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Variability of total exposure to PM_{2.5} related to indoor and outdoor pollution sources Krakow study in pregnant women

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Abstract

The study is a part of an ongoing prospective cohort study on the relationship between the exposure to environmental factors during pregnancy and birth outcomes and health of newborns. We have measured personal PM_{2.5} level in the group of 407 non-smoking pregnant women during the 2nd trimester of pregnancy. On average, the participants from the city center were exposed to higher exposure than those from the outer city area (GM=42.0 µg/m³, 95% CI: 36.8–48.0 vs. 35.8 µg/m³, 95% CI: 33.5–38.2 µg/m³). More than 20% of study subjects were affected by high level of PM_{2.5} pollution (above 65 µg/m³). PM_{2.5} concentrations were higher during the heating season (GM=43.4 µg/m³, 95% CI: 40.1–46.9 µg/m³) compared to non-heating season (GM=29.8 µg/m³, 95% CI: 27.5–32.2 µg/m³). Out of all potential outdoor air pollution sources (high traffic density, bus depot, waste incinerator, industry etc.) considered in the bivariate analysis, only the proximity of industrial plant showed significant impact on the personal exposure (GM=54.3 µg/m³, 95% CI: 39.4–74.8 µg/m³) compared with corresponding figure for those who did not declare living near the industrial premises (GM=36.2 µg/m³, 95% CI: 34.1–38.4 µg/m³). The subjects declaring high exposure to ETS (>10 cigarettes daily) have shown very high level of personal exposure (GM=88.8 µg/m³, 95% CI: 73.9–106.7 µg/m³) compared with lower ETS exposure (≤10 cigarettes) (GM=46.3 µg/m³, 95% CI: 40.0–53.5 µg/m³) and no-ETS exposure group (GM=33.9 µg/m³, 95% CI: 31.8–36.1 µg/m³). The contribution of the background ambient PM₁₀ level was very strong determinant of the total personal exposure to PM_{2.5} and it explained about 31% of variance between the subjects followed by environmental tobacco smoke (10%), home

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heating by coal/wood stoves (2%), other types of heating (2%) and the industrial plant localization in the proximity of household (1%).

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1. Introduction

Reproductive epidemiology provides evidence that the fetus and infants are likely to be significantly more sensitive to a variety of environmental toxicants than adults. This is due to differential exposure, physiologic immaturity, and a longer lifetime over which disease initiated in the early life can develop. Newborns and young children are especially vulnerable to the toxic effects of ETS, PAHs, particulate matter, nitrosamines, pesticides, polychlorinated biphenyls (PCBs), metals, and radiation (Perera et al., 2002).

There is a large body of evidence that, in addition to parental smoking (Jedrychowski et al., 1977; Martinez et al., 1994; Shaw et al., 1996; Wasserman et al., 1996; Wyszynski et al., 1997) and environmental tobacco smoke (Jedrychowski and Flak, 1996; Mainous and Hueston, 1994; Ogawa et al., 1991; Perera et al., 2004; Windham et al., 1999), outdoor and indoor air pollutants may increase the risk of adverse birth outcomes including lowered birth weight, premature births and intrauterine growth retardation (Axelsson and Molin, 1988; Bhopal et al., 1998; Bobak, 2000; Dejmek et al., 1999; Lin et al., 2001; Pereira et al., 1998; Perera et al., 1998, 2003; Ritz et al., 2000; Sram, 1999; Wang et al., 1997; Woodruff et al., 1997; Xu et al., 1995). It is assumed that the indoor and outdoor areas may be important sources of chemical exposures for the pregnant women, the fetus, and the newborns. Toxic chemicals may particularly be present in proximity to industrial complexes and hazardous waste sites, as well as from local combustion sources, such as cars, trucks and buses routes.

The major difficulty in studying birth outcomes associated with air pollution is in assessing the exposure. In the previous studies the investigators have quantified the concentration of outdoor air pollutants in the residence area and assigned exposure figures to the study subjects or used the area-based exposures to approximate individual exposures. The main goal of our study is to describe the variability of total personal

PM_{2.5} exposure in pregnant women and to identify key exposure determinants based on the background ambient PM₁₀ concentrations measured at the fixed site located in the center of the city, additionally accounting for residence area, season and potential sources of outdoor and indoor air pollution.

2. Material and methods

The study is a part of an ongoing prospective cohort study on the relationship between the prenatal quality of environment and health of newborns and children. For this study, women attending ambulatory prenatal clinics in the first and second trimesters of pregnancy were eligible. The enrollment included 414 women recruited between November 2000 and March 2003. The exclusion criteria included smoking, a history of pregnancy-related diabetes or hypertension, as these might have the impact on the health of the babies.

