistry methods have been used for the measurement and analysis of monomeric and polymeric HDI present in both the aerosol and vapor phases. Some common sampling devices include a variety of cassettes with treated filters, such as Institute of Medicine (IOM) sampler, Occupational Safety and Health Administration Method 42 (OSHA42) sampler, and IsoChek sampler, as well as impingers or bubblers filled with absorbing solution.

Both single-stage and dual-stage filter cassettes have been used to sample isocyanates in the occupational setting.[20] The dual-stage samplers typically contain a first stage that is loaded with an untreated polytetrafluoroethylene (PTFE) prefilter (designed to collect isocyanate aerosols), and the second stage is loaded with a glass fiber filter (GFF) impregnated with a derivatizing agent (designed to collect and derivatize isocyanate vapors). With single-stage sampling, a PTFE filter is not used, and as a result, the impregnated GFF collects and derivatizes isocyanates in both aerosol and vapor phases.

A commonly used single-stage sampling method is OSHA42,[21] which utilizes a GFF impregnated with 1-(2-pyridyl) piperazine (1-2PP) to sample diisocyanate monomer. A commonly used dual-stage sampler is IsoChek (Omega Specialty Instrument Co., Houston, Texas), which employs 9-(N-methylaminomethyl)anthracene (MAMA) for derivatization. The analytical method provided by the commercially available IsoChek reports diisocyanate monomer as well as all polyisocyanates expressed as total reactive isocyanates (TRIG). TRIG is defined as the sum of free NCO groups (i.e., comprising all isocyanate species) present in a sample.[22] However, this is a subjective definition that is dependent on the analytical scheme used to define total NCO. In addition, there are several impinger methods (e.g., NIOSH 5521, NIOSH 5522, proposed NIOSH 5525), which have been modified for single-stage filter sampling of isocyanates.

Several studies [11,12,18,19,22–28] have been performed to evaluate and compare some of these sampler types. However, the evidence is inconclusive regarding the suitability and accuracy of these methods for monitoring isocyanate exposure in different settings. Therefore, the objective of this study was to compare sampling devices commonly used to quantify exposure to monomeric and polymeric HDI in the spray painting environment. Our ability to measure isocyanate exposure properly is critical for exposure and risk assessment to predict systemic exposure, to develop sensitive and predictive models through multiple exposure routes, and ultimately to protect the health of workers.

METHODS

Air Samplers

A total of 13 air samplers were compared for measuring monomeric and polymeric HDI levels. Along with glass midget impingers with frit (reference sampler), we evaluated the performance of single- and dual-stage 37-mm polypropylene (PP) and polystyrene (PS) samplers either open- or closed-face, and IOM samplers with plastic and stainless steel inserts, as well as OSHA42, IsoChek, and Washington State Division of Safety and Health (WA-DOSH) samplers. These samplers were selected because they have previously been used to monitor monomeric and polymeric HDI exposures in research studies as well as by practicing industrial hygienists for regulatory purposes. We decided to include both PP and PS materials because we found lower recoveries of HDI for PS as compared with PP in laboratory experiments (results not published), which supported Huynh et al.[29] findings that showed higher recovery from PP cassettes. The different samplers are described below and further summarized in Table I. All chemicals used in this study were obtained from Sigma Aldrich (St. Louis, Mo.) unless otherwise specified. All samplers analyzed at UNC laboratory were prepared no more than 2 weeks prior to sampling.

Single- and Dual-Stage PP and PS Samplers

The single-stage PP and PS samplers contained a 37-mm GFF (Type AE; SKC, Eighty Four, Pa.) impregnated with MPP solution [1-(2-methoxyphenyl)-piperazine (MPP), 192.3 g/mol; 1.09 g/mL in toluene] designed to collect and derivatize isocyanate vapors. The dual-stage PP and PS samplers contained an untreated polytetrafluoroethylene (PTFE) pre-filter, designed to collect isocyanate aerosols, and an impregnated GFF. Before GFFs were placed into a single- or dual-cassette housing, they were impregnated with 400 μL of 12 g/L MPP in toluene, which corresponds to 4.8 mg of MPP, and then allowed to dry for 15 min.

IOM Samplers

IOM samplers with either stainless steel or plastic insert were prepared by impregnating a 25-mm GFF (SKC) with 400 μL MPP solution, which corresponds to 4.8 mg of MPP (consistent with PP/PS samplers). Before placing the GFF into a sampler, 200 μL of 12 g/L MPP in toluene was applied to the filter and allowed to dry for 15 min, after which an additional 200 μL of 12 g/L MPP in toluene was applied and allowed to dry for 15 min.

OSHA42

A 37-mm GFF was coated with 0.1 mg of 1-(2-pyridyl) piperazine (1–2PP) and housed in a PS cassette. These samplers (Galson Laboratories, Syracuse, N.Y.) were used to monitor concentrations of HDI monomer.

TABLE I. Summary of Samplers, Experimental Conditions, and Analytical Techniques

	Impinger	Single-Stage	Dual-Stage	IOM	Single-Stage OSHA42	Dual-Stage IsoChek	Dual-Stage WA-DOSH
Housing	25-mL midget impinger with frit	37-mm PP or PS	37-mm PP or PS	25-mm SS or plastic	37-mm PS	37-mm PS	37-mm PS
Housing Mode	NA	Open- or closed-face	Open- or closed-face	Open-face	Open-face	Closed-face	Closed-face
Sample Medium	15 mL of 2 g/L MPP in 30% DMF/ACN (30 mg)	GFF with MPP (4.8 mg)	5 μm PTFE GFF with MPP (4.8 mg)	GFF with MPP (4.8 mg)	GFF with 1-2PP (0.1 mg)	5 μm PTFE GFF with MAMA (0.1 mg)	5 μm PTFE GFF with MAMA (0.1 mg)
Flow Rate	1 L/min	1 L/min	1 L/min	2 L/min	1 L/min	1 L/min	1 L/min
Analyte	HDI monomer HDI polyisocyanates (biuret and isocyanurate)	HDI monomer HDI polyisocyanates (biuret and isocyanurate)	HDI monomer HDI polyisocyanates (biuret and isocyanurate)	HDI monomer HDI polyisocyanates (biuret and isocyanurate)	HDI monomer	HDI monomer HDI polyisocyanates (total NCO)	HDI monomer HDI polyisocyanates (biuret and isocyanurate)
Analytical Technique	LC-MS	LC-MS	LC-MS	LC-MS	HPLC-UV or FL	HPLC-PDA UV	HPLC-DAD and FLD
LOD^{A} (μg)	monomer 0.002 biuret 0.02 isocyanurate 0.02	monomer 0.002 biuret 0.02 isocyanurate 0.02	monomer 0.002 biuret 0.02 isocyanurate 0.02	monomer 0.002 biuret 0.02 isocyanurate 0.02	0.1^{B}	monomer and polyisocyanate 0.03^{B}	monomer 0.005 biuret 1.7 isocyanurate 1.2

Notes: PP = polypropylene; PS = polystyrene; SS = stainless steel; NA = not applicable; MPP = 1-(2-methoxyphenyl)-piperazine; DMF = *N*,*N*-dimethylformamide; ACN = acetonitrile; GFF = glass fiber filter; PTFE = polytetrafluoroethylene; 1-2PP = 1-(2-pyridyl) piperazine; MAMA = 9-(*N*-methylaminomethyl)anthracene; LC-MS = liquid chromatography/mass spectrometry; HPLC = high-performance liquid chromatography; UV = ultraviolet detector; FL = fluorescence detector; PDA = photodiode array detector; DAD = diode array detector.

^{A}Instrumental limit of detection: μg per filter.

^{B}Based on limit of quantitation (reporting limit) provided by accredited laboratory.

IsoChek

This sampler was a dual-stage, 37-mm PS cassette (Galson). The first stage included a 5-μm PTFE filter designed to capture aerosols, while the second stage included a 37-mm GFF impregnated with 9-(*N*-methylaminomethyl)anthracene (MAMA) designed to capture and derivatize isocyanate vapors.

WA-DOSH

The WA-DOSH sampler uses the same dual-stage cassette, filters, and derivatizing agents as the commercially available IsoChek sampler described above. A different analytical technique is utilized for the analysis of the WA-DOSH sampler by the Washington State DOSH laboratory, an AIHA-accredited laboratory. The WA-DOSH Labor and Industry (L&I) method directly measures the mass of individual diisocyanate polymers and expresses each diisocyanate in units of $\mu g/m^3$.

Impinger

Glass midget impingers with frit (SKC 225-36-2) were filled with 15 mL of derivatizing solution that was made by dissolving 2 g of MPP in 1 L of 30% v/v solution of *N*,*N*-dimethylformamide (DMF, 73.09 g/mol) in acetonitrile (ACN, 41.05 g/mol). The theoretical amount of derivatizing agent (MPP) in each impinger was 30 mg.

Spray Painting Procedure and Sample Collection

As shown in Figure 1, six samplers (A–F) of the same type and three impingers (I1–I3) were attached to a cardboard backing. The samplers were attached to a high-flow pump (SKC) operated at 1 or 2 L/min. The pumps were calibrated before and after sampling using a DryCal (BIOS Corp., Butler, N.J.) primary flow meter. Clearcoat was sprayed directly above the samplers with a high-volume, low-pressure (HVLP) spray gun, producing an overspray that was deposited over the samplers. The same painter was used throughout the study and was instructed to stand approximately 1 m from the samplers. The painter sprayed the clearcoat over the top of the samplers across the cardboard backing four times during each spray period. Spraying was conducted a total of three times throughout the 15-min sample period (once every 5 min) using a multi-use clear with either HDI-containing fast or slow activator-reducer (3:1 clear to activator by volume). For quality control, blank sample controls were obtained by opening and closing prepared cassettes in the field setting. In addition, bulk samples (10 μL) of the clearcoat being sprayed were collected each time a new batch of clearcoat was mixed (N = 12).

