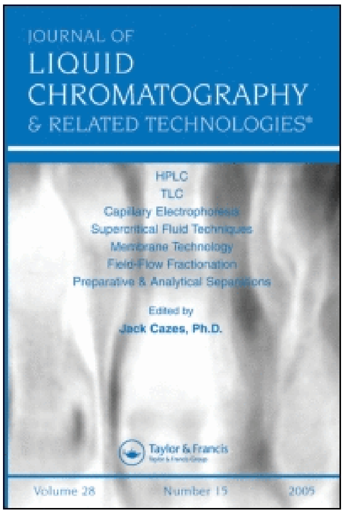

Journal of Liquid Chromatography & Related Technologies
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597273

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To cite this Article Tinnerberg, H. , Karlsson, D. , Dalene, M. and Skarping, G.(1997) 'Determination of Toluene Diisocyanate in Air Using DI-n-Butylamine and 9-N-Methyl-Aminomethyl-Anthracene as Derivatization Reagents', Journal of Liquid Chromatography & Related Technologies, 20: 14, 2207 — 2219

To link to this Article: DOI: 10.1080/10826079708006557

URL: http://dx.doi.org/10.1080/10826079708006557

J. LIQ. CHROM. & REL. TECHNOL., 20(14), 2207–2219 (1997)

DETERMINATION OF TOLUENE DIISOCYANATE IN AIR USING DI-n-BUTYLAMINE AND 9-N-METHYL-AMINOMETHYL-ANTHRACENE AS DERIVATIZATION REAGENTS

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ABSTRACT

Toluene diisocyanate (TDI) air levels were studied at two TDI-polyurethane (TDI-PUR) factories. One plant was manufacturing TDI-PUR foam and the other produced flame laminated textiles. Sampling was performed with impinger flasks containing 9-N-methyl-aminomethyl-anthracene in toluene as the isocyanate-derivatization reagent, followed by LC-UV, and impinger flasks containing di-n-butylamine (DBA) in toluene as the isocyanate-derivatisation reagent, followed by the derivatisation of amines with ethylchloroformate and determination using LC-UV-MS. The assessment of isocyanates in air using conventional LC-methods, involves a risk for underestimation of the air concentrations. Structural information about isocyanates and amines were obtained using the DBA-method with MS. In the samples, isocyanate concentrations up to 57 mg m^{-3} of TDI were observed. TDA was found in air at concentrations up to 70 µg m^{-3}. The data of the high air concentrations observed at the two PUR-factories in this study is not part of an exposure assessment but they greatly stress the need to use fail-safe work environment hygiene.

INTRODUCTION

Exposure to isocyanates is a well-known occupational hazard. Exposure to high concentrations of isocyanates is known to produce irritations of the mucous membranes, and they have sensitising properties and may cause asthma and possibly a progressive impairment of pulmonary function.[1]

Isocyanates are reactive compounds that cannot feasibly be analysed as such. For the last 25 years the determination of isocyanates has been based essentially on derivatisation with various amine reagents due to the high reaction rate between isocyanates and amines. New amine reagents have been presented with the purpose of improving the chromatography, detection limits, and selectivity and for the determination of total reactive isocyanate groups.[2-6] Sampling has mainly been performed using impinger flasks or impregnated filters. At present, methods based on sampling on impregnated filters are used in many countries, as sampling and handling are simplified.

Comparative measurements of isocyanates in air have focused upon the comparison between wet and solvent-free sampling.[7-10] For particles collected on filters, there are risks for competitive reactions between the isocyanate and the amine reagent and other compounds present in the aerosol particle.[11] When sampling, using impinger flasks, it is known that some particle sizes are not efficiently collected.[12] The most frequently used isocyanate reagents have been compared to other reagents and about the same results are found using the same sampling technique. The comparisons have, however, most often been made for vapours or aerosols of monomeric isocyanates. The derivatisation yield, in complex isocyanate atmospheres and work atmospheres containing interfering compounds, has only sparsely been studied. The influence of several interfering compounds, known to be present in the work environment, on the derivatisation reaction in toluene spiked with TDI for two amine reagents, 9-N-methyl-aminomethyl-anthracene (MAMA) and 1-(2-methoxy-phenyl) piperazine (MOP), showed severe losses.[13]

In a series of papers[14-16] we have described the use of di-n-butylamine (DBA) as derivatisation reagent for isocyanates with further selective derivatisation of amines with ethyl chloroformate (ET) for determination of isocyanates, aminoisocyanates and amines in a complex mixture in the work environment. DBA was found to be a robust reagent reacting fast with the isocyanate to protect the isocyanate groups and without known interferences.

