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ORIGINAL PAPER

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OCCUPATIONAL EXPOSURE TO SELECTED ISOCYANATES IN POLISH INDUSTRY

ZAWODOWE NARAŻENIE NA WYBRANE IZOCYJANIANY W POLSKIM PRZEMYŚLE

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Abstract

Background: Isocyanates constitute a group of highly reactive, low molecular weight chemicals used worldwide for polyurethane manufacturing. The occupational exposure to these compounds is a major cause of occupational asthma, thus it is very important to monitor their concentration in the workplace atmosphere. The aim of the study was to measure the concentration of 4,4'-methylenediphenyl diisocyanate (MDI; CAS 101-68-8), toluene-2,4-di-isocyanate (2,4-TDI; CAS 584-84-9), toluene-2,6-di-isocyanate (2,6-TDI; CAS 91-08-7) and hexamethylene di-isocyanate (HDI; CAS 822-06-0) in the work environment for evaluation of the occupational exposure to these compounds. **Material and Methods:** Determination of concentrations of selected isocyanates was carried out in 21 manufacturing plants, during different industrial processes. The collected air samples (personal samples) were analyzed by means of the high-performance liquid chromatography (HPLC). **Results:** The presented results represent the 1st data on the occupational exposure to isocyanates in Poland. This set of data is generally indicative of concentrations of analyzed isocyanates that are low and do not exceed the maximum admissible concentration (MAC) values in Poland. Elevated concentrations (above the MAC value) were found only for the TDI in the course of manufacturing of polyurethane foam blocks. **Conclusions:** Results of many studies show that low concentrations of isocyanates (particularly of low volatility like for example MDI) in the air cannot exclude the possibility of additional absorption of these compounds through skin. Taking into consideration all the uncertainties associated with the evaluation of the risk of exposure to isocyanates based solely on measurement of their levels in the air, it would seem that the simultaneous application of environmental and biological monitoring would only facilitate a reliable assessment of the occupational exposure risk. Med Pr 2015;66(3):291–301

Key words: isocyanates, occupational exposure, polyurethanes, 4,4'-methylenediphenyl diisocyanate, toluene diisocyanate, hexamethylene diisocyanate

Streszczenie

Wstęp: Izocyjaniany stanowią grupę małocząsteczkowych silnie reaktywnych związków chemicznych szeroko stosowanych do produkcji tworzyw poliuretanowych. Uważa się, że zawodowe narażenie na te związki to jeden z głównych czynników powstawania astmy zawodowej i z tego względu istotne jest stałe monitorowanie ich stężeń w środowisku pracy. Celem pracy było wykonanie pomiarów stężeń metylenobis(fenyloizocyjanianu) (MDI; CAS 101-68-8), diizocyjanianu tolueno-2,4-diylu (2,4-TDI; CAS 584-84-9), diizocyjanianu tolueno-2,6-diylu (2,6-TDI; CAS 91-08-7), diizocyjanianuheksano-1,6-diylu (HDI; CAS 822-06-0) w środowisku pracy jako podstawy do oceny zawodowego narażenia na te związki. **Materiał i metody:** Oznaczenia stężeń wybranych izocyjanianów zostały przeprowadzone w 21 zakładach pracy podczas różnych procesów produkcyjnych. Pobrane próbki powietrza analizowano z zastosowaniem wysokosprawnej chromatografii cieczowej (high-performance liquid chromatography – HPLC). **Wyniki:** Przedstawione wyniki są pierwszymi w Polsce ilościowymi danymi dotyczącymi zawodowego narażenia na izocyjaniany. Wynika z nich, że generalnie stężenia oznaczanych związków pozostają na niskim poziomie i nie przekraczają ustanowionych wartości najwyższego dopuszczalnego stężenia (NDS). Przekroczenia wartości normatywnych stwierdzono jedynie w przypadku TDI podczas produkcji bloków pianki poliuretanowej. **Wnioski:** Wyniki wielu badań wskazują, że w przypadku niskich stężeń izocyjanianów w powietrzu (szczególnie słabo lotnego MDI) nie można wykluczyć możliwości wchłaniania tych związków przez skórę. Biorąc pod uwagę wszystkie niepewności związane z oceną zawodowego narażenia na izocyjaniany dokonywaną wyłącznie w oparciu o pomiary ich stężeń w powietrzu wydaje się, że jedynie jednoczesne stosowanie monitoringu środowiskowego i monitoringu biologicznego mogłoby pozwolić na wiarygodną ocenę narażenia zawodowego. Med. Pr. 2015;66(3):291–301

Słowa kluczowe: izocyjaniany, narażenie zawodowe, poliuretany, 4,4'-metylenobis(fenyloizocyjanian), toluilenodiizocyjanian, diizocyjanian heksano-1,6-diylu

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INTRODUCTION

Isocyanates constitute a group of highly reactive, low molecular weight chemicals used worldwide for manufacturing of polyurethane foam or as components of paints, lacquers or glues. Polyurethanes are applied in many sectors of the economy, and primarily in the construction sector, foundries, footwear, automobile, aeronautical, and shipbuilding industries, and as insulating material for manufacturing of household appliances.