Sample Processing and Analysis

PP, PS, and IOM Samplers

Immediately after sampling, both the PTFE and GFF from single- and dual-stage PP and PS, as well as from IOM cassettes, were placed into 20-mL glass vials (I-Chem, Thermo Fisher Scientific, Rockwood, Tenn.) containing 5 mL of derivatizing solution (2 g/L MPP in 30% DMF-ACN solution) to minimize the time for any competing reactions, such as isocyanate polymerization. Samples were shaken thoroughly and then stored in a cooler (~4°C) until returned to our laboratory at UNC and stored at –40°C until analyzed. For analysis, samples were returned to room temperature, and acetic anhydride was added (100 μL) to acetylate residual MPP. After 15 min, internal standard (52 pmol/μL 1,8-octamethylene diisocyanate; ODIU) was added (100 μL) to give an internal standard concentration of 1 pmol/μL. Samples were analyzed for HDI monomer, biuret, and isocyanurate using liquid chromatography-mass spectrometry (LC-MS) as described elsewhere.[30]

OSHA42

Samples were handled according to manufacturer's specifications. After sampling, the cassettes with GFFs in place were sealed and stored at –40°C until shipment in a cooler (~4°C) to Galson Laboratories (an AIHA-accredited laboratory) for analysis. Samples were processed and analyzed for HDI monomer by OSHA42 method, which utilizes solvent desorption and high-performance liquid chromatography (HPLC) analysis using ultraviolet (UV) or fluorescence (FL) detector.[21]

IsoChek

Samples were handled according to the manufacturer's specifications. After sampling, the PTFE filter was immediately placed into 5 mL of methoxy-2-phenyl-1-piperazine reagent (MOPIP) in toluene (0.1 mg/mL) to derivatize aerosols. The vials containing PTFE filters and the cassettes with GFFs in place were sealed and stored at –40°C until shipment in a cooler (~4°C) to Galson Laboratories for analysis.

Both the PTFE filters and GFFs were analyzed using HPLC with photodiode array detector (PDA) UV for HDI monomer and polyisocyanates. The IsoChek method does not identify the types of polyisocyanates present based on specific polyisocyanate standards. Instead, polyisocyanates of HDI are identified by comparing a diode array scan of the associated monomer standard with a diode array scan of the samples to identify the presence of polyisocyanate peaks. Once identified, the areas of these peaks are summed and quantified using the response factor of the monomer peak and concentration calculated using the molecular weight of an NCO equivalent (42 g/mol).

WA-DOSH

Samples were handled according to the WA-DOSH L&I method specifications (L&I 0050 and L&I 0067). After sampling was completed, the PTFE filter was immediately removed from the cassette and placed in a jar with 4 mL of MOPIP in toluene solution (1 mg/mL), and the cassettes with GFFs in place were sealed. The samples were stored at –40°C until analysis by WA-DOSH state laboratory using HPLC with diode array detector (DAD) and FL UV as described in WA-DOSH L&I methods 0050 and 0067.[31,32] The WA-DOSH L&I method directly measures the mass of individual

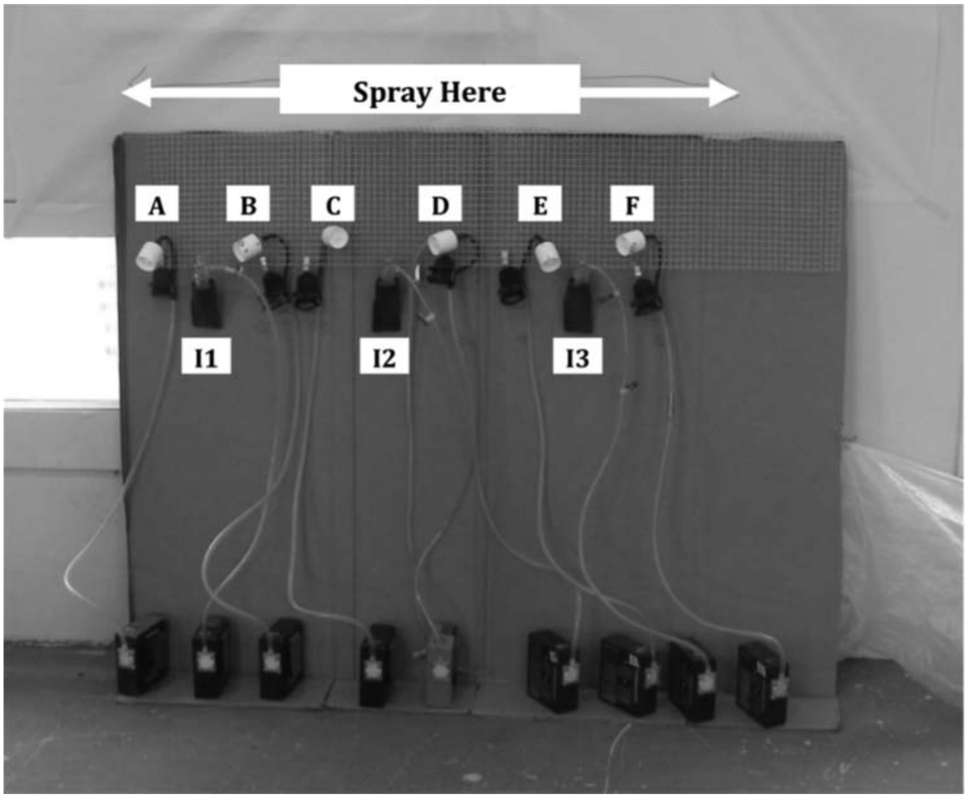

FIGURE 1. Sampler setup during spray painting (I1 = reference Impinger 1 compared with Samplers A and B; I2 = reference Impinger 2 compared with Samplers C and D; I3 = reference Impinger 3 compared with Samplers E and F).

diisocyanate polymers and expresses each diisocyanate in units of $\mu g/m^3$.

Impingers

After sample collection, the solution evaporated from the impinger during sampling was replaced with derivatizing solution (2 g/L MPP in 30% DMF/ACN) to obtain a total volume of 15 mL. The sampling solution was then transferred into a 20-mL glass vial (I-Chem) and placed in a cooler (∼4°C) and returned to our laboratory at UNC for storage at –40°C until analyzed. For analysis, samples were returned to room temperature, and acetic anhydride was added (200 μL) to acetylate residual MPP. After 15 min, internal standard (77 pmol/μL ODIU) was added (200 μL) to give an internal standard concentration of 1 pmol/μL. Samples were analyzed using LC-MS as described elsewhere.(30)

Bulk Samples

Bulk sample of a mixed clearcoat (10 μL) was drawn into a 20-μL pipette and dispensed into a glass vial (I-Chem) filled with 15 mL of derivatizing solution (2 g/L MPP in 30% DMF/ACN). The pipette tip was also ejected into the solution to eliminate sidewall losses due to the viscosity of the clearcoat. The samples were then placed into a cooler (∼4°C) and returned to our laboratory at UNC for storage at –40°C until analyzed. For analysis, samples were returned to room temperature, and acetic anhydride was added (200 μL) to acetylate residual MPP. After 15 min, internal standard (2 pmol/μL ODIU) was combined (1:1 v/v ratio) with aliquots of each paint sample to give an internal standard concentration of 1 pmol/μL. Samples were analyzed using LC-MS as described elsewhere.(30)

Data Analysis

The relative standard error (RSE) and relative standard deviation (RSD) for the three impinger samples and six cassette samples collected during each sampling run were calculated. We further calculated an overall mean RSE and RSD among the sampling runs for both fast- and slow-drying clearcoats. Paired *t*-test (α-level of 0.05) was used to determine if the variability among impingers and cassette samplers was significantly different.

PP, PS, and IOM Samplers

For dual-stage samplers, the sum of the mass on the filters (PTFE and GFF) was calculated. Levels below the limit of detection (LOD) or limit of quantitation (LOQ) were assigned values by dividing the respective limits by $\sqrt{2}$.(33) The ratio of the HDI concentration in the filter(s) to the concentration measured with the impinger was determined, and the ratios were natural log-transformed to satisfy the normality assumption. Shapiro-Wilks tests for normality indicated that the ratios were approximately log-normally distributed for HDI monomer ($W = 0.99$), biuret ($W = 0.95$), and isocyanurate ($W = 0.96$).

The data were analyzed using SAS 9.1 statistical software (SAS Institute, Cary, N.C.) at α-level of 0.05. A paired *t*-test was used to determine if samplers were significantly different from the adjacent impinger samples. General linear modeling (SAS PROC GLM) with the least squares approach was used to investigate the differences in the measured amounts of HDI monomer, biuret, and isocyanurate between the samplers. GLM analysis of covariance (ANCOVA) type III sum of squares, with adjustment for reference impinger, was utilized to determine if the variables (1) clearcoat (fast- or slow-drying), (2) sampling style (open- or closed-face), (3) cassette stage (single- or dual-stage), or (4) cassette type (PP or PS; IOM plastic or IOM steel) were influencing the observed cassette to impinger ratios for HDI monomer, biuret, and isocyanurate.

Differences in the least square means of the sampler to impinger ratios for HDI monomer, biuret, and isocyanurate were investigated for six sampler combinations: (1) one-stage open-face, (2) one-stage closed-face, (3) dual-stage open-face, (4) dual-stage closed-face, (5) IOM plastic, and (6) IOM steel. Tukey-Kramer adjustment for multiple comparisons was utilized and the data were stratified by clearcoat drying time (fast or slow).