In this paper, toluene diisocyanate (TDI) air levels at two polyurethane (PUR)-factories were studied using DBA as the derivatisation reagent. Comparative measurements were made with the MAMA reagent.

MATERIALS AND METHODS

Apparatus

LC-MS: A Quattro quadrupole mass spectrometer (MS) (VG-Organic, Altrincham, Cheshire, England) was used in the electrospray (ESP) mode, monitoring positive ions. For ESP the cone voltage was 50 V and the temperature of the ion source was 140°C. The MS was connected to a Rheos 4000 HPLC solvent delivery system (Flux Instruments, Karlskoga, Sweden). The flow of the pump was 400 μL min^{-1} connected to an Accurate splitter (LC Packings Amsterdam Netherlands) which gave a flow of 40 μL min^{-1} through the column. The column was a Sephasil C_{18} 1 x 250 mm with 5 μm particles (LC Packings Amsterdam Netherlands). A Kontron 433 capillary UV-detector with a 5μL cell volume (Kontron, Basel, Switzerland) was connected in series with the LC-MS system and the UV signal (λ = 240 nm) was recorded. One μL loop injection was made with a CMA/200 Refrigerated Autosampler (Carnegie Inc., Stockholm, Sweden). The gradient elution consisted of solution A 95/5 acetonitrile/water and B 95/5 water/acetonitrile. The elution started with 80% A and 20% B. After one minute the composition was linearly raised to 95% A and 5% B for 20 minutes and, was thereafter, isocratic for 20 minutes. Isocratic elution was performed with 95% A and 5% B. With the isocratic elution the $(M+1)^+$ ions of TDI and MDI, as internal standard, were monitored. For the gradient elution, 8 ions were monitored (m/z= 267, 350, 415, 433, 498, 582, 645, and 730 amu; dwell time 0.2 s), among those the $(M+1)^+$ ions of TDI, toluene aminoisocyanate (TAI), toluene diamine (TDA), and dimers and trimers of isocyanates and aminoisocyanates.

LC-UV: For the determination of MAMA-derivatives, a Millipore Waters (Millipore-Waters, Milford, MA, USA) 600 Multisolvent Delivery System, a Waters 712 WISP with variable injection volume, and a Waters 490 Programmable Multiwavelength detector (254 nm) was used. The LC column was a Hypersil BDS C_{18} 4.6 x 150 mm with 5 μm particles. Chromatograms were evaluated using a MAXIMA 820 Chromatography Workstation

(Millipore, Milford, MA, USA). The mobile phase (1.0 mL min^{-1}) consisted of 70% acetonitrile and 30% water with 3% triethylamine adjusted to pH 3 with phosphoric acid.

The samples were evaporated at 40°C in a Speed-Vac 290 centrifuge (Savant, Farmingdale, NY, USA).

Chemicals

Chemicals used were isooctane, toluene, and HPLC grade acetonitrile from Lab-Scan (Dublin, Ireland). Pyridine and $NaHCO_3$ were from E. Merck (Darmstadt, Germany); technical grade TDI (80/20 2,4-TDI/2,6-TDI) and ET from Janssen Chimica (Beerse, Belgium); MAMA and DBA from Aldrich Chemie (Steinham, Germany); 2,4- and 2,6-TDI derivatives of MAMA from Synthelec (Lund, Sweden); 2,4- and 2,6-TDI-DBA and 4,4′-methylenediphenyl diisocyanate-DBA (MDI-DBA) derivatives were synthesised at our laboratory.[14]

Standard Solutions

A standard solution of TDI was freshly prepared by dissolving accurately weighed amounts in isooctane. The solutions were further diluted in toluene to the appropriate concentrations. MDI-DBA was dissolved in acetonitrile and further diluted to appropriate concentrations.