The harmful effect of isocyanates involves irritation of mucous membranes and skin. The most common symptoms of the harmful effects of isocyanates include cough, rhinitis, irritation of eyes, throat, and allergic reactions on the skin.

Isocyanates are recognized as one of the most frequent causes of occupational asthma. It is believed that the occupational exposure to these compounds may be accountable for up to 20% of all confirmed cases of occupational asthma [1]. Clinical symptoms may develop after a few months and even after a few years following the exposure. In many cases, the symptoms of asthma do not disappear after the exposure is interrupted. Asthma and allergic diseases are not the only harmful results of the exposure to isocyanates. The International Agency for Research on Cancer (IARC), based on animal studies, has included TDI isomers in the group 2B, i.e., the group of compounds that are possibly carcinogenic to humans [2].

Results of toxicity studies and the increasing number of workers occupationally exposed to this group of compounds have led to significant changes in the maximum admissible concentrations (MAC) in Poland (Table 1) [3].

At present, evaluation of the occupational exposure to isocyanates is based on environmental or biological monitoring of the exposed workers. This is associated with the existence of normative values based on health criteria (admissible concentrations in the air) [3,4] or concentrations of metabolites of these compounds in urine [5]. The 'non-measurement' method for estimating the concentration of harmful substances in the workplace, developed for the purpose of the REACH (Registration, Evaluation and Authorization and restriction of Chemicals) framework regulations [6] is another way to assess the exposure to chemicals. It is based on mathematical models using different exposure scenarios, and the physicochemical data on chemical substances [7–10]. The use of such models had also been attempted for isocyanates [11]. However, it seems that, despite the encouraging results, at the present moment the non-measurement method of assessing the occupational exposure is not suitable yet to replace the methods based on the measurements performed at the workplace.

Aims of the study

The aim of the study was to assay the concentration of 4,4'-methylenediphenyl diisocyanate (MDI; CAS 101-68-8), toluene-2,4-di-isocyanate (2,4-TDI; CAS 584-84-9), toluene-2,6-di-isocyanate (2,6-TDI; CAS 91-08-7) and hexamethylene-di-isocyanate (HDI; CAS 822-06-0) in the work environment during various manufacturing processes and, from the resultant data, to evaluate the occupational exposure to isocyanates.

Study design

The study spans over the years 2002–2012. Determinations of concentrations of the selected isocyanates were

Table 1. Threshold Limit Values (TLV) for isocyanates in Poland in 2002 and 2009
Tabela 1. Wartość normatywów higienicznych dla izocyjanianów w Polsce w latach 2002 i 2009

Compound Związek	MAC NDS [mg/m³]		STEL NDSCh [mg/m³]		Ceiling NDSP [mg/m³]	
	2002	2009	2002	2009	2002	2009*
MDI	0.050	0.030		0.090	0.20	–
2,4-TDI	0.035	0.007	0.07	0.021		
2,6-TDI	0.035	0.007	0.07	0.021		
HDI	0.050	0.040	0.15	0.080		

MAC – maximum admissible concentration / NDS – najwyższe dopuszczalne stężenie, STEL – short term exposure limit / NDSCh – najwyższe dopuszczalne stężenie chwilowe, Ceiling / NDSP – najwyższe dopuszczalne stężenie pułapowe.
MDI – 4,4'-methylenediphenyl diisocyanate / metylenobis(fenyloizocyjanian), 2,4-TDI – toluene-2,4-di-isocyanate / diizocyjanian tolueno-2,4-diylu, 2,6-TDI – toluene-2,6-di-isocyanate / diizocyjanian tolueno-2,6-diylu, HDI – hexamethylene di-isocyanate / diizocyjanian heksano-1,6-diylu.
* Not established / Nie ustanowiono.

performed under contracts with industry or as a part of study projects conducted by the Nofer Institute of Occupational Medicine (NIOM), Łódź, Poland. Surveys were done in 21 factories located in Poland. Breathing zone air samples were collected from 129 of workers exposed to diisocyanates during different types of industrial processes. Manufacturing data in specified workplaces has been compiled in the Table 2.