OSHA42, IsoChek, and WA-DOSH Samplers

The results of the OSHA42 and IsoChek (Galson Laboratories) and WA-DOSH (WA State DOSH Laboratory) samples were compared with the impinger samples analyzed at UNC. For the impinger samples corresponding with IsoChek samples, the results for HDI polyisocyanate are expressed in mg/m^3 NCO in air calculated as the concentration (C) of the compound divided by its molecular weight (MW) and multiplied by the number (N) of NCO groups and the MW of NCO (42 g/mol):

$$(C_{compound}/MW_{compound}) \times N_{NCO} \times MW_{NCO}.^{(34)} \qquad \textbf{(1)}$$

The results for HDI biuret and isocyanurate were converted to mg/m^3 NCO in air and summed for the impinger samples corresponding with IsoChek samples only. Levels below the LOD or LOQ were assigned values by dividing the respective limits by $\sqrt{2}$.[33] Paired *t*-test (α-level of 0.05) was used to determine if these samplers measured significantly different amounts of monomeric and polymeric HDI from the adjacent impinger samples. Student's *t*-test (α-level of 0.05) was used to determine if these samplers measured significantly different amounts of monomeric and polymeric HDI when using a fast- or slow-drying clearcoat.

Bulk Sample

The bulk paint samples were analyzed in our laboratory at UNC. Student's *t*-test (α-level of 0.05) was used to determine if significant differences existed among concentrations of HDI monomer, biuret, and isocyanurate between a fast- and slow-drying clearcoat.

RESULTS

All samplers measured levels of monomeric and polymeric HDI that were within ranges reported in the occupational field settings.[13,20] HDI monomer, biuret, and isocyanurate concentration ratios (i.e., the sampler concentration divided by the impinger concentration) by clearcoat type for samplers are summarized in the box and whisker plots in Figures 2, 3, and 4, respectively. OSHA42 and IsoChek samplers are not plotted for HDI biuret and isocyanurate as these analytes were not measured by these samplers. Also note that the HDI monomer levels measured by IsoChek (N = 12) and the HDI biuret levels measured by WA-DOSH (fast-drying clearcoat only, N = 6) were below respective LOD and LOQ and were therefore calculated using respective LOD or LOQ divided by the $\sqrt{2}$.[33]

The overall mean RSE and RSD among the sampling runs for both a fast- and slow-drying clearcoat are summarized in Table II. Paired *t*-test revealed that the impinger samplers were significantly less variable than cassette samplers for HDI biuret when a fast-drying clearcoat was applied ($p = 0.04$). Paired *t*-test also showed that the cassette samplers were significantly less variable than the impinger samplers for HDI monomer when a slow-drying clearcoat was applied ($p = 0.01$). For all other instances, the variability among impingers and cassette samplers was not significantly different.

PP, PS, and IOM Samplers

The geometric mean (GM) air levels ($\mu g/m^3$) of monomeric and polymeric HDI measured by impingers as well as PP, PS, and IOM samplers stratified by clearcoat drying-time are summarized in Table III. As depicted in Figures 2–4, when a fast-drying clearcoat was applied, the single-stage open-face PS sampler was in best agreement with impinger samplers for HDI monomer, biuret, and isocyanurate [GM (95% confidence interval; 95%CI): 1.19 (0.78–1.8), 0.92 (0.48–1.8), 0.92 (0.56–1.5), respectively]. For slow-drying clearcoat, the dual-stage open-face PP sampler was in best agreement with impinger samplers for HDI monomer, biuret, and isocyanurate [GM (95%CI): 1.07 (0.60–1.9), 1.54 (0.80–3.0), 1.30 (0.59–2.9), respectively]. For biuret, GM ratios for all samplers were about 2-fold higher when a slow-drying clearcoat was sprayed compared with fast-drying clearcoat (Student's *t*-test, $p < 0.0001$); this significant trend was not observed for HDI monomer and isocyanurate.

Significantly more HDI monomer, biuret, and isocyanurate were measured by impingers (1.3–1.9-fold) compared with the PP/PS single-stage (N = 59), PP/PS dual-stage (N = 59), and IOM (N = 24) samplers (p-values <0.005; data not shown). However, significant differences were not always observed among impingers when the samplers were stratified by different characteristics. For example, when fast-drying clearcoat was applied, the open-face single-stage samplers (N = 12) did not differ from the impingers for HDI monomer ($p = 0.11$). When slow-drying clearcoat was applied, the open-face single-stage (N = 12) and dual-stage (N = 12)

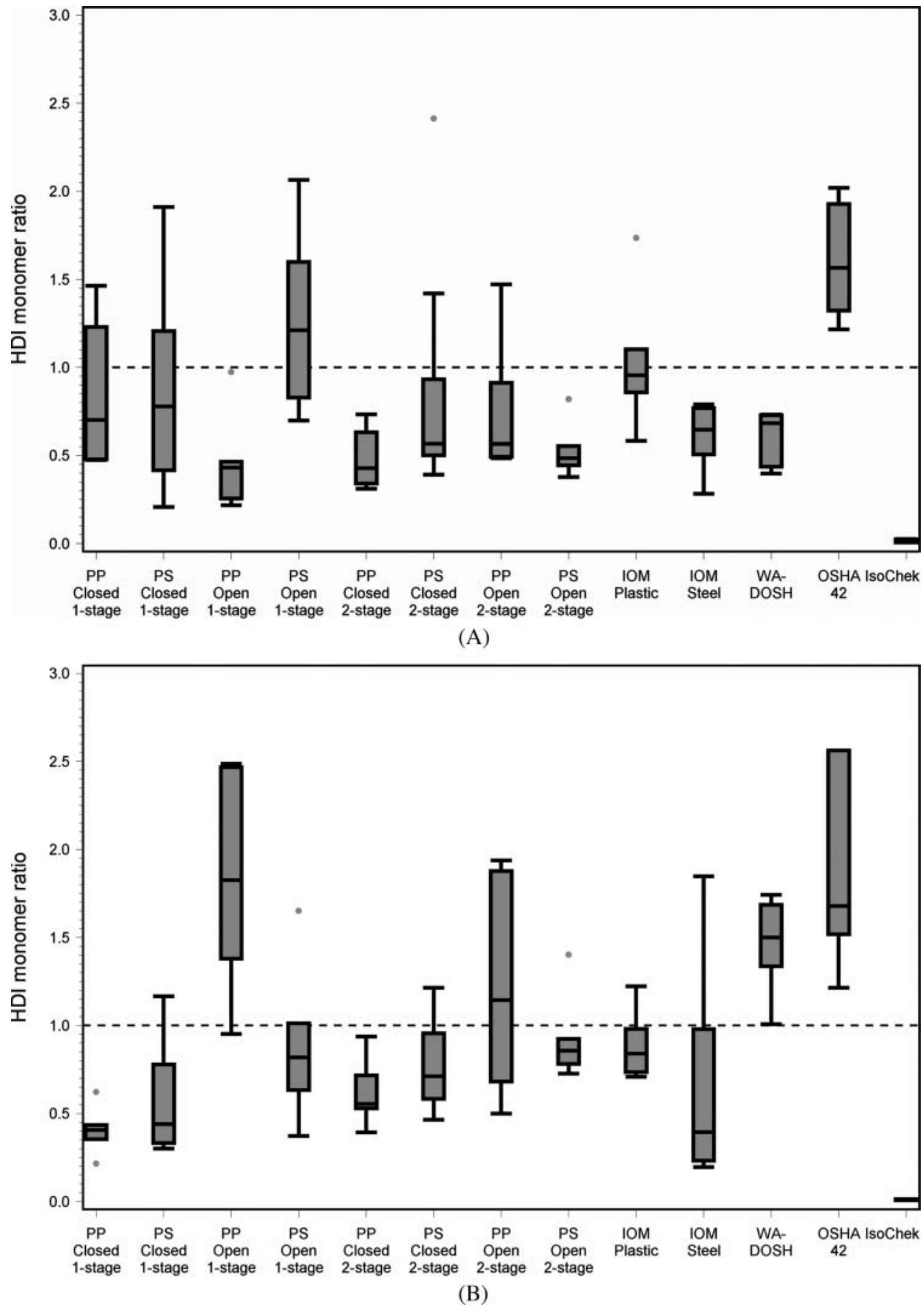

FIGURE 2. Box and whisker plots for HDI monomer for fast-drying (A) and slow-drying (B) clearcoat by sampler type. The top error bar represents the maximum observation below the upper fence (1.5 times interquartile range) and the bottom error bar the minimum observation. The top of the box is the 75th percentile while the bottom is the 25th percentile. The line in the box is the median and the dot is the maximum observation.

samplers did not differ from the impingers for HDI monomer ($p = 0.38$ and $p = 0.90$, respectively), biuret ($p = 0.73$ and $p = 0.90$, respectively), and isocyanurate ($p = 0.42$ and $p = 0.47$, respectively). Regardless of the clearcoat formulation, the IOM plastic samplers ($N = 12$) did not differ from the impingers for HDI monomer ($p = 0.35$).