Recruited women were interviewed and given a description of the study and requirements for participation in the project. Upon enrollment, a detailed questionnaire was administered to each subject to elicit demographic data and household characteristics. Data on potential indoor sources of particulate matter (environmental tobacco smoke, heating system in household, gas cooking appliances etc.) and a time-activity diary over the 48-h sampling period were collected in a household questionnaire by the trained interviewers. Questions about potential sources of outdoor particulate matter considered proximity (within 100 m) of crossroads, busy traffic roads, bus stops or bus depots and industrial plants. Subject's exposure to environmental tobacco smoke (ETS) at home was grouped into ETS exposure categories according to number of cigarettes smoked by household members inside in the presence of woman during the sampling period. The residence area was divided in two strata, i.e. the city center with old and high

density housing and the outer city area covering the peripheral part of the city with blocks of flats located over the larger area. The use of home heating system during the air sampling was categorized into three groups: 1) heating system not used, 2) central/electric/gas systems used, and 3) coal/wood stoves used. Heating season covered the period between October 16th and March 15th and the non-heating season between March 16th and October 15th.

Data on PM₁₀ levels measured by the fixed site air monitoring station in the city center square (above 10 m above the ground) were the source of the background exposure. The continuous monitoring technique by the beta-absorption monitor was used to measure PM₁₀. The data were available for 305 subjects as the station occasionally was out of work and the complete background air pollution data were not obtainable. The observed geometric mean of PM₁₀ concentrations over the study period was 35.7 µg/m³ with the range 11.0–112.7 µg/m³.

3. Assessment of personal exposure to fine particles

Measurements of personal PM_{2.5} were carried out in women in the second trimester of pregnancy. Personal measurements were done by placing the Personal Exposure Monitor Sampler (PEMS, Harvard School of Public Health) with 37 mm diameter teflon filter in the backpack which the woman was instructed to wear during the day and to place it on a close chair or table when remaining in the same room or by her bed during the night. The sampling pumps (BGI, Waltham, MA, USA) were powered by re-chargeable battery of 32-h capacity and produced a flow of 2 l of air/min. Flow rates were determined using DC-Lite Flow Meter (BIOS International Corporation) which was calibrated using Gilibrator™ 2 (Gilian®, SENSIDYNE Inc.) standards. Inlet of sampler was placed outside the backpack close to breathing zone. During the second day of monitoring, air monitoring staff visited the subject's home to check if the monitor had been running continuously without operating failures, to change the battery-pack and administer related household questionnaires. A staff member returned again to the woman's home on the third day to collect the equipment. Immediately after collection the samples were inventoried and stored in the refrigerator at

– 18 °C. Once per month, PEMS filters were shipped on the dry ice to Harvard University.

Weighing operations of filters before and after air sampling were carried out at the Harvard laboratory. At the laboratory of Harvard School of Public Health, the samples were conditioned for 48 h in temperature- and humidity-controlled room (18–24 °C, 40 ± 5% relative humidity). Then they were weighed using microbalance (Mettler Model MT5) with limit of detection of 6 µg. All filters were weighted twice and the average weight was used as a filter weight. When the difference in the duplicate filters weights exceeded 5 µg the filter was weighted again and the average of two closest weights was used.

To ensure quality of air monitoring and data analysis of PM_{2.5} pollution, all samples were collected according to the standardized field study protocol. To avoid potential contamination resulting from improper handling, transport or storage, we included analysis of 59 blank samples with field samples. Loading and handling procedures of field blanks were identical to those for exposed filters, but no air was drawn through blank filters. Mean net mass of field blank-weight (2.4 µg) was subtracted from the raw sampled filters' mass. Each sample was coded as to the accuracy of flow rate, duration and completeness of documentation. The study included 414 personal measurements, however, 7 samples were excluded from the analysis due to short duration of sampling, technical problems with the air pumps or incomplete documentation.

Personal PM_{2.5} concentration was calculated according to the formula:

$$\text{PM}_{2.5} \left[\mu\text{g}/\text{m}^3 \right] = 1000 * (\text{mass difference}) [\mu\text{g}] / (\text{mean flow} [\text{dm}^3/\text{min}] * \text{time} [\text{min}]).$$

Mean flow was calculated as the average of mean flows during the first and the second day of measurement.