Table 2. Types of production output and activities of workers participating to the study
Tabela 2. Rodzaj produkcji i czynności wykonywanych przez pracowników uczestniczących w badaniu

Plant Zakład	Year Rok	Industrial process (task) Proces przemysłowy (czynność)	Analysed compound Analizowany związek
A	2002	manufacturing of soles (molding) / produkcja podeszw (odlewanie form)	MDI
B	2002	manufacturing of various items from rigid foam (molding) / produkcja różnych wyrobów ze sztywnej pianki (odlewanie form)	MDI
C	2002	manufacturing of construction boards (gluing of layers, insulation with PUR foam) / produkcja płyt konstrukcyjnych (klejenie warstw, izolowanie pianką PUR)	MDI
D	2004	manufacturing of heating elements (screen printing) / produkcja elementów grzejnych (malowanie metodą sitodruku)	HDI
E	2004	manufacturing of furniture (packing (securing) of furniture elements) / produkcja mebli (pakowanie (zabezpieczanie) elementów mebli)	MDI
F	2005	continuous PUR blocks manufacturing / produkcja bloków pianki poliuretanowej	MDI/TDI
G	2007	manufacturing of equipment for catering (insulation with PUR foam) / produkcja sprzętu dla gastronomii (wypełnianie pianką poliuretanową)	MDI
H[a]	2007	manufacturing of car interiors (gluing, laminating) / produkcja elementów wnętrz samochodów (klejenie elementów, laminowanie)	HDI
I[a]	2007 2009	manufacturing of household appliance (insulation with PUR foam) / produkcja sprzętu AGD (wypełnianie (izolacja) pianką poliuretanową)	MDI
J[a]	2007	manufacturing of bulbs (gluing of bulb elements) / produkcja żarówek (klejenie elementów)	HDI
K	2007	manufacturing of construction boards (gluing of layers, insulation with PUR foam) / produkcja płyt konstrukcyjnych (klejenie warstw, izolowanie pianką PUR)	MDI
L	2008	manufacturing of particle boards (gluing) / produkcja płyt wiórowych (klejenie)	MDI
M	2011	manufacturing of optical fiber (gluing of optical fiber elements) / produkcja światłowodów (klejenie elementów światłowodu)	MDI
N	2011	continuous PUR blocks manufacturing (foaming head operation, cutting of PUR blocks, paper stripping, maintenance tasks) / produkcja bloków pianki poliuretanowej (obsługa głowicy spieniającej, przecinanie bloków, zwijanie papieru, prace konserwacyjne)	MDI/TDI
O	2012	manufacturing of air filters for cars (molding, assembling) / produkcja filtrów powietrza do aut (odlewanie form, składanie elementów filtrów)	MDI
P	2012	manufacturing of construction boards (gluing of layers, insulation with PUR foam) / produkcja płyt konstrukcyjnych (klejenie warstw, izolowanie pianką PUR)	MDI
R	2012	manufacturing of parts for agriculture machinery (molding, spraying) / produkcja części do maszyn rolniczych (odlewanie form, natryskiwanie powłok poliuretanowych)	MDI
S	2012	continuous PUR blocks manufacturing (foaming head operation, cutting of PUR blocks, paper stripping, maintenance tasks) / produkcja bloków pianki poliuretanowej (obsługa głowicy spieniającej, przecinanie bloków, zwijanie papieru, konserwacja linii)	TDI
T	2012	manufacturing of parts for machinery (molding, grinding, assembling) / produkcja części maszyn (odlewanie form, szlifowanie, składanie elementów)	MDI
U	2012	manufacturing of gates and fences (gluing of layers of construction boards) / produkcja bram i ogrodzeń (klejenie warstw płyt konstrukcyjnych)	MDI
W	2012	laboratory testing (molding, spraying of polyurethane coating, chemical analysis) / testy laboratoryjne (próbne odlewy, natryskowe nakładanie powłok poliuretanowych, analizy chemiczne)	MDI

[a] Plants surveyed twice / Zakłady objęte badaniami 2-krotnie.
PUR – polyurethan / poliuretan, MDI – 4,4'-methylenediphenyl diisocyanate / metylenobis(fenyloizocyjanian), TDI – mixture of 2,4-TDI and 2,6-TDI isomers / mieszanina izomerów 2,4-TDI i 2,6-TDI.

MATERIAL AND METHODS

The analytical method used for determination of diisocyanate concentrations was based on the Occupational Safety and Health Administration (OSHA) [12,13] and the Health and Safety Executive (HSE) [14] methodologies. The applied methodology was fully validated and accredited by the Polish Centre for Accreditation.

Chemicals

Acetonitrile (ACN) was purchased from JT BAKER, (Deventer, Holland), 1-(2-pyridyl)piperazine (1,2-PP) – from Sigma-Aldrich (USA St Louis), ammonium acetate and dimethyl sulphoxide (DMSO) were purchased from Avantor Performance Materials Poland (Polskie Odczynniki Chemiczne – POCh, Gliwice, Poland). During the period from 2001 to 2009, standards of 2,4-TDI, 2,6-TDI, HDI and MDI derivatives were prepared according to the OSHA 42 and OSHA 47 methods. After 2010, standards of isocyanate derivatives were purchased from AccuStandard (New Haven, USA).