Sampling and Storage

Air sampling was performed using an SKC universal sampler model 224 (SKC, PA USA). Thirty mL all glass midget impinger flasks, containing 10 mL of 0.01 mol l^{-1} DBA or 0.0001 mol l^{-1} MAMA in toluene were used. Air flows (1 l min^{-1}) were measured, both before and after each sampling, with a bubble flow meter, Gilian Gilibrator (Gilian Instr. Corp., USA). New MAMA solutions were prepared about one week before the comparative measurements were made. Samples derivatised with MAMA were stored in darkness in a refrigerator.

Work-up Procedure

DBA: After sampling, the solution, containing isocyanate urea derivatives and aromatic amines was evaporated to dryness in a vacuum centrifuge. The dry residue was dissolved in 2 mL toluene. Carbamate esters were formed in a two phase derivatisation procedure by the addition of 1 mL of a 2 M carbonate buffer (pH 9.5), 50 μl ethyl chloroformate and 10 μl pyridine. The mixture was shaken for 5 min and 1.5 mL of the organic phase was then evaporated to dryness and dissolved in 1 mL acetonitrile containing MDI-DBA. The solution was then injected into the LC-UV-MS system.

MAMA: Samples containing the MAMA-derivatives were evaporated and dissolved in mobile phase and then injected into the LC-UV system.

Quantification

Calibration curves were obtained by adding known amounts of an 80/20 TDI mixture in the range of 21.8-2180 ng to toluene solutions of DBA and MAMA. Duplicate work-up, with double injections, were made for each concentration and the peak areas were calculated. Calibration curves were also obtained for the DBA and MAMA-derivatives of TDI. Samples expected to represent high concentrations of TDI were diluted before the first analysis. Samples outside the calibration curve were further diluted in mobile phase and reanalysed. LC-MS quantification was performed monitoring the $(M+1)^+$ ions of 2,4- and 2,6-TDI-DBA using MDI-DBA as internal standard. For the isocratic chromatographic conditions used, the sum of 2,4-and 2,6-TDI was obtained, as the 2,4- and 2,6-TDI-DBA peaks co-eluted. TAI and TDA were quantified in a few samples by LC-UV. In the LC-UV chromatograms the 2,4- and 2,6-TDI-MAMA peaks were well separated and quantified using external standards. For comparison between the DBA and MAMA methods the sum is given in the results.

Field Studies

Air samples were taken at two industrial PUR-plants. Plant A manufactured flexible polyurethane foam in continuous foam blocks. TDI was used in an 80:20 mixture of 2,4- and 2,6-TDI. TDI was mixed with a polyol component and was poured, with a foaming nozzle, onto moving kraft paper. In the well-ventilated curing tunnel a thin fog was observed and the light was slightly scattered. Eight workers were involved in the production. Personal respiratory devices were used at procedures expected to release high concentrations of TDI. Biomarkers and air levels of TDI have earlier been reported at this plant.[17]

Plant B used the PUR-foam produced in plant A and coated it with textile fabric by flame lamination. The surface of the PUR foam was partly melted by an open flame, immediately thereafter the textile fabric was applied. In the same room a control station was located where the workers controlled the ready made product and cut it in smaller pieces. TDI-PUR foam slices were occasionally joined by welding and in a laboratory the product was controlled for, among many things, its flammability. The lamination apparatus was rinsed and cleaned a few times every week. Biomarkers and air levels of TDI have earlier been reported at this plant.[18]

Sampling was simultaneously performed with two impingers placed next to each other, one containing DBA and the other one MAMA. The samples were taken at different locations at the two plants, even in places where no workers were normally present without personal respiratory devices and were not representative for exposure assessment. In plant A samples were taken at different locations in the curing tunnel (CT), one meter from the foaming nozzle (FN), in the "working area" (WA), and where they cut (CUT) the foam blocks into smaller pieces. In plant B samples were taken around the lamination apparatus (LA) and in the smoke produced during the lamination (SMOKE), in the control area (CA), and in the laboratory (LAB). Samples were also taken during lamination and cleaning (CL) and during welding work (WE). The sampling periods varied between 5-14 minutes. In plant A 22 sets of samples were taken and in plant B, 11.