4. Statistical analysis

The statistical analysis was performed using BMDP software. Due to the skewness of the distributions of personal exposures, air concentrations data were log transformed to normalize the distribution. In the bivariate analysis we used analysis of variance to examine differences in level of air pollution between

areas/exposure sources and seasons. The relative contribution of outdoor and indoor factors to 48-h personal exposure was evaluated using forward stepwise multiple linear regression models where variables were introduced in decreasing order of significance. The following predictive variables were included in all models: 1) residence area, 2) ETS exposure at home, 3) proximity of industrial plant, 4) home heating systems used. The final regression model also included the corresponding ambient background measurements of PM₁₀ obtained from the air pollution monitoring station located in the city center.

5. Results

Characteristics of the study population together with the distribution of potential outdoor and indoor sources of air pollution were shown in Table 1. The majority of the study subjects (82%) lived in the outer city area. In our study more than 50% of participants had university education. About 11% of respondents had apartments located in proximity of bus depots, 5% lived near the industrial plants and 77% in the proximity of crossroads. Exposure to environmental tobacco smoke (ETS) declared 20% women. About half of measurements of personal PM_{2.5} were performed in the winter season during which various house heating systems were used. Out of this, 91% used municipal, gas- or electricity-operated house heating systems. During 48-h sampling period gas cooking appliances were operated in 95% households and candles were burned in 8% of homes. The participants spent indoors most of their time during the sampling period (87%).

On average, the residents from the city center were exposed to higher exposure than those from the outer city area (42.0 vs. 35.8 µg/m³). As expected, personal PM_{2.5} concentrations were significantly higher during the heating season (43.4 µg/m³) compared to non-heating season (29.8 µg/m³). We did observe higher personal PM_{2.5} exposure measured in the heating season when coal/wood stoves were in operation (48.2 µg/m³) and when the home central/gas/electric heating was on (40.6 µg/m³) compared with the corresponding exposure in the non-heating season (30.9 µg/m³). Out of all potential outdoor air pollution sources under consideration in the bivariate analysis

Table 1

Characteristics of the population and main study variables

Variables	N	%
Season		
Non-heating	232	57.0
Heating	175	43.0
Residence area		
Outer city area	330	81.8
City center	77	18.9
ETS exposure during air sampling		
Not exposed	325	79.9
1–10 cigarettes/day	68	16.7
>10 cigarettes/day	14	3.4
Usage of home heating system during air sampling		
Not used	156	38.3
Central/electric/gas heating	228	56.0
Coal/wood stove heating	23	5.7
Proximity of bus depot	46	11.3
Proximity of industrial plant	20	4.9
Proximity of cross-roads	312	76.7
High traffic density in neighboring streets		
No	119	29.2
Yes	288	70.8
Burning candles during air sampling		
No	375	92.1
Yes	32	7.9
Gas cooking appliances used during air sampling		
No	22	5.4
Yes	385	94.6
Time spent outdoors (in %) ^a		
≤5.3%	204	50.1
>5.3%	203	49.9
Time spent in transit (in %) ^a		
≤4.4%	208	51.1
>4.4%	199	48.8

^a Categories based on median values of variable distribution.

(high traffic density in neighboring streets, bus depot, waste incinerator, industry, etc.) only the proximity of industrial plant showed significant impact on the personal exposure (54.3 µg/m³) of the study subjects compared with those who did not declare living near the industrial premises (36.2 µg/m³) (Table 2).

Out of indoor sources ETS was responsible for high figures of personal PM_{2.5} exposure. The participants declaring high exposure to ETS (>10 cigarettes) have shown more than twofold personal exposure (88.8 µg/m³), and those with lower ETS exposure (≤10 cigarettes) have shown also higher PM_{2.5} concentrations (46.3 µg/m³) compared with the group without ETS exposure (33.9 µg/m³). Burning candles inside home during the sampling time also increased personal exposure (45.6 vs. 36.2 µg/m³).