Collection of air samples

Prior to collection of air samples, glass fiber filters (Whatman GF/A) were coated with the 2 mg/ml solution of 1,2-PP in acetonitrile. Air samples (200 l, 1 l/min) were collected in the breathing zone of workers using GliAir-3 (Gillian) individual aspirators. Filters with collected air samples were placed in air-tight containers, and stored at 4°C until the analysis.

Analytical procedure

Filters were extracted with mixture (2 ml) of ACN:DMSO (9:1 v:v) in a rotary shaker (1 h). Extracts were transferred via syringe polytetrafluoroethylene (PTFE) filters (Supelco) to the autosampler vial and analyzed using the Waters Alliance 2695 high-performance liquid chromatography (HPLC) system equipped with the Waters 2475 fluorescence detector (FLD) and the Waters 2996 photodiode array detector (PAD). Calibration standards were prepared on 1,2-PP coated filters spiked with consecutive dilutions of 2,4-TDI, 2,6-TDI, HDI and MDI derivative mixtures. After evaporation of solvent, filters were treated in the same way as the sample filters.

Chromatographic separations were performed on Sulelcosil LC-CN (2002–2011) or Ascentis RP-Amide (2012) (Supelco) columns. Chromatographic conditions and validation parameters of the analytical method are specified in the Tables 3 and 4. Chromatograms of standards of 2,4-TDI, HDI, 2,6-TDI, MDI derivatives and one of the analyzed air samples are shown on the Figure 1.

Table 3. HPLC conditions for determination of selected diisocyanates
Tabela 3. Warunki oznaczania wybranych izocyjanianów techniką HPLC

Parameter Parametr	Analytical conditions Warunki analityczne	
Analytical column / Kolumna analityczna	Supelcosil LC-CN, 250×3 mm, 5 mm	Ascentis RP Amide, 150×2.1, 5 mm
Mobile phase / Faza ruchoma	ACN:AA	ACN:AA
Gradient / Gradient [min (ACN:AA)]	0 (0:100)	0 (10:90)
	22 (55:45)	6 (50:50)
	25 (0:100)	15 (50:50)
	35 (0:100)	16 (10:90)
	–	26 (10:90)
Column temperature / Temperatura kolumny	35°C	35°C
Flow rate / Strumień objętości	0.4 ml/min	0.5 ml/min
Sample volume / Objętość próbki	10 ml	10 µl
FLD $\lambda_{ex}/\lambda_{em}$	260/370 nm	260/370 nm
PAD scan (range) / Skan (zakres)	200–400 nm	200–400 nm

HPLC – high-performance liquid chromatography / wysokosprawna chromatografia cieczowa, ACN – acetonitrile / acetonitryl, AA – ammonium acetate buffer (0.01 M, pH = 5.5) / bufor octanowy (0,01 mol/l, pH = 5,5), FLD – fluorescence detector / detektor fluorescencyjny, PAD – photodiode array detector / detektor diodowy.
λ_{ex} – excitation wavelengths / długość fali wzbudzenia, λ_{em} – emission wavelengths / długość fali emisji.

Table 4. Validation parameters of the analytical method applied
Tabela 4. Dane walidacyjne stosowanej metody analitycznej

Parameter Parametr	2,4-TDI	2,6-TDI	HDI	MDI
Range / Zakres [µg/2 ml]	0.028–2.80	0.028–2.80	0.16–16	0.12–12
Regression coefficient / Współczynnik regresji (r)	0.999	0.999	0.999	0.999
Relative standard deviation / Względne odchylenie standardowe [%]	5.60	5.70	2.20	4.70
Average* extraction efficiency (rotary shaker: 60 min, 2 ml ACN:DMSO (9:1)) / Średnia wartość współczynnika odzysku (wytrząsarka rotacyjna: 60 min, 2 ml CN:DMSO (9:1)) [%]	95.10	94.80	98.70	94.50
Average* retention efficiency (200 l air sample, flow rate 1 l/min) / Średnia wartość retencji (200 l powietrza, strumień o objętości 1 l/min) [%]	92.80	93.20	105.30	101.20
Average* recovery after storage (30 days, refrigerator) / Średnia wartość współczynnika odzysku (30 dni w chłodziarce) [%]	91.50	90.50	95.60	98.10
Limit of quantitation / Granica oznaczania ilościowego [µg/m^3]	0.14	0.14	0.80	0.60
Precision (within a day) / Precyzja (w ciągu dnia) [%]	9.20	11.30	8.20	8.40

* Arithmetic mean from replicate (N = 6) determinations of analytical standards at concentrations equal 1/50, 1/10 and 1/2 of the MAC value / Średnia arytmetyczna z powtórzeń (N = 6) analiz wzorców o stężeniach równych 1/50, 1/10 i 1/2 wartości NDS.
Abbreviations as in the Table 1 / Skróty jak w tabeli 1.