The influences of clearcoat type, sampling style, cassette stage, and cassette type on the observed cassette to impinger ratios for HDI monomer, biuret, and isocyanurate are presented in Table IV. For PP and PS samplers, the type of clearcoat was a significant variable influencing HDI monomer ($p = 0.0064$) and biuret ($p < 0.0001$) ratios. The ratios when the

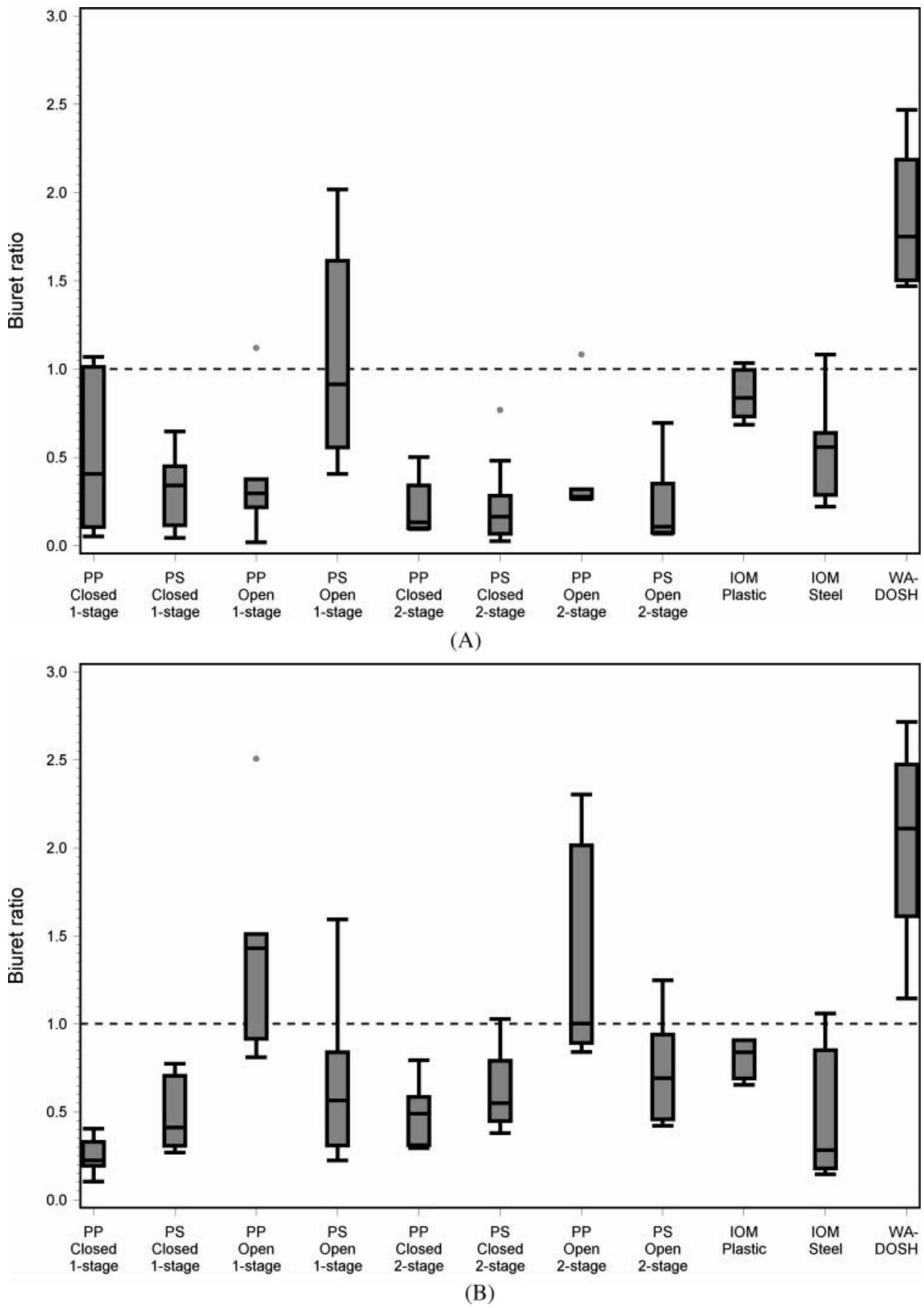

FIGURE 3. Box and whisker plots for biuret for fast-drying (A) and slow-drying (B) clearcoat by sampler type. The top error bar represents the maximum observation below the upper fence (1.5 times interquartile range) and the bottom error bar the minimum observation. The top of the box is the 75th percentile while the bottom is the 25th percentile. The line in the box is the median and the dot is the maximum observation.

slow-drying clearcoat was applied were 1.1- and 2.5-fold higher than the fast-drying clearcoat for HDI monomer and biuret, respectively. Significant differences were observed between sampling styles (open- or closed-face) for all analytes (p-values <0.01) but not between cassette stages (single- or dual-stage) or cassette types (PP or PS) (p-values >0.22). For all analytes, the open-face samplers had ratios 1.4–1.9-fold higher compared with those of the closed-face samplers. However, when stratified by clearcoat (data not shown), significant differences between open- and closed-face samplers (Student's *t*-test, $p < 0.05$) were observed for all analytes only when a slow-drying clearcoat was applied and for HDI biuret when a fast-drying clearcoat was applied (open-face samplers 2-fold higher).

Although we did not observe significant differences between the cassette stages (single- or dual-stage), we stratified the data by cassette stage because the sampler systems are different in construction (data not shown). We observed significantly greater ratios (1.6-fold) for all analytes when using a closed-face dual-stage PP/PS sampler (N = 18) compared with a closed-face single-stage PP/PS sampler (N = 17) only when slow-drying clearcoat was sprayed (Student's *t*-test, p-values <0.02). In a previous study,[20] single-stage PS samplers were observed to measure significantly more HDI monomer and

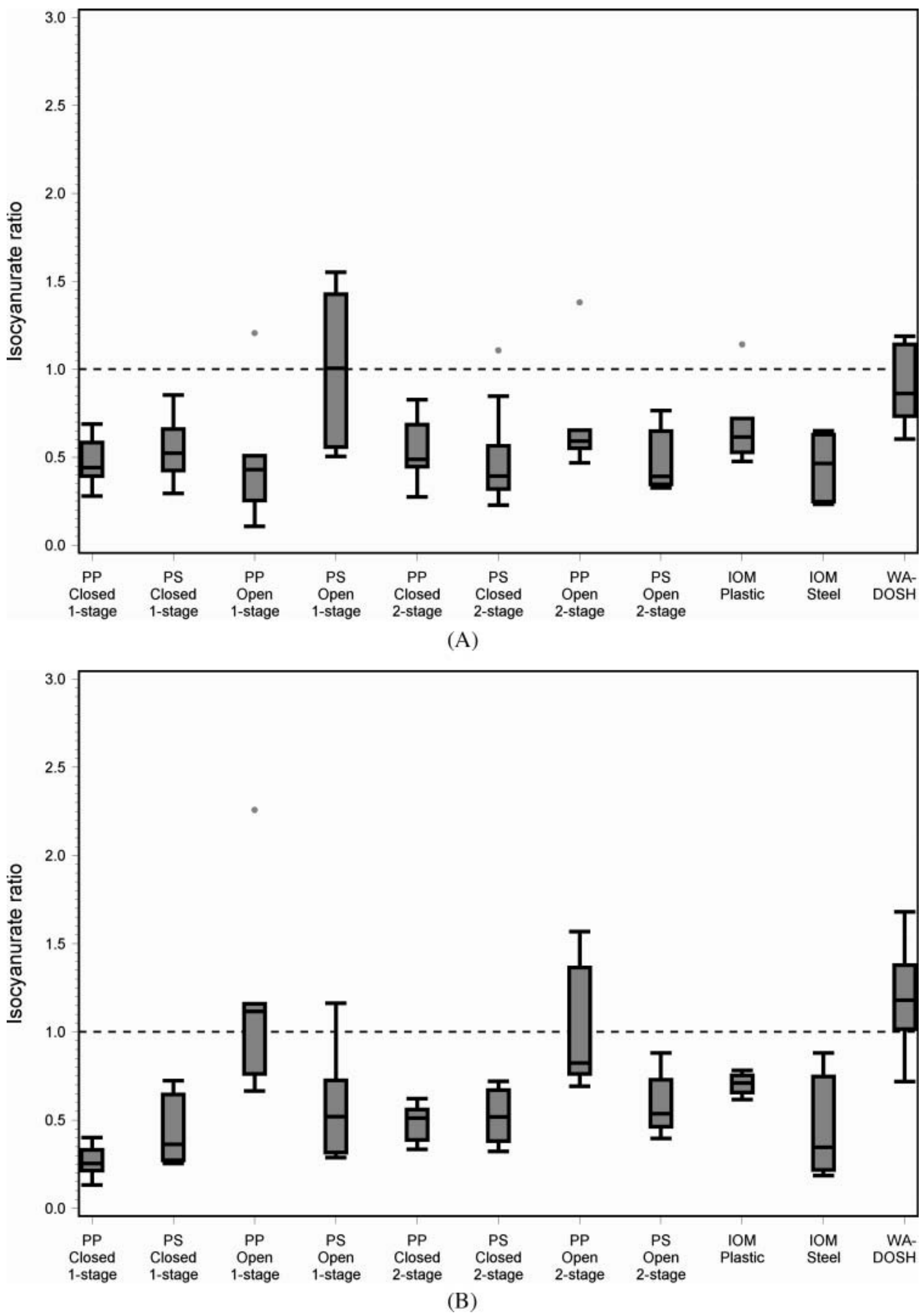

FIGURE 4. Box and whisker plots for isocyanurate for fast-drying (A) and slow-drying (B) clearcoat by sampler type. The top error bar represents the maximum observation below the upper fence (1.5 times interquartile range) and the bottom error bar the minimum observation. The top of the box is the 75th percentile while the bottom is the 25th percentile. The line in the box is the median and the dot is the maximum observation.

TABLE II. Overall Relative Standard Error (RSE) and Relative Standard Deviation (RSD) of Impingers and Cassettes Across Sampling Runs

	Overall RSE ± RSD (%)		
	HDI	Biuret	Isocyanurate
Fast-Drying Clearcoat			
Impinger (N = 15)	19.1 ± 8.2	15.3 ± 9	11.8 ± 4.9
Cassette (N = 15,13,14)[A]	12.9 ± 7.6	25.5 ± 13.3	14.2 ± 10.1
Slow-Drying Clearcoat			
Impinger (N = 15)	17.6 ± 6.8	15.4 ± 8.5	12.6 ± 7.7
Cassette (N = 15,13,14)[A]	11.7 ± 6.9	15.6 ± 7.0	14.0 ± 10.8

[A]For HDI, biuret, and isocyanurate, respectively.

isocyanurate than dual-stage PS samplers. Thus, we stratified the data to compare closed-face single and dual-stage PS samplers (data not shown). Only when slow-drying clearcoat was applied did we observe significantly greater HDI monomer ratios with the dual-stage [N = 12, GM (95%CI) = 0.74 (0.61–0.90)] compared with the single-stage [N = 11, GM (95%CI) = 0.49 (0.36–0.68)] PS samplers (Student's *t*-test, $p = 0.04$).