RESULTS AND DISCUSSION

Quantification

Virtually linear calibration curves were obtained for TDI-DBA and TDI-MAMA in the range 21.8-2180 ng mL^{-1}. The correlation coefficients were 0.9998 (n=20) for MAMA using UV-detection and 0.9984 (n=12) for LC-MS determinations using MDI-DBA as IS. The calibration curves for diluted TDI-DBA- and TDI-MAMA- derivatives were virtually the same as calibration curves for TDI spiked DBA and MAMA toluene solutions.

Field study

The estimated air levels in plant A and plant B using DBA- and MAMA-reagents are displayed in Table 1 (Plant A) and 2 (Plant B) and Figures 1 and 2. The difference in concentrations between samples taken at the same place

Table 1

Comparative Measurements at Plant A

Location	MAMA-Measurements (TDI)	DBA-Measurements (TDI)
CT (2m)	0.12 mg m^{-3}	0.22 mg m^{-3}
CT (4m)	2.1 mg m^{-3}	8.9 mg m^{-3}
CT (4m)	2.0 mg m^{-3}	7.1 mg m^{-3}
CT (8m)	1.6 mg m^{-3}	9.7 mg m^{-3}
CT (8m)	0.17 mg m^{-3}	0.25 mg m^{-3}
CT (10m)	2.4μg m^{-3}	25 μg m^{-3}
CT (10m)	0.16 mg m^{-3}	4.5 mg m^{-3}
CT (10m)	16 μg m^{-3}	41 μg m^{-3}
CT (10m)	69 μg m^{-3}	44 mg m^{-3}
FN	18 μg m^{-3}	28 μg m^{-3}
FN	24 μg m^{-3}	36 μg m^{-3}
FN	0.61 mg m^{-3}	0.52 mg m^{-3}
FN	0.50mg m^{-3}	0.25 mg m^{-3}
2m from FN	4.2 μg m^{-3}	7.7 μg m^{-3}
FN and WA	42 μg m^{-3}	40 μg m^{-3}
WA	3.7 μg m^{-3}	8.1 μg m^{-3}
WA	3.6 μg m^{-3}	4.2 μg m^{-3}
WA	2.3 μg m^{-3}	2.9 μg m^{-3}
WA	1.2 μg m^{-3}	2.2 μg m^{-3}
WA	5.2 μg m^{-3}	6.1 μg m^{-3}
WA	0.5 μg m^{-3}	1.6 μg m^{-3}
CUT	8.7 μg m^{-3}	12 μg m^{-3}

CT - curing tunnel, the distances given are in metres from the foaming nozzle.
FN - foaming nozzle.
WA - working area.
CUT - cutter.

but at different times in plant A may be due to several factors. The TDI concentrations differ greatly depending on where the samples were taken, e.g. distance from the foaming nozzle and distance from the centre of the curing tunnel. Different foams types (densities) were produced and the emission of TDI will most likely be affected.

Table 2

Comparative Measurements at Plant B

Location	MAMA-Measurements (TDI)	DBA-Measurements (TDI)
LA	2.8 $\mu g\ m^{-3}$	1.2 $\mu g\ m^{-3}$
LA	2.6 $\mu g\ m^{-3}$	6.5 $\mu g\ m^{-3}$
LA	10 $\mu g\ m^{-3}$	9.6 $\mu g\ m^{-3}$
LA	17 $\mu g\ m^{-3}$	35 $\mu g\ m^{-3}$
LA	31 $\mu g\ m^{-3}$	25 $\mu g\ m^{-3}$
LA and CL	2.2 $\mu g\ m^{-3}$	3.5 $\mu g\ m^{-3}$
CA	1.0 $\mu g\ m^{-3}$	1.5 $\mu g\ m^{-3}$
CA	6.4 $\mu g\ m^{-3}$	4.8 $\mu g\ m^{-3}$
WE	27 $\mu g\ m^{-3}$	20 $\mu g\ m^{-3}$
LAB	2.8 $\mu g\ m^{-3}$	2.9 $\mu g\ m^{-3}$
SMOKE	2.4 $mg\ m^{-3}$	57 $mg\ m^{-3}$