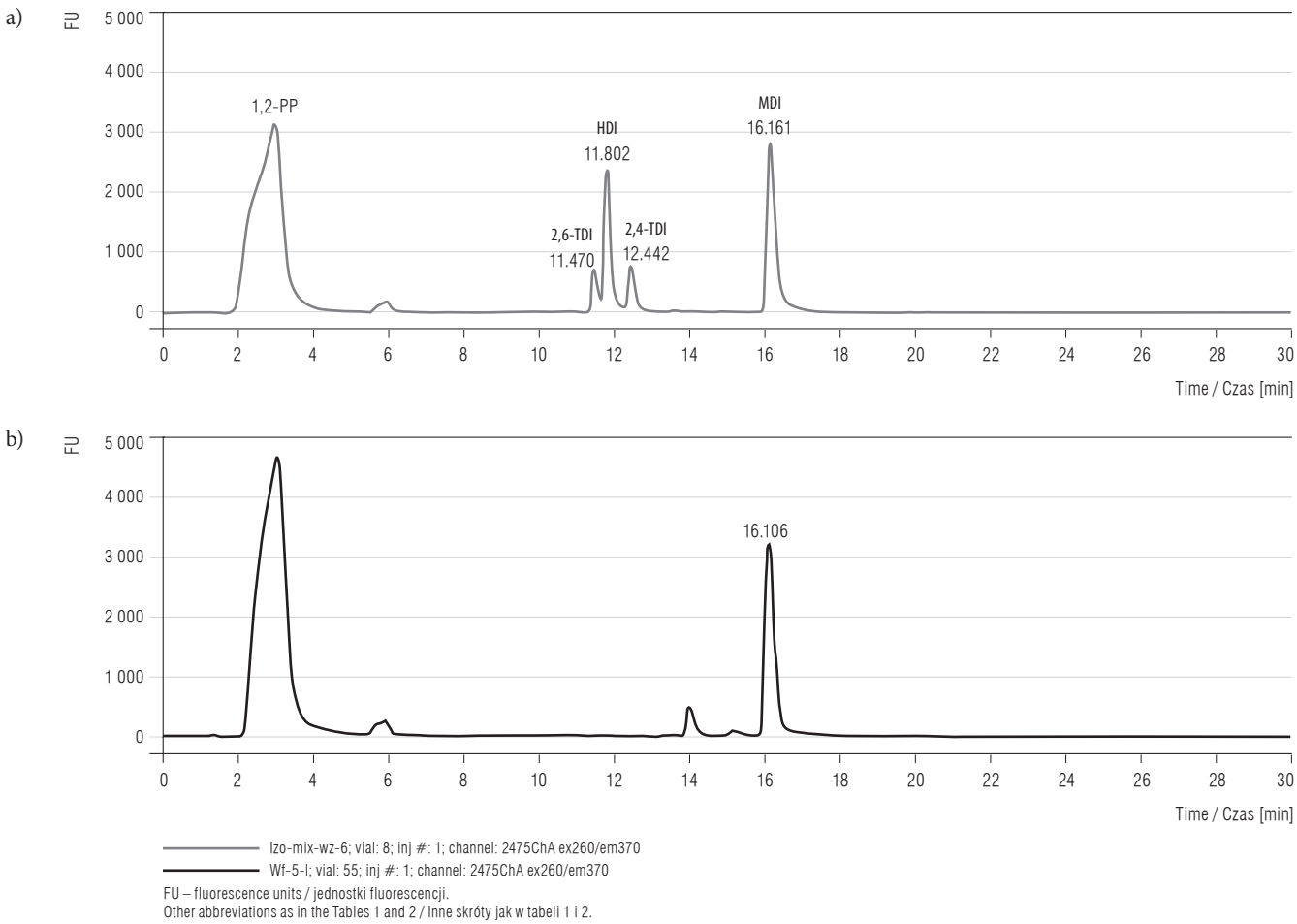

Fig. 1. Chromatogram of: a) diisocyanates derivatives standards, b) 1 of the analysed samples
Ryc. 1. Chromatogram: a) wzorców pochodnych diizocyjanianów, b) 1 z analizowanych próbek

RESULTS

Results of surveys are presented in Table 5. The largest group of plants was the one using MDI in manufacturing. For a total of 91 workplaces, in as much as 69 cases (76%), the assayed concentrations of MDI were below the limit of quantitation (LOQ) of the analytical method used (0.6 μg/m^3) or (the Plant O) MDI was not detected in any of the analyzed air samples. The highest concentrations of MDI were observed in the Plant I during application of polyurethane foam as an insulation for household appliances. The assayed concentrations of MDI during this task were between 11.5–18 μg/m^3, which corresponded to about 1/3 of the former MAC value. Surveys made at the same plant 2 years later show a 15-fold reduction of MDI concentrations in the working atmosphere.