For IOM samplers, clearcoat drying time significantly affected HDI monomer ($p = 0.036$) and biuret ($p = 0.001$) concentrations (Table IV). When a fast-drying clearcoat was sprayed, the ratios for IOM samplers were 1.3- and 1.4-fold higher for HDI monomer and biuret, respectively, than when a slow-drying clearcoat was applied. Significant differences were observed between the IOM plastic and IOM steel samplers for biuret ($p = 0.015$) and isocyanurate ($p = 0.050$) (Table IV). For all analytes, the ratios for IOM plastic samplers were about 2.0-fold higher than the IOM steel samplers.

We did not observe significant difference in monomeric and polymeric HDI ratios between the material types of the samplers (PP or PS); thus, we combined these samplers into one group to assess the differences in the least square means of the sampler to impinger ratios for HDI monomer (Table V), biuret (Table VI), and isocyanurate (Table VII) with the six samplers analyzed at UNC (PP, PS, and IOM). Some notable differences are that for slow-drying clearcoat, the single-stage and dual-stage open-face samplers measured more HDI monomer, biuret, and isocyanurate than the single-stage closed-face samplers. For fast-drying clearcoat, the single-stage open-face samplers measured more HDI biuret and isocyanurate than the dual-stage closed-face samplers.

OSHA42, IsoChek, and WA-DOSH Samplers

The mean air levels ($\mu g/m^3$) of monomeric and polymeric HDI measured by OSHA42, IsoChek, and WA-DOSH samplers and corresponding impingers are summarized in Table VIII. The results of paired *t*-tests between samplers and impingers are also summarized in Table VIII. The HDI monomer concentrations measured with the OSHA42 samplers and analyzed by Galson were significantly higher (1.2–3.1-fold; $p = 0.001$) than the corresponding impinger samples, which were analyzed at UNC.

For HDI monomer, all samples collected with IsoChek and analyzed by Galson were below the LOQ (0.03 μg). IsoChek samplers measured significantly more HDI polyisocyanates (i.e., total NCO concentration) than did the impingers ($p = 0.03$). Although not significant, the IsoChek measured more HDI polyisocyanates when a slow-drying clearcoat was applied (Student's *t*-test, $p = 0.44$; data not shown).

Significant difference was observed between WA-DOSH samplers, analyzed by WA DOSH laboratory, and the impingers, analyzed by UNC, for biuret ($p = 0.007$) but not for HDI monomer ($p = 0.78$) and isocyanurate ($p = 0.66$). Further, significant difference between the fast- and slow-drying clearcoat was observed for HDI monomer ($p < 0.001$) and biuret ($p = 0.032$) but not for isocyanurate ($p = 0.12$) (data not shown). All the WA-DOSH samples (N = 6) analyzed for biuret when a fast-drying clearcoat was applied were below the LOD (1.7 μg). The ratios for WA-DOSH samplers were greater when a slow-drying clearcoat was applied compared with a fast-drying clearcoat for HDI monomer (2.4-fold) followed by biuret (1.5-fold).

Bulk Samples

Six samples of both fast- and slow-drying clearcoat were collected during this study. The results of the bulk paint sample analyses are presented in Table IX. The concentration (mg/L) of HDI monomer and biuret in the slow-drying clearcoat was significantly greater than that of the fast-drying clearcoat (Student's *t*-test, $p = 0.016$ and $p = 0.001$, respectively). No significant difference in the concentration of isocyanurate was observed between the fast- and slow-drying clearcoat (Student's *t*-test, $p = 0.349$).

DISCUSSION

In this study, we evaluated 13 different air samplers (i.e., midget impinger with frit, single- and dual-stage PP and PS samplers in both open- and closed-face mode, IOM samplers

TABLE III. Geometric mean (GM) Air Levels of Monomeric and Polymeric HDI Measured with PP, PS, and IOM Samplers and Impingers Stratified by Clearcoat

		HDI ($\mu g/m^3$)			Biuret ($\mu g/m^3$)			Isocyanurate ($\mu g/m^3$)		
Cassette Type	Sample Size (N)	GM	Range	No. <LOD	GM	Range	No. <LOD	GM	Range	No. <LOD
Fast-Drying Clearcoat										
Impinger	36	8.58	3.55–22.8	0	28.4	14.15–69.6	0	3425	1986–6708	0
IOM Plastic	6	5.86	3.46–7.82	0	24.5	14.7–37.0	0	2207	1434–4348	0
IOM Steel	6	5.19	3.46–9.93	0	17.8	9.00–33.6	0	1715	994–3110	0
1-Stage closed-face PP	6	3.72	2.38–6.99	0	5.81	0.92–18.9	1	1283	907–1979	0
1-Stage open-face PP	6	5.64	2.38–16.3	0	9.96	0.75–52.8	1	2149	560–8081	0
2-Stage closed-face PP	6	2.87	2.37–3.72	0	2.70	1.33–7.98	0 (6)[A]	1181	722–2029	0 (1)[A]
2-Stage open-face PP	5	8.31	6.07–9.80	0 (1)[B]	13.8	7.92–32.0	0 (5)[A]	2861	2286–4828	0
1-Stage closed-face PS	12	5.02	2.25–9.40	0	6.32	0.84–15.9	1	1594	982–2408	0
1-Stage open-face PS	6	10.9	6.81–14.0	0	21.8	14.3–40.1	0	2913	2178–4423	0
2-Stage closed-face PS	12	7.18	3.59–13.6	0	5.55	1.74–19.0	0 (5)[A]	1493	712–2492	0
2-Stage open-face PS	6	5.78	3.79–7.15	0	3.76	1.77–19.2	2 (3)[A]	1632	1111–3199	0
Slow-Drying Clearcoat										
Impinger	36	14.6	2.84–64.8	0	207	56.7–926.4	0	3032	1041–12090	0
IOM plastic	6	10.5	8.19–12.6	0	165	143–193	0	1901	1552–2394	0
IOM steel	6	8.29	4.75–19.5	0	104	65.8–182	0	1369	864–2100	0
1-Stage closed-face PP	6	4.80	3.23–6.24	0	50.6	26.3–92.3	0	810	508–1259	0
1-Stage open-face PP	6	26.9	15.8–40.1	0	301	177–551	0	3260	1813–8177	0
2-Stage closed-face PP	6	8.40	5.82–11.3	0	71.0	41.6–116	0 (6)[A]	1142	734–1491	0
2-Stage open-face PP	6	12.9	9.08–37.6	0	208	128–674	0 (5)[A]	2714	1650–12686	0
1-Stage closed-face PS	11	13.8	4.68–40.6	0	168	47.1–324	0	2233	739–4558	0
1-Stage open-face PS	6	3.79	2.87–5.10	0	62.4	39.3–101	0	934	639–1325	0
2-Stage closed-face PS	12	17.6	10.8–24.8	0	159	93.5–247	0 (11)[A]	2154	1498–2970	0
2-Stage open-face PS	6	6.43	5.00–11.6	0	74.4	39.7–139	0 (3)[A]	1077	739–1642	0

[A]Dual-stage filters results are the sum of both filters, however bottom filter (GFF) <LOD but top filter (PTFE) >LOQ. Numbers in parentheses represent the number of GFFs <LOD.
[B]Dual-stage filter results are the sum of both filters, however top filter (PTFE) <LOD but bottom filter (GFF) >LOQ. Numbers in parentheses represent the number of PTFEs <LOD.

TABLE IV. Effect of Clearcoat Type, Sampling Style, Cassette Stage, and Cassette Type on the Sampler-Impinger Ratios for HDI Monomer, Biuret, and Isocyanurate

	Analyte		
Variable	HDI (p-value)	Biuret (p-value)	Isocyanurate (p-value)
PP and PS Samplers			
Clearcoat (fast- or slow-drying)	**0.0064**	**<0.0001**	0.7377
Sampling style (open- or closed-face)	**0.0078**	**0.0011**	**0.0004**
Cassette stage (single- or dual-stage)	0.6746	0.2217	0.7757
Cassette type (PP or PS)	0.2229	0.9578	0.9053
IOM Samplers			
Clearcoat (fast- or slow-drying)	**0.0359**	**0.0011**	0.3264
Cassette type (plastic or steel)	0.2696	**0.0154**	**0.0504**

Note: **Bold** = significant at α-level of 0.05.

with plastic and stainless steel insert, OSHA42, IsoChek, and WA-DOSH samplers) to quantitatively measure exposure to monomeric and polymeric HDI in the spray painting environment. To account for variability between each sampling run and variability of the paint spray across the samplers, we used midget impinger with frit as a reference sampler and standardized the cassette sampler results by dividing the measured concentration by the concentration measured with the adjacent impinger.

The impingers measured significantly more HDI monomer, biuret, and isocyanurate than the cassette samplers analyzed at UNC. This finding likely reflects the belief that impingers collect isocyanate species more efficiently than filter cassettes because the sample is drawn into a liquid solution of derivatizing agent, thereby reducing the potential for polymerization.[12] Further, aerosols dissolve in the impinger solution, facilitating the reaction between isocyanates and derivatizing agent. Neither filters nor impingers adequately sample for the entire range of isocyanate species likely to be encountered in the workplace.[12] Particles smaller than 2 μm and greater than 20 μm in diameter are not efficiently collected by an impinger, and isocyanate species present in large particles are not efficiently derivatized when collected on reagent-coated filters.[12,28,35,36]

Average mass mean aerodynamic diameters (MMAD) of overspray paint mists have been measured in the breathing zone when HVLP spray guns were used. Carlton and Flynn[37] reported an average MMAD 18.9 μm, while Sabty-Dailey et al.[38] reported an average MMAD of 5.9 μm. Based on these studies, impingers should perform reasonably well for the particle sizes generated during automotive spray painting.