Table 2
Total personal exposure to PM_{2.5} and potential outdoor and indoor sources of air pollution (N=407)

Variables	Geometric mean	95% Confidence interval	P level ^a
Total study sample (N=407)	36.89	34.79–39.11	
Season			
Non-heating	29.77	27.51–32.21	P<0.001
Heating	43.37	40.12–46.88	
Residence area			
Outer city area	35.78	33.53–38.19	P=0.034
City center	42.03	36.77–48.04	
ETS exposure during air sampling			
Not exposed	33.88	31.84–36.05	P<0.001
1–10 cigarettes/day	46.25	40.01–53.45	
>10 cigarettes/day	88.77	73.85–106.72	
Usage of home heating system during air sampling			
Not used	30.86	28.19–33.77	P<0.001
Central/electric/gas heating	40.58	37.50–43.19	
Coal/wood stove heating	48.16	39.77–58.32	
Proximity of bus depot			
No	37.14	34.91–39.51	P=0.527
Yes	34.99	29.03–42.18	
Proximity of industrial plant			
No	36.16	34.09–38.36	P=0.003
Yes	54.29	39.39–74.83	
Proximity of cross-roads			
No	38.46	34.23–43.22	P=0.439
Yes	36.42	34.03–38.98	
Candles used			
No	36.23	34.10–38.49	P=0.037
Yes	45.60	36.33–57.23	
Gas cooking appliances used during air sampling			
No	36.97	28.84–47.39	P=0.995
Yes	36.94	34.87–39.13	
Time spent outdoors(in %) ^b			
≤5.3%	36.61	33.90–39.53	P=0.750
>5.3%	37.28	34.35–40.46	
Time spent in transit (in %) ^b			
≤4.4%	36.83	34.02–39.88	P=0.915
>4.4%	37.06	34.24–40.11	

^a Analysis of variance.

^b Categories based on median values of variable distribution.

The first model of the multivariate linear regression analysis for log(PM_{2.5}) personal level and a set of the dependent variables being significant in bivariate analysis did not include the background PM₁₀ data obtained from the fixed air monitoring station (Table 3). The forward stepwise regression analysis confirmed that the model explained 19% of the total variability in personal PM_{2.5} exposure between the subjects. The environmental tobacco smoke contributed to about 11% to this variability. Besides, using coal/wood stoves during the sampling time contributed in

3% of variance among subjects, other types of heating in 2%, the residence area located within the city center in 1% and living in the proximity of industrial plant contributed in less than 1%. Season of the year was not included in this model as it was highly correlated with the used heating system. Inclusion into the multivariate model of other variables such as gas cooking or using candles during the measurement period did not improve the proportion of explained variability.

The second model of the stepwise multivariate linear regression for log(PM_{2.5}) personal level and

Table 3

Results of the forward stepwise multiple linear regression for personal exposure to PM_{2.5} related to a set of variables describing potential sources of air pollution outdoors and indoors

Variable	Regr. Coeff.	SE	P	Multiple		Change in R ²	F to enter
				R	R ²		
ETS exposure to >10 cigarettes/day ^a	0.40	0.07	0.00	0.276	0.076	0.076	33.44
ETS exposure to 1–10 cigarettes/day ^a	0.14	0.03	0.00	0.334	0.113	0.037	16.93
Coal/wood heating ^b	0.17	0.05	0.00	0.384	0.147	0.034	15.90
Central/gas/electric heating ^b	0.11	0.02	0.00	0.412	0.170	0.023	10.87
City center	0.07	0.03	0.03	0.425	0.180	0.011	5.31
Proximity of industrial plant	0.11	0.05	0.04	0.435	0.189	0.009	4.37

The model does not include PM₁₀ data from the fixed monitoring station ($N=407$).

R² of model=0.189, F ratio=15.56, $P<0.001$.

^a Reference category: ETS exposure not reported.

^b Reference category: heating system not used.

the same set of the dependent variables as in the first model, in addition included the ambient data from the municipal fixed air monitoring station (Table 4). The latter regression model explained 46% on the total variance between subjects. The strongest component of variance (31%) was attributed to outdoor PM₁₀ concentration measured at the fixed site in the city center. Other sources of air pollution contributed to a much less extent to the total personal exposure; environmental tobacco smoke in 10%, coal/wood stoves used (2%), other types of household heating systems used (2%) and the proximity of industrial plant (1%). Season of the year was not included in the model as it was highly correlated with the PM₁₀ level. Inclusion into the model of other variables such as residence area, gas cooking or using candles during the measurement period did not improve the proportion of explained variability.

6. Discussion

This is the first large scale air pollution study conducted in Poland and in the central and eastern Europe that assessed the level of personal exposure to fine particles. To our knowledge, it is also the first study ever done in Europe on personal exposure to fine particles in pregnant women. Though the study group was narrowed to pregnant women, the findings may be to a great extent representative of the average exposure to fine particles among Krakow citizens. More than 20% of study subjects were affected by PM_{2.5} level higher than 65 $\mu\text{g}/\text{m}^3$, which is the EPA daily standard (US EPA, 2000). However, the WHO guidelines for PM_{2.5} exposure are much lower (20 $\mu\text{g}/\text{m}^3$) but they refer to the annual mean levels (WHO, 2001).