LA - laminating apparatus.
CL - cleaning of laminating apparatus.
CA - control area.
WE - welding.
LAB - laboratory.
SMOKE - collected in the smoke during flame lamination

The foaming process varied between 1.5-2.5 hours and several foam qualities were produced in the same block foaming process. Typically one quality was produced for about 10-30 minutes. In plant B the work-procedures were about the same from one day to another. This is reflected by the smaller differences in estimated air concentrations for samples taken at the same place.

All samples (n=33) were divided into 2 groups, one with concentrations up to the Swedish occupational exposure limit (OEL) and the second with concentrations above the OEL. For the samples with the lower concentrations the DBA-method gave a significantly higher concentration (two tailed paired t-test 95% confidence level; n=23) as compared to the MAMA method (Figure 1). The same result was obtained when tested with a non-parametric test.

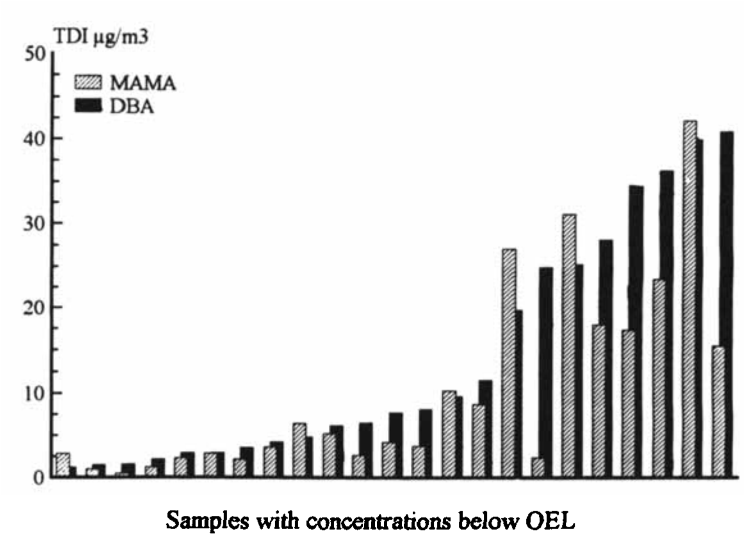

Figure 1. The results for the concentrations below the OEL for the DBA- and MAMA-reagent in impingers.

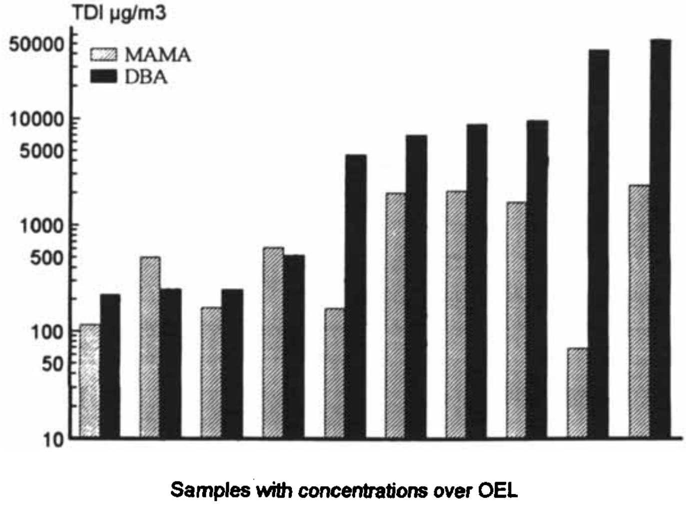

Figure 2. The results for the concentrations over the OEL for the DBA- and MAMA-reagent in impingers. Observe the logarithmic y-scale.

For the second group (Figure 2), no significant difference was seen when using the two tailed paired t-test at a 95% confidence level, probably due to the high standard deviation. By using the Wilcoxon signed rank test (two-tailed) a significant difference was seen.