Filter cassette samplers have been compared with impingers in several studies.[19,22,24,27] Under a simulated spray painting environment, Ekman et al.[24] observed no significant difference ($\alpha = 0.05$) in the performance of closed-face single-stage filter sampler and an impinger when the same derivatizing agent (MPP) was used to quantify HDI monomer. However, we observed a significant difference between the closed-face single-stage filter samplers and impingers containing the same derivatizing agent. The open-face single-stage sampler was in best agreement with the impinger. This sampler was not significantly different from impinger for all analytes when a slow-drying clearcoat was applied or for HDI monomer when a fast-drying clearcoat was applied. When open-face sampling is employed, there are concerns regarding the potential for aerosols depositing or impacting on the filters instead of being drawn into the filters. This potential was minimized in this study because the sampler cassettes were positioned to minimize deposition of the overspray.

The variability across the impingers and filter cassette samplers during each sampling run was similar. Although we did not collect replicate sampling runs for all of the sampler types, we collected replicate sampling runs for the closed-face single- and dual-stage PS samplers. As expected, the variability for impinger and cassette samplers was not significantly different for the replicate sampling runs. The main source of this variability is likely the result from potentially uneven spraying during sampling runs. Therefore, we used the impinger as a reference sampler across all spray applications and sampling runs.

As may be expected in field sampling conditions, the measurements made by each sampler type were not extremely precise (Figures 2–4). Because the same analytical method was used for single- and dual-stage PP and PS samplers, IOM samplers, and impingers, the respective sampling results are directly comparable, and the analytical method is unlikely to be a source of any differences. The PP and PS sampler ratios for HDI monomer and biuret were significantly greater when a slow-drying clearcoat was applied compared with a fast-drying clearcoat. Although we observed significantly less HDI monomer and biuret in the bulk paint samples for the fast-drying clearcoat, it is unlikely that the paint concentration is responsible for these differences because the results were standardized using reference impinger concentrations.

However with a fast-drying clearcoat, losses may have occurred because of rapid polymerization on the filters' surfaces. This rapid polymerization may also explain why we did not observe a significant difference between open- and closed-face samplers when a fast-drying clearcoat was applied. An open-face sampler distributes aerosols and vapors over a greater filter surface area, increasing the isocyanates contact with the derivatizing agent. This may explain why the open-face samplers measured significantly more monomeric and

TABLE V. Comparison of the Least Square Means of the Sampler-Impinger Ratios for HDI Monomer (p-values)

	Single-Stage Closed-Face	Single-Stage Open-Face	Dual-Stage Closed-Face	Dual-Stage Open-Face	IOM Plastic	IOM Steel
Fast-Drying Clearcoat						
Single-stage closed-face	1.0000					
Single-stage open-face	0.5103					
Dual-stage closed-face	0.9999	0.5554				
Dual-stage open-face	0.9292	0.9771	0.9589			
IOM plastic	0.8154	0.9999	0.8949	0.9993		
IOM steel	1.0000	0.7401	1.0000	0.9734	0.9242	1.0000
Slow-Drying Clearcoat						
Single-stage closed-face	1.0000					
Single-stage open-face	(**0.0007**)					
Dual-stage closed-face	0.1159	0.1918				
Dual-stage open-face	(**0.0085**)	0.9550	0.6417			
IOM plastic	0.1042	0.8718	0.9533	0.9981		
IOM steel	0.9999	0.0168	0.5870	0.0901	0.3339	1.0000

Notes: **Bold** = significant at α-level of 0.05. Values in parentheses indicate higher ratios for the sampler on the left side of the table.

polymeric HDI than the closed-face samplers when slow-drying clearcoat was applied. When fast-drying clearcoat was applied, this effect was likely diminished due to rapid polymerization, resulting in similar performance for open- and closed-face samplers.

Our previous investigations of breathing-zone concentrations of monomeric and polymeric HDI in North Carolina and Washington State revealed that closed-face single-stage PS samplers measured significantly higher levels of monomeric and polymeric HDI than closed-face dual-stage PS samplers.[20] Further investigation of this data (not published previously) suggested that there could be other causes for the observed sampling bias. We observed significant differences in variables associated with air concentrations between the single- and dual-stage sampling events for air samples collected in WA in downdraft booths. We observed significantly greater levels ($p < 0.05$) of all analytes in the paint, longer paint times, and greater intensity of exposure when single-stage samplers were used compared with dual-stage samplers. We also observed significantly greater booth flow rates ($p = 0.02$) with dual-stage samplers, which could also contribute to the observed sampling bias.

When we previously performed side-by-side sampling using single- and dual-stage PS samplers in North Carolina we observed that the single-stage samplers measured significantly higher levels of HDI monomer and isocyanurate.[20] Although this finding supports a true sampling bias, the results may have been influenced by worker practices as well as insufficient number and diversity of side-by-side samples. The positioning of the sampler on the worker, painter orientation, and geospatial distribution of paint overspray are possible factors associated with these differences. Factors associated with worker practices were eliminated in this current study because filter cassettes and impingers were not worn by workers, and we used reference impinger samples to account for the distribution and intensity of paint overspray.

Using a more controlled study design, we found significantly greater ratios for closed-face, dual-stage (N = 12, GM = 0.74) compared with the single-stage (N = 11, GM = 0.49) PS samplers for HDI monomer when a slow-drying clearcoat was applied. In our previous study,[20] we observed that in North Carolina the closed-face dual-stage PS samplers measured higher HDI monomer concentrations than the closed-face single-stage PS samplers. Further investigation of the NC data set (not published previously) indicated no significant differences ($p > 0.05$) between single and dual-stage sampling events in paint concentrations, paint times, intensity of exposure, or booth flow rates.

When we combined the PP and PS samplers from the current study, we observed significantly lower concentrations measured with closed-face single-stage samplers (N = 17) compared with closed-face dual-stage samplers (N = 18) when a slow-drying clearcoat was applied. Removing the aerosol with untreated PTFE filters may allow for greater contact of vapor with the derivatizing agent, thus allowing for more complete derivatization with the impregnated GFF. Breakthrough may be more likely with the single-stage samplers than with the dual-stage samplers. These filters were extracted immediately after sampling, and therefore, the potential for losses due to polymerization was minimized. Nevertheless, we observed significant differences between impinger and dual-stage closed-face samplers (both PP and PS) for all analytes when a slow-drying clearcoat was applied. This indicates that closed-face dual-stage as well as the closed-face single-stage samplers do not perform as well as the impinger in collecting monomeric and polymeric HDI.

TABLE VI. Comparison of the Least Square Means of the Sampler-Impinger Ratios for HDI Biuret (p-values)

	Single-Stage Closed-Face	Single-Stage Open-Face	Dual-Stage Closed-Face	Dual-Stage Open-Face	IOM Plastic	IOM Steel
Fast-Drying Clearcoat						
Single-stage closed-face	1.0000					
Single-stage open-face	0.0623					
Dual-stage closed-face	0.9401	**0.0032**				
Dual-stage open-face	0.9516	0.4160	0.5063			
IOM plastic	0.0799	0.9998	**(0.0171)**	0.5177		
IOM steel	0.2819	0.9999	0.0615	0.7839	0.9975	1.0000
Slow-Drying Clearcoat						
Single-stage closed-face	1.0000					
Single-stage open-face	**(0.0015)**					
Dual-stage closed-face	0.2571	0.1581				
Dual-stage open-face	**(0.0003)**	0.9980	0.0540			
IOM plastic	**(0.0444)**	0.9912	0.6673	0.9334		
IOM steel	1.0000	**0.0163**	0.6340	0.0054	0.1385	1.0000

Notes: **Bold** = significant at α-level of 0.05. Values in parentheses indicate higher ratios for the sampler on the left side of the table.

We observed significantly lower ratios of HDI monomer, biuret, and isocyanurate when an IOM sampler with a stainless steel insert was used, rather than a plastic insert. Bello et al.[22] compared IOM steel samplers loaded with 25-mm quartz fiber filters impregnated with 500 μg of 1-(9-anthracenylmethyl) piperazine (MAP) with impingers containing MAP. They observed that impingers and treated filter IOM steel samplers perform equally well with respect to collection efficiency for the monomer and total polymeric HDI.

However, in our study we observed significant differences between impingers and IOM steel samplers for all analytes. We also observed significant differences between impingers and IOM plastic samplers for biuret and isocyanurate but not for HDI monomer. After sampling, Bello et al.[22] immediately transferred filters and inserts into a jar containing MAP derivatizing agent. In our study, we did not extract the inserts in derivatizing agent. Consequently, losses may have occurred from the isocyanate species sticking to the walls of

TABLE VII. Comparison of the Least Square Means of the Sampler-Impinger Ratios for HDI Isocyanurate (p-values)

	Single-Stage Closed-Face	Single-Stage Open-Face	Dual-Stage Closed-Face	Dual-Stage Open-Face	IOM Plastic	IOM Steel
Fast-Drying Clearcoat						
Single-stage closed-face	1.0000					
Single-stage open-face	0.1090					
Dual-stage closed-face	0.9924	0.2223				
Dual-stage open-face	0.3092	0.9974	0.5270			
IOM plastic	0.8435	0.9340	0.9757	0.9925		
IOM steel	1.000	0.2703	0.9965	0.5023	0.9162	1.0000
Slow-Drying Clearcoat						
Single-stage closed-face	1.0000					
Single-stage open-face	**(0.0009)**					
Dual-stage closed-face	0.4027	0.0682				
Dual-stage open-face	**(0.0005)**	1.0000	**(0.0479)**			
IOM plastic	0.0544	0.9672	0.5969	0.9508		
IOM steel	0.9983	0.0321	0.9324	**0.0243**	0.2970	1.0000

Notes: **Bold** = significant at α-level of 0.05. Values in parentheses indicate higher ratios for the sampler on the left side of the table.