Elevated concentrations of MDI (above 1/2 of the current MAC value) were also registered in the Plant R, where different products like netting, conveyor belt rollers, mixer parts, and polyurethane cladding for large parts (rollers, pipelines) were manufactured

Table 5. Concentration (TWA) of selected isocyanates in air samples collected during different industrial processes
Tabela 5. Stężenie (średnie ważone) wybranych izocyjanianów w próbkach powietrza pobranych podczas różnych procesów przemysłowych

Plant Zakład (N = 21)	Employees Pracownicy (N = 129) [n]	Concentration (range (Me)) Stężenie (zakres (Me)) [μg/m^3]		
		MDI	HDI	TDI[b]
A	2	0.9–1.2 (1.0)		
B	2	0.9–2.7 (1.8)		
C	4	< 0.6–5.2 (3.5)		
D	3		6.0–8.0 (7.0)	
E	10	< 0.6		
F	6	< 0.6		7.0–12.7 (9.8)
G	1	< 0.6		
H[a]	2		< 0.8–1.0 (0.7)	
	1		< 0.8	
I[a]	2	11.5–18.0 (15.0)		
	3	< 0.6–1.2 (0.7)		
J[a]	3		< 0.8–0.8 (0.8)	
	3		< 0.8	
K	2	< 0.6		
L	2	< 0.6–0.7 (0.4)		
M	2		< 0.8	
N	20	< 0.6		0.2–58.8 (4.0)
O	16	n.d.		
P	8	< 0.6		
R	12	< 0.6–17.4 (3.4)		
S	6			1.9–12.6 (5.3)
T	11	< 0.6–3.3 (0.8)		
U	4	< 0.6		
W	4	< 0.6		

TWA – 8-hour time-weighted average / średnia ważona w przeliczeniu na 8-godzinny okres odniesienia.
[a] Plants surveyed twice / Zakłady objęte badaniami 2-krotnie.
[b] Sum of concentrations of 2,4-TDI and 2,6-TDI isomers / Suma stężeń izomerów 2,4-TDI i 2,6-TDI.
Me – median / mediana, n.d. – not detected / nie wykryto.
Other abbreviations as in the Tables 1 and 2 / Inne skróty jak w tabeli 1 i 2.

by molding or spraying. Data on MDI concentrations at various workplaces of this plant is presented in the Table 6. The highest exposure is related to the spraying task. Concentration of MDI measured during spraying amounted to 17.4 mg/m^3 and exceeded 1/2 of MAC value. The median value of MDI concentration calculated for sprayer and sprayer helpers stood at 7 μg/m^3 (about 1/4 MAC). Concentrations of MDI measured during molding were 10 times lower and did not exceed 1/50 of Polish MAC value.

Determinations of HDI concentrations were conducted in the following plants: the plant manufacturing heating elements (the Plant D – painting with HDI based paints), the plant manufacturing components of automobile interiors (the Plant H – gluing and laminating) and the plant manufacturing light bulbs (the Plant J – gluing of bulb elements). Only in the Plant D, where heating elements were painted using screen printing method, did HDI concentration approximate 1/5 of the current MAC value (40 μg/m^3). In the remaining cases the concentrations of this compound were low and did not exceed 1 μg/m^3.

Taking into account identical MAC values and similar toxic properties of 2,4-TDI and 2,6-TDI, the results for TDI are specified as the sums of concentrations of both isomers. The highest concentrations of this compound were found in plants manufacturing polyurethane blocks using the continuous process (the Plant F, N and S). In the case of the Plant F, the air samples were collected by another laboratory and sent to the NIOM for analysis purposes. To our best knowledge, the data for the Plants F and N refers to the same plant, but we have

Table 6. Concentration of MDI (TWA) in the course of manufacturing parts for agriculture machinery (the Plant R)
Tabela 6. Stężenie MDI (średnie ważone) podczas produkcji części maszyn rolniczych (Zakład R)

Task Czynność	Workers Pracownicy (N = 129) [n]	MDI concentration Stężenie MDI [μg/m^3]		
		range zakres	M	Me
Molding / Odlewanie form	6	< 0.6–1.6	0.9	0.7
Spraying / Natryskiwanie	1	17.4	–	–
Spraying – auxiliary works / Natryskiwanie – prace pomocnicze	4	< 0.6–7.3	4.8	5.8
Laboratory tests / Testy laboratoryjne	1	< 0.6	–	–

M – mean / średnia.
Other abbreviations as in the Tables 1 and 5 / Inne skróty jak w tabeli 1 i 5.