When performing sampling followed by the immediate derivatisation of isocyanates, which is the basis of all isocyanate methods nowadays, it is of crucial importance that the amount of reagent is sufficient to derivatise and protect all isocyanate groups present. As we have earlier reported, the derivatisation reaction involving, e.g. MAMA or MOP is not instant and it may take hours to complete. The reaction rate depends on the concentration and properties of the reagent used.

If the amount of isocyanates greatly exceeds the amount of reagent, only a very small proportion will form the di-derivatised TDI-reagent-derivative and the mono-derivatised TDI-reagent-derivative and underivatised TDI will dominate. This will obviously result in a great underestimation of the TDI air concentration. Increasing the amount of the reagent will increase the concentration range that can be measured. This results, however, in problems due to the solubility of the derivatives formed and artefacts in the chromatograms. When using DBA, a higher concentration of the reagent can be used compared to other methods as the excess reagent is evaporated in the work-up procedure and will not disturb the chromatographic run. This results in faster reaction rates and a larger linearity of the method.

It is, therefore, not surprising that we saw high concentrations of TDI in some of the higher samples using DBA, where the MAMA samples showed low concentrations as the MAMA-reagent was present in too low concentrations. For the DBA samples indicating lower concentrations more similar results, but still significantly different, were obtained. The lower amounts of TDI-MAMA, as compared to TDI-DBA, indicate the presence of interfering compounds.

When derivatising isocyanates with DBA and amines with ET followed by LC-MS measurements, information of other kinds of isocyanates and amines found in the working atmospheres is also obtained. This is clearly demonstrated for the samples taken at the flame lamination plant where thermal degradation products of TDI-PUR dominated and isocyanate- and amine- containing compounds, other than TDI, were found. In one sample, taken when the workers were cleaning the flame lamination equipment, TDI was found in the magnitude of 3 $\mu g\ m^{-3}$, TAIs about 0.1 $\mu g\ m^{-3}$ and TDA about 70 $\mu g\ m^{-3}$ (Figure 3).

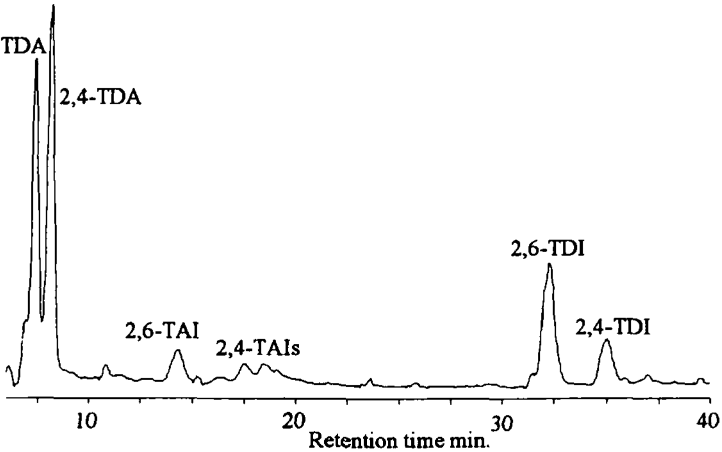

Figure 3. A total ion current chromatogram, when using gradient LC-elution and monitoring 8 ions, for a sample collected at plant B where the exposure was to thermal degradation products of TDI-PUR. This actual sample was collected when the workers were cleaning the flame lamination apparatus. The peaks correspond to about 3μg/m^3 TDI, 0.1 μg/m^3 TAI and 70 μg/m^3 TDA.

CONCLUSION

The assessment of isocyanates in air using conventional LC-methods involves the risk of underestimation of the air concentrations. As DBA can be used in much higher concentrations the risk of underestimating the air concentrations is much less and the linearity increases. Also the reaction rate increases several orders of magnitude.

The DBA method gives, in addition, structural information for other kinds of isocyanates and amines. The high air concentrations observed at the two PUR-factories in this study greatly stresses the need to use fail-safe work environment hygiene.

ACKNOWLEDGMENTS

We gratefully acknowledge the Swedish Work Environmental Fund and the Medical Faculty, Lund University for financial support.

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Received February 26, 1997
Accepted March 31, 1997
Manuscript 4376