TABLE VIII. Mean Air Levels of Monomeric and Polymeric HDI, with Sampler-Impinger Paired *t*-Test Results

		HDI Monomer (μg/m^3)				HDI Biuret (μg/m^3)				HDI Isocyanurate (μg/m^3)				HDI Polyisocyanates (μg/m^3 NCO)			
		Sampler^A		Impinger^B		Sampler^A		Impinger^B		Sampler^A		Impinger^B		Sampler^A		Impinger^{B,C}	
Sampler	**Clearcoat**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**	**Mean**	**Range**
OSHA42	Fast-drying	14	9—20	7	6—8	NA	NA	18	15—23	NA	NA	3071	2642—3493	NA	NA	NA	NA
	Slow-drying	15	12—17	8	7—10	NA	NA	124	95—160	NA	NA	1993	1652—2382	NA	NA	NA	NA
					p = 0.001				ND				ND				ND
IsoChek	Fast-drying	<LOQ	<LOQ	9	4—12	NA	NA	23	17—35	NA	NA	3461	2755—4697	1030	770—1300	870	700—1200
	Slow-drying	<LOQ	<LOQ	10	7—12	NA	NA	120	115—130	NA	NA	2042	1974—2140	750	560—910	540	520—570
					ND^D				ND				ND				**p = 0.03**
WA-DOSH	Fast-drying	9	6—12	15	11—18	<LOD	<LOD	42	30—52	4727	3551—5622	5446	4100—6352	NA	NA	NA	NA
	Slow-drying	17	12—24	12	9—17	277	212—515	140	98—189	2667	2079—4869	2258	1691—2896	NA	NA	NA	NA
					p = 0.78				**p = 0.007**^{E}				p = 0.66				ND

Note: **Bold** p-value = significant at α-level of 0.05; NA = not applicable; ND = not determined.
^{A}Sample size (N) = 6.
^{B}Impingers were analyzed using a different analytical method;[31] N = 3.
^{C}Impingers converted to NCO using Eq. 1.
^{D}p-value not calculated because IsoChek data <LOQ.
^{E}p-value calculated using LOD/$\sqrt{2}$.

TABLE IX. Summary of Bulk-Paint Sample Analyses

	Mean ± STD	95% CI	p-value
HDI (mg/L)			
Fast-drying (N = 6)	200 ± 20	170–220	**0.016**
Slow-drying (N = 6)	430 ± 160	260–590	
Biuret (mg/L)			
Fast-drying (N = 6)	1020 ± 150	860–1190	**0.001**
Slow-drying (N = 6)	7470 ± 2350	5000–9940	
Isocyanurate (mg/L)			
Fast-drying (N = 6)	134, 090 ± 8, 980	124,700–143,510	0.349
Slow-drying (N = 6)	125, 400 ± 19, 710	104,700–146,100	

Note: Bold p-value = significant at-level of 0.05.
STD = standard deviation; CI = confidence interval.

the inserts. This could also account for the differences between the plastic and steel inserts. Plastic is more likely than steel to become negatively charged, and polyurethane paint aerosols may also become negatively charged. Consequently, the improved collection efficiency of the plastic inserts may have reflected the generation of static electricity during sampling, which prevented paint aerosols from sticking to the surface. HDI monomer vapor would not necessarily be attached to paint aerosols and hence would not become negatively charged; this could further explain why the measurement of HDI monomer did not differ between IOM sampler insert types.

The OSHA42, IsoChek, and WA-DOSH samplers were analyzed by different laboratories using different analytical methods and procedures, which most likely accounts for the observed variability. Consequently, we cannot compare these results directly with those for PS, PP, and IOM samplers. Nonetheless, some important observations can be made. First, significantly higher HDI monomer concentrations (1.2–3.1-fold) were measured with OSHA42 compared with the impinger. A potential exists for overestimation of HDI monomer concentration with OSHA42 because this method utilizes a less specific/sensitive UV detection, compared with the MS detection used for the impinger samples. It is unlikely that the differences between OSHA42 and impinger are because of sampler design.

We did not observe significant differences between impingers and single-stage open-face samplers that utilized the same derivatizing agent; therefore, the differences between the impingers used in this study and OSHA42 are likely due to differences in the analytical methods. Levine[(25)] stated that when using the UV detector, the baseline noise is high at the quoted method LOD. Another limitation of the OSHA42 method is that it identifies and quantifies only the isocyanate monomer.[(39)] However, many automotive coatings based on HDI polyisocyanates typically contain small amounts (<1%) of volatile monomers and larger amounts (>99%) of non-volatile polyisocyanates.[(23,40,41)] Because OSHA42 may also underestimate isocyanate in aerosol form when sampling for extended periods,[(26)] it has been suggested that additional derivatizing agent (1-2PP) should be added to the filter.[(42)]

However, underestimation in our study is unlikely because we sampled for only 15 min. In a comparison study of isocyanate sampling methods for monomeric and polymeric HDI in spray painting environments, OSHA42 had the greatest variability when compared with NIOSH Method 5521, NIOSH Method 5522, Total Aerosol Mass Method (TAMM), the proposed NIOSH Method 5525, and IsoChek.[(19)] We did not observe much variability in OSHA42 samplers; however, this may reflect the lack of sensitivity and specificity of the analytical method and the fact that the measured levels were close to the detection limit.

Second, the results for all the IsoChek samplers were below the LOQ for HDI monomer although the corresponding impinger samples measured levels above the LOQ for IsoChek. This is concerning as adverse health effects can occur at very low exposures levels, and this information is critical when conducting exposure and risk assessment. Several concerns of the performance of the IsoChek have been indicated in the literature,[(35,39)] and it has been stated that the dual-stage filter sampling system may produce biased results due to evaporation of aerosol from the PTFE filter and adsorption of vapor onto the PTFE filter.[(35)]

In a controlled laboratory study, IsoChek was observed to significantly underestimate toulene diusocyonate and diphenylmethane diisocyante monomer concentrations and inaccurately apportioned them into vapor and aerosol phases.[(39)] However, in a field study performed by England et al.,[(19)] the IsoChek measured HDI monomer concentrations that did not differ significantly from four other commonly used sampling methods (NIOSH 5521, NIOSH 5522, proposed NIOSH method, and OSHA42). HDI monitor levels measured with the impinger were 3–10 times greater than the IsoChek LOQ. It appears that IsoChek greatly underestimates HDI monomer in the spray painting environment. When using IsoChek, losses may occur because GFF is not immediately extracted in the field, accounting for some of the differences in HDI monomer levels.

England et al.[19] also reported that IsoChek, NIOSH 5522, NIOSH 5521, and the TAMM were significantly different from one another when sampling for HDI-based polyisocyanates. They concluded that TAMM measured the most HDI polyisocyanates followed by IsoChek, then NIOSH 5521, and finally NIOSH 5522.[19] We observed that the IsoChek measured more HDI polyisocyanates than the respective impingers. This is likely due to the fact that the method used to analyze the impinger samples is specific for the HDI polyisocyanates biuret and isocyanurate, while the IsoChek reports HDI polyisocyanates in the form of TRIG or the sum of free NCO groups found in all isocyanate species of a sample,[22] which could include higher molecular weight polyisocyanates and prepolymers.

Third, of the three samplers that were analyzed with different methods by laboratories other than UNC (i.e., IsoChek, OSHA42, and WA-DOSH), the WA-DOSH samplers were in the best agreement with impingers. The reason why the WA-DOSH samplers detected HDI monomer, while the IsoChek did not, likely reflects the fact that the LOD for HDI monomer is six times lower in the WA-DOSH L&I method. Like the IsoChek, the GFF in the WA-DOSH sampler was not immediately extracted in the field. Therefore, the observed difference in HDI monomer levels between IsoChek and impinger is most likely due to the poorer sensitivity of the IsoChek method. The WA-DOSH samplers underestimated HDI monomer concentrations when a fast-drying clearcoat was applied. However, this is not unexpected for reasons previously discussed, such as species reactivity and losses as a result of polymerization on the surface of filters.

Although we observed slightly higher levels of biuret and isocyanurate as compared with the impinger when a slow-drying clearcoat was applied, this may reflect the lack of pure analytical standards to analyze the WA-DOSH samples. All of the WA-DOSH samplers analyzed for biuret when a fast-drying clearcoat was applied were below the LOD (1.7 μg), which provides additional evidence of the high reactivity of biuret and respective sampling challenges.

The ability to measure isocyanate exposure accurately is critical for exposure and risk assessment in order to predict systemic exposure, to develop sensitive and predictive models through multiple exposure routes, and ultimately to protect the health of workers. In summary, we observed significant differences in sampler performance between fast- and slow-drying clearcoat. We also observed open-face sampling to be the most effective when sampling for monomeric and polymeric HDI. Like any study, this one has its limitations and additional studies should be performed where larger sample sizes are tested. We did not control for wind currents in this study or for the amount of spray being applied. However, we attempted to control for these confounders by using impingers as reference samples. Future studies should aim to better control for these variables and employ additional impingers so that each sampler is paired with only one impinger.

CONCLUSIONS

Overall, the single-stage open-face sampler was in best agreement with the impinger for measuring monomeric and polymeric HDI during spray painting in the automotive refinishing industry. Of all the three samplers analyzed by laboratories other than UNC (i.e., OSHA42, IsoChek, and WA-DOSH), the WA-DOSH was in the best agreement with the impingers. When selecting a sampling device for monomeric and polymeric HDI in the automotive refinishing industry, one must take into consideration the product being sampled, specifically the clearcoat drying time. Caution should be used when interpreting filter cassette sampler results, especially when atmospheres containing fast-drying clearcoat aerosols are sampled. When fast-drying clearcoat was applied, almost all samplers used in this study underestimated HDI polyisocyanate concentrations. Further investigation of the sampling techniques used to monitor isocyanates is warranted.

ACKNOWLEDGMENTS

This study was supported by grants from the National Institute for Occupational Safety and Health (T42 OH008673). The authors are grateful to South Seattle Community College for their help in collecting the samples in Washington State.