Table 7. Concentration of TDI (TWA) in the course of manufacturing flexible polyurethane foam blocks
Tabela 7. Stężenie TDI (średnie ważone) podczas produkcji bloków pianki poliuretanowej

Workplace (task) Stanowisko pracy (czynność)	Plant N Zakład N			Plant S Zakład S		
	workers pracownicy (N = 129) [n]	sum of concentrations of 2,4-TDI and 2,6-TDI suma stężeń izomerów 2,4-TDI i 2,6-TDI [μg/m^3]		workers pracownicy (N = 129) [n]	sum of concentrations of 2,4-TDI and 2,6-TDI suma stężeń izomerów 2,4-TDI i 2,6-TDI [μg/m^3]	
		range zakres	M (Me)		range zakres	M (Me)
Foaming head operator / Operator głowicy spieniającej	10	0.6–11.3	3.7 (1.8)	3	1.9–7.3	3.8 (2.2)
Cutting machine operator / Operator przecinarki	3	0.2–6.5	3.6 (4.5)	2	3.1–4.7	3.9 (3.9)
Maintenance tasks / Prace konserwacyjno-naprawcze	2	9.9–41.5	25.7 (25.7)	–	–	–
Folding paper / Zwijanie papieru	5	0.3–58.7	26.3 (17.0)	1	–	12.6

Abbreviations as in the Tables 1, 5 and 6 / Skróty jak w tabelach 1, 5 i 6.

not received any information about tasks performed by workers in the Plant F. Thus, results for the Plants F an N are specified in the table as the data collected in 2 different plants. Concentrations of TDI registered in the Plant N in 8 cases (N = 20) exceeded the cumulative exposure index (CEI) for TDI. In the Plant S, the CEI value was exceeded in 2 cases (N = 6).

At the remaining workplaces of both plants (a foaming head operator, cutting machine operator) the concentrations registered were lower and the values fluctuated around 1/2 MAC value. The data related to the results of measurements made in both plants is presented in the Table 7.

DISCUSSION

The presented results constitute the first quantified data on the occupational exposure to isocyanates in Poland. They show that, in general, the concentrations of the studied isocyanates are within the range of the values of respective hygienic standards currently valid in Poland.

The data presented in the Table 5 is similar to the data presented in the literature. In a study published in 2009, Booth et al. [15] presented results of a 16-year (1984–1999) study on concentrations of MDI assayed during various activities connected with the application of this chemical. For a total of 8134 measurements (4551 stationary and 3583 individual) in almost 75% of the cases the concentrations of MDI were below the detection limit of the analytical method used [15]. Kääriä et al. [16] registered similarly low concentrations of MDI in the workplace environment of 3 Finnish factories manufacturing refrigerators and freezers. For a total number of 205 personal air samples, in 131 cases (64%) MDI concentrations were below the LOQ (0.03 μg/m^3) of the employed analytical method. The highest measured concentration of MDI was 3.3 μg/m^3, i.e., 3% of the Finnish occupational exposure limit (OEL). Our results, for the similar technological process (insulation of household appliances with rigid polyurethane foam – the Plant G and Plant I) are close to the results quoted above. The results obtained in 2007 in the Plant I, where the mean concentration of MDI was 15 μg/m^3 (about 1/3 of the MAC value valid in 2007) served the single exception. After improvements made in this plant (more efficient ventilation, better organization of work), concentrations of MDI dropped to the mean value of 0.7 μg/m^3.

For the spraying process (insulation of buildings), Crespo and Galán [17] reported (for the sprayers) MDI concentrations of 77 and 400 μg/m^3 for outdoor and indoor operations, respectively. The levels of exposure measured for helpers were lower, but were still as high as 45 μg/m^3 and 308 μg/m^3 for outdoor and indoor operations, respectively. For a similar technological process (spraying of polyurethane cladding – the Plant R) but of course incomparably lower volume of production output, concentration of MDI was 17.4 μg/m^3 (sprayer) and 4.8 μg/m^3 (helpers: N = 4). Those values refer to 8 h work shift. Concentrations of MDI measured during the 1st 4 h of work (including spraying operation) were much higher, 37 μg/m^3 (sprayer) and 15.3 μg/m^3 (helpers). During the 2nd part of the work shift, when workers were performing other tasks, MDI concentrations did not exceeded the LOQ value (0.6 μg/m^3).