Estimated average PM_{2.5} concentrations have been found as relatively high in Krakow residents (geo-

Table 4

Results of the forward stepwise multiple linear regression analysis for personal exposure to PM_{2.5} related to a set of variables describing potential sources of air pollution outdoors and indoors

Variable	Regr. Coeff.	SE	P	Multiple		Change in R ²	F to enter
				R	R ²		
Log(PM ₁₀)	0.68	0.06	0.00	0.558	0.311	0.311	136.19
ETS exposure to >10 cigarettes/day ^a	0.40	0.06	0.00	0.606	0.368	0.057	26.96
ETS exposure to 1–10 cigarettes/day ^a	0.16	0.03	0.00	0.644	0.415	0.047	24.12
Central/gas/electric heating ^b	0.08	0.02	0.00	0.670	0.449	0.019	10.41
Coal/wood heating ^b	0.18	0.06	0.00	0.655	0.429	0.015	7.74
Proximity of industrial plant	0.15	0.06	0.01	0.678	0.460	0.012	6.33

The model includes PM₁₀ data from the fixed monitoring station ($N=304$).

R² of model=0.460, F ratio=42.18, $P<0.001$.

^a Reference category: no ETS exposure reported.

^b Reference category: heating system not used.

metric mean: $36.8 \mu\text{g}/\text{m}^3$) if compared with the corresponding figures reported from several previous studies. For instance, a large multi-center study on personal $\text{PM}_{2.5}$ exposure (EXPOLIS) in four European cities (Athens, Basel, Helsinki and Prague), carried out in the population samples including active smokers, has shown that the 48-h personal $\text{PM}_{2.5}$ pollution ranged from $16 \mu\text{g}/\text{m}^3$ in Helsinki to $37 \mu\text{g}/\text{m}^3$ in Athens (Kruize et al., 2003).

In the earlier studies on personal PM_{10} exposure, the effect of background ambient air pollution was an important contributor. The results of our study showed that the contribution of the background PM_{10} level was a strong determinant of the total personal exposure to $\text{PM}_{2.5}$ and accounted for about 31% of exposure variance between study subjects, despite the fact that participants spent most of their daily time indoors. This is consistent with the PTEAM study, the first large-scale probability-based study of personal exposure to particles which supported the idea of using the central site in the city as an indicator of ambient concentrations over wider area (Ozkaynak et al., 1996).

We confirmed the observation of other investigators that environmental tobacco smoke is the key indoor contributor to personal $\text{PM}_{2.5}$ exposure. This is in good agreement with earlier published studies of Dockery and Spengler (1980), Gauvin et al. (2002), Janssen et al. (1999), Philips et al. (1998), and Wallace (1996) conducted in children and adults.

The adjusted effect of household heating on the personal exposure to $\text{PM}_{2.5}$ was relatively small. Against expectations, we could not confirm the effect of using gas appliances for heating or cooking. Previous studies on the contribution of gas appliances within home gave contradictory results. Ozkaynak et al. (1996) showed that the 39% of variability in PM_{10} personal exposure was explained by ETS, outdoor PM_{10} levels and type of energy used for cooking. Some investigators found traffic intensity as the second most important contributing agent besides ETS (Carrer et al., 1997; Gauvin et al., 2002; Janssen et al., 1998). We did not confirm in our study the significant effect of traffic on the personal $\text{PM}_{2.5}$ level. None of the analyzed traffic related variables (traffic intensity in neighboring streets, proximity of bus depots or crossroads), treated separately or in various combinations showed significant contribution to personal

exposure. This lack of effect may result from several potential sources of bias, such as underestimated by the respondents traffic or correlation of the traffic related variables with the background air pollution level.

In summary, our study confirmed that the contribution of the background PM_{10} level was strong determinant of the total personal exposure to $\text{PM}_{2.5}$ and it explained about 31% of exposure variance between study subjects, despite the fact that participants spent most of their daily time indoors. Adjusted effect of indoor sources except for ETS was of marginal importance. Average personal exposure over 48-h to fine particles among pregnant women in Krakow was relatively high and 20% of the study participants were exposed to concentrations exceeding $65 \mu\text{g}/\text{m}^3$. This may pose a risk for developing fetus and newborns. The effects of the prenatal personal exposure to fine particles will subsequently be assessed in the cohort of newborns over the five-year follow-up period.

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