REFERENCES

1. "Criteria for a Recommended Standard: Occupational Exposure to Diisocyanates" (Pub. No. 78–215). [Online] Available at http://www.cdc.gov/niosh/78-215.html (Accessed July 28, 2010).
2. "Pocket Guide to Chemical Hazards." (Pub. No. 2005–149, 2007) [Online] Available at http://www.cdc.gov/niosh/npg/default.html (Accessed July 28, 2010).
3. "NORA Priority Areas: Asthma and Chronic Obstructive Pulmonary Disease." [Online] Available at http://www.cdc.gov/niosh/docs/96-115/diseas.html (Accessed July 28, 2010).
4. **Adams, W.G.:** Long-term effects on the health of men engaged in the manufacture of toluene di-isocyanate. *Br. J. Ind. Med. 32*(*1*):72–78 (1975).
5. **Butcher, B.T., C.E. Mapp, and L.M. Fabbri**: *Polyisocyanates and Their Prepolymers*. New York: Marcel Dekker, Inc., 1993.
6. **Diem, J.E., R.N. Jones, D.J. Hendrick, et al.:** Five-year longitudinal study of workers employed in a new toluene diisocyanate manufacturing plant. *Am. Rev. Respir. Dis. 126*(*3*):420–428 (1982).
7. **Porter, C.V., R.L. Higgins, and L.D. Scheel:** A retrospective study of clinical, physiologic and immunologic changes in workers exposed to toluene diisocyanate. *Am. Ind. Hyg. Assoc. J. 36*:159–168 (1975).
8. **Weill, H.:** Epidemiologic and medical-legal aspects of occupational asthma. *J. Allergy Clin. Immunol. 64*:662–664 (1979).
9. **White, W.G., E. Sugden, M.J. Morris, et al.:** Isocyanate-induced asthma in a car factory. *Lancet 1*:756–760 (1988).
10. "Preventing Asthma and Death from Diisocyanate Exposure." (Pub. 96-111, 1996) [Online] Available at http://www.cdc.gov/niosh/asthma.html (Accessed July 28, 2010).
11. **Streicher, R.P., C.M. Reh, R. Key-Schwartz, et al.:** Selecting isocyanate sampling and analytical methods. *Appl. Occup. Environ. Hyg. 17*:157–162 (2002).

12. **Streicher, R.P.**, **E.R. Kennedy**, and **C.D. Lorberau:** Strategies for the simultaneous collection of vapours and aerosols with emphasis on isocyanate sampling. *Analyst 119*(*1*):89–97 (1994).
13. **Janko, M.**, **K. McCarthy**, **M. Fajer**, **et al.:** Occupational exposure to 1,6-hexamethylene diisocyanate-based polyisocyanates in the state of Oregon, 1980–1990. *Am. Ind. Hyg. Assoc. J. 53*:331–338 (1992).
14. **Lesage, J.**, **N. Goyer**, **F. Desjardins**, **et al.:** Workers' exposure to isocyanates. *Am. Ind. Hyg. Assoc. J. 53*:146–153 (1992).
15. **Myer, H.E.**, **S.T. O'Block**, and **V. Dharmarajan:** A survey of airborne HDI, HDI-based polyisocyanate and solvent concentrations in the manufacture and application of polyurethane coatings. *Am. Ind. Hyg. Assoc. J. 54*:663–670 (1993).
16. **Pisaniello, D.L.**, and **L. Muriale:** The use of isocyanate paints in auto refinishing—A survey of isocyanate exposures and related work practices in South Australia. *Ann. Occup. Hyg. 33*(*4*):563–572 (1989).
17. **Goyer, N.:** Performance of painting booths equipped with down-draft ventilation. *Am. Ind. Hyg. Assoc. J. 56*:258–265 (1995).
18. **Rudzinski, W.E.**, **B. Dahlquist**, **S.A. Svejda**, **et al.:** Sampling and analysis of isocyanates in spray-painting operations. *Am. Ind. Hyg. Assoc. J. 56*:284–289 (1995).
19. **England, E.**, **R. Key-Schwartz**, **J. Lesage**, **et al.:** Comparison of sampling methods for monomer and polyisocyanates of 1,6-hexamethylene diisocyanate during spray finishing operations. *Appl. Occup. Environ. Hyg. 15*:472–478 (2000).
20. **Fent, K.W.**, **L.G. Gaines**, **J.M. Thomasen**, **et al.:** Quantification and statistical modeling—Part I: Breathing-zone concentrations of monomeric and polymeric 1,6-hexamethylene diisocyanate. *Ann. Occup. Hyg. 53*(*7*):677–689 (2009).
21. "OSHA Sampling & Analytical Methods: Diisocyanates: Method 42."1983 [Online] Available at http://www.osha.gov/dts/sltc/methods/organic/org042/org042.html (Accessed July 28, 2010).
22. **Bello, D.**, **R.P. Streicher**, **Y.C. Liu**, **et al.:** Field comparison of impingers and treated filters for sampling of total aliphatic isocyanates with the MAP reagent. *Am. Ind. Hyg. Assoc. J. 63*(*6*):790–796 (2002).
23. **Bello, D.**, **R.P. Streicher**, **and S.R. Woskie:** Evaluation of the NIOSH draft method 5525 for determination of the total reactive isocyanate group (TRIG) for aliphatic isocyanates in autobody repair shops. *J. Environ. Monit. 4*(*3*): 351–360 (2002).
24. **Ekman, J.**, **J.O. Levin**, **R. Lindahl**, **et al.:** Comparison of sampling methods for 1,6-hexamethylene diisocyanate (HDI) in a commercial spray box. *Analyst 127*(*1*):169–173 (2002).
25. **Levine, S.P.:** Critical review of methods for sampling, analysis, and monitoring of vapor-phase toluene diisocyanate. *Appl. Occup. Environ. Hyg. 17*:878–890 (2002).
26. **Podolak, G.E.**, **R.A. Cassidy**, **G.G. Esposito**, **et al.:** Collection and analysis of airborne hexamethylene diisocyanate by a modified OSHA method. In *Sampling and Calibration for Atmospheric Measurements (ASTM STP 957)*. West Conshohocken, PA: American Society for Testing and Materials, 1987. pp. 203–214.
27. **Sennbro, C.J.**, **J. Ekman**, **C.H. Lindh**, **et al.:** Determination of isocyanates in air using 1-(2-methoxyphenyl)piperazine-impregnated filters: Long-term sampling performance and field comparison with impingers with dibutylamine. *Ann. Occup. Hyg. 48*(*5*):415–424 (2004).
28. **Streicher, R.P.**, **C.M. Reh**, **R.J. Key-Schwartz**, **et al.:** Determination of airborne isocyanate exposure: Considerations in method selection. *Am. Ind. Hyg. Assoc. J. 61*(*4*):544–556 (2000).
29. **Huynh, C.K.**, **T. Vu-Duc**, and **H. Savolainen:** Design and evaluation of a solid sampler for the monitoring of airborne 1,6-hexamethylene diisocyanate (HDI) and its prepolymers in two-component spray painting. *Am. Ind. Hyg. Assoc. J. 53*:157–162 (1992).
30. **Fent, K.W.**, **K. Jayaraj**, **L.M. Ball**, **et al.:** Quantitative monitoring of dermal and inhalation exposure to 1,6-hexamethylene diisocyanate monomer and oligomers. *J. Environ. Monit. 10*(*4*):500–507 (2008).
31. **Washington State Division of Occupational Safety and Health:** L&I Method 0050: HDI, IPDI, and MDI (Vapor) MAMA Derivatives, 2005. Available on request.
32. **Washington State Division of Occupational Safety and Health:** "L&I Method 0067: HDI and IPDI Polyisocyanate Aerosol, 2008. Available on request from Washington State Department of Labor and Industry, Olympia, Wash.
33. **Hornung, R.W.**, **and R.L. Reed:** Estimation of average concentration in presence of nondetectable values. *Appl. Occup. Environ. Hyg. 5*:46–51 (1990).
34. **Pronk, A.**, **E. Tielemans**, **G. Skarping**, **et al.:** Inhalation exposure to isocyanates of car body repair shop workers and industrial spray painters. *Ann. Occup. Hyg. 50*(*1*):1–14 (2006).
35. **Nordqvist, Y.**, **U. Nilsson**, **A. Colmsjo**, **et al.:** A chemosorptive cylindrical denuder designed for personal exposure measurements of isocyanates-evaluation on generated aerosols of 4,4'-methylenediphenyl diisocyanate. *J. Environ. Monit. 7*(*5*):469–474 (2005).
36. **Spanne, M.**, **P. Grzybowski**, **and M. Bohgard:** Collection efficiency for submicron particles of a commonly used impinger. *Am. Ind. Hyg. Assoc. J. 60*:540–544 (1999).
37. **Carlton, G.N.**, **and M.R. Flynn:** The influence of spray painting parameters on breathing zone particle size distributions. *Appl. Occup. Environ. Hyg. 12*:744–750 (1997).
38. **Sabty-Daily, R.A.**, **W.C. Hinds**, **and J.R. Froines:** Size distribution of chromate paint aerosol generated in a bench-scale spray booth. *Ann. Occup. Hyg. 49*(*1*):33–45 (2005).
39. **Rando, R.J.**, **H.G. Poovey**, **and D.R. Mokadam**: Laboratory comparison of sampling methods for reactive isocyanate vapors and aerosols. In *Isocyanates: Sampling, Analysis, and Health Effects (ASTM STP 1408)*. West Conshohocken, PA: American Society for Testing and Materials, 2002.
40. **Liu, Y.**, **M.H. Stowe**, **D. Bello**, **et al.:** Skin exposure to aliphatic polyisocyanates in the auto body repair and refinishing industry: III. A personal exposure algorithm. *Ann. Occup. Hyg. 53*(*1*):33–40 (2009).
41. **Bello, D.**, **J. Sparer**, **C.A. Redlich**, **et al.:** Slow curing of aliphatic polyisocyanate paints in automotive refinishing: A potential source for skin exposure. *J. Occup. Environ. Hyg. 4*:406–411 (2007).
42. **Dharmarajan, V.**, **Lingg, R.D.**, **Booth, K.S.**, **et al.:** Recent developments in the sampling and analysis of isocyanates in air. In *Sampling and Calibration for Atmospheric Measurements*, J.K. Taylor (ed.). Philadelphia, PA: American Society for Testing and Materials, 1987. pp. 190–202.