In Great Britain, Creely et al. [18] studied 21 plants, at which isocyanates (MDI, TDI, HDI, isophorone diisocyanate (IPDI)) were being used. For a total of 70 air samples, in 50 samples the concentrations of isocyanates (expressed as the NCO group) were lower than the LOQ of the analytical method used (1 μg/m^3), and in only 3 of the cases (spray painters), concentrations of TDI exce-eded the OEL value (20 μg/m^3). In studies conducted by Sennbro et al. [19] in 13 Swedish manufacturing plants, high concentrations of TDI were detected in the course of manufacturing polyurethane foam blocks (2 plants). Average levels of TDI (total of 2,4-TDI and 2,6-TDI) in the 1st plant (N = 6) were 7.3 μg/m^3 and in the 2nd plant (N = 4) – 29.1 μg/m^3, and were close to the results obtained for the same manufacturing process in our study (the Plant F, Plant N and Plant S).

Elevated concentrations of TDI determined for manufacturing of polyurethane foam blocks as well as MDI concentrations measured during spraying of polyurethane cladding are typical for the described manufacturing processes and performed tasks. Such results should be however assessed with great caution since the respiratory protection equipment (RPE) was used at some workplaces to minimize the exposure. The evaluation of role and influence of the RPE used by workers constitutes a separate problem. The Polish standard on the principles of air sample collection [20] requires from the person making measurements to document the presence of the RPE worn by workers, but the principles listed in the standard do not specify how it should be interpreted.

Isocyanates are considered as one of the main chemical compounds responsible for the development of occupational asthma. In a study published in 2012,

Baur et al. [21] reviewed accessible literature concerning the incidence of irritating compounds responsible for the development of occupational asthma in work environments, as well as factors favoring the development of this disease. In 474 papers, authors detailed 188 factors (chemical compounds, professions, activities) causally associated with the development of occupational asthma. Out of this number, the strongest connection with this disease was attributed to 17 factors, including isocyanates.

The mechanism of generation of occupational asthma has not been completely explained. Many studies [22–24] indicate the possibility that occupational asthma may result from the prolonged exposure to low concentrations of isocyanates. Skin adsorption of isocyanates also seems to play an important role in the process of development of the changes in the respiratory system. Arrandale et al. [25] studied the relationship between changes appearing on skin and changes in airways of painters using lacquers containing isocyanates (HDI) and among bakers exposed to flour dust. For lacquer painters employed in automobile repair workshops, the authors established strong and statistically significant relationships between skin changes and pulmonary symptoms. Results of other studies also indicate the possibility of a relationship between allergic changes and the development of pathological symptoms (including occupational asthma) in lungs and airways [26–28]. This means that even in the case of proven low levels of isocyanates in work environments, one cannot exclude the possibility of the development of pulmonary diseases.

The estimation of the occupational dermal exposure to isocyanates is difficult and the results are likely to be imprecise. The method of biological monitoring based on the measurement of selected metabolites of these compounds in urine seems to be in this instance a significantly better and more adequate method for the assay of the occupational exposure to isocyanates independent of the absorption route.

The results of many scientific studies show that in spite of low levels of isocyanates in the ambient air, concentrations of their metabolites in biological material (urine, blood) samples collected from workers were several times higher than the concentrations of the compounds in the control groups. Kääriä et al. [16] found that despite the low levels of MDI in workplace atmosphere (64% of cases below the LOQ) the urinary concentrations of MDI metabolite (4,4'-methylenedianiline – MDA) above the LOQ were detected in 94% of the collected samples. The same authors conducted similar studies on the exposure to TDI isomers. Although the measured TDI levels in the air were significantly higher than in the case of MDI, in the group of persons exposed to low levels of TDI (below LOQ), they also confirmed elevated levels of the metabolites of this compound in urine [29]. In studies conducted in 21 companies in Great Britain, Creely et al. [18] found that only in 4% of collected air samples the concentration of the determined compound exceeded the OEL value, while levels of its metabolites in urine exceeded the British Biological Monitoring Guidance Value (BMGV – 1 mmol/mol of creatinine) in 23 cases (33%) [5].

CONCLUSIONS

The presented data is the 1st attempt in Poland to evaluate the occupational exposure to isocyanates during various industrial processes. We are aware that this data is incomplete – in some cases – because of the small size of the groups of workers and because of the inability (chiefly because of refusals to participate) to conduct studies during all processes associated with the use of isocyanates. We are also aware that some of results should be viewed with caution, namely in the instances of use of the respiratory protective equipment. On the other hand, low levels of isocyanates (particularly of low volatility MDI) in the air, cannot exclude the possibility of additional absorption of these compounds through skin.

Taking into consideration all the uncertainties associated with the evaluation of the risk of exposure to isocyanates based solely on measurement of their levels in the air, it would seem that only the simultaneous application of both forms of monitoring (environmental and biological) would facilitate a reliable assessment of the occupational exposure risk. The continuation of such a study would seem necessary in order to attempt to define uniform reference values for biological monitoring of isocyanates.

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