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Assessing traffic and polycyclic aromatic hydrocarbon exposure in Montreal, Canada

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HIGHLIGHTS

- We compared PAH biomarkers with an innovative method to measure traffic density.
- Both biomarkers can be used effectively in general population studies.
- PAH biomarker levels among females were higher than males.
- Smoking was the strongest determinant.
- Among non-smokers, barbequed meat consumption contributes to PAH level.

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ABSTRACT

Introduction: The International Agency for Research on Cancer classifies specific polycyclic aromatic hydrocarbons (PAHs) as probable carcinogens. This study compares two PAH biomarkers and their relationship with geographic information system (GIS) based traffic density (a proxy of PAH exposure), and explores the determinants of the PAH biomarkers.

Methods: A cross-sectional study was conducted in Montreal with 200 volunteers (107 females and 93 males) ages 20 to 53 years. Data were collected by questionnaire, urine samples were used for biomarker analysis, and innovative GIS-based time- and distance-weighted traffic densities (TDWTD) were calculated for all locations of participants during the 48 h prior to urine collection.

Results: Detection rates of the two biomarkers were greater than 95%. Female participants had higher 1-OHP and 1-OHPG levels than males, and no relationship was detected between TDWTD in 48 h and the two PAH biomarkers. Biomarker levels were related to smoking more than one pack of cigarettes in the previous 48 h, and among non-smokers, barbecued meat consumption increased the level of urinary 1-OHP (exp β: 1.45, 95% CI: 1.07 to 1.98).

Conclusions: Both 1-OHP and 1-OHPG can be used to assess the relatively low PAH levels to which the general population is exposed. With the exception of smoking, the impact of PAH exposure factors on the biomarkers is relatively small in this study population.

1. Introduction

Polycyclic aromatic hydrocarbons (PAHs) are a class of chemical compounds widespread in the environment (Baek et al., 1991). The International Agency for Research on Cancer (IARC) has classified exhaust from diesel engines as a carcinogen and certain PAHs as probable or possible carcinogens (IARC, 1987–1996, 2012). The most likely carcinogenic mechanism is through DNA adducts (Baird et al., 2005).

Major urinary metabolites of pyrene, 1-hydroxypyrene (1-OHP) and 1-hydroxypyrene-glucuronide (1-OHPG) have been widely used to measure occupational exposures to PAHs (Strickland and Kang, 1999). Several studies have suggested that 1-OHP/1-OHPG levels vary across occupations (Hansen et al., 2008; Kang et al., 1995; Lai et al., 2004), while others have shown that active and/or passive smokers excrete higher amounts of 1-OHP/1-OHPG when compared to non-smokers (Fagundes et al., 2006; Gunier et al., 2006; Hong et al., 1999; Lee et al., 2009). In addition, elevated 1-OHP or 1-OHPG levels have been detected

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among consumers of charbroiled or smoked meat and fish (Gunier et al., 2006; Hansen et al., 2008; Lee et al., 2009; Yang et al., 2003). In urban areas and near major roads, traffic-related air pollution is a source of PAHs (Hansen et al., 2005). Finally, 1-OHP and 1-OHPG levels may also be related to age, sex, body mass index (BMI) and alcohol consumption (Hansen et al., 2008).

Geographic information system (GIS)-based traffic density estimation is a promising method to measure past personal traffic exposure (Heinrich et al., 2005).

One of the problems with these estimation methods is that they generally have not considered all traffic sources such as traffic at residences and/or workplaces (Gunier et al., 2006; Hu et al., 2006). As such, we decided to adapt a GIS-based method that incorporated both time- and distance-weighted traffic densities (TDWTD). Our method takes into account all potential sources of traffic exposure, on roads, at home, work and elsewhere.

While urine levels of 1-OHP/1-OHPG have been used to estimate PAH exposure in occupational studies, it is still unknown whether these biomarkers can be widely used in the general population where individuals generally have low PAH exposures. In addition, questions remain regarding which biomarker (1-OHP or 1-OHPG) is more sensitive, that is, better able to detect low levels of PAH (Bouchard and Viau, 1999; Singh et al., 1995). It is also unknown if these measures are sufficiently reliable to reflect the true variation in population exposures to PAH. Furthermore, the factors influencing the variation of 1-OHP or 1-OHPG levels in urine are not well established (Gunier et al., 2006; Hansen et al., 2008).

We undertook a comparison of the two biomarkers and their relationship with GIS-based traffic density, assessing the between- and within-person variation of the biomarkers, and we explored the determinants of 1-OHP/1-OHPG levels in urine. Specifically, we examined which sources of PAH exposure are the determinants (predictors) of these two PAH biomarkers.

2. Material and methods

2.1. Design and study population

A cross-sectional study was conducted in Montreal in the summer of 2011. The DMTI CanMap® Route Logistics file and Postal Code boundary file from 2011 were used to obtain postal codes within three buffer zones of major roads/highways in Montreal: a 500-foot buffer zone (high traffic impact zone), a 500–750-foot buffer zone (medium traffic impact zone) and a 750–1000-foot buffer zone (low traffic impact zone) (DMTI CanMap® RouteLogistics, 2011; DMTI Platinum Postal Code OM Suite, 2011; Huen et al., 2006). Random sampling was conducted separately in each impact zone using the household telephone numbers associated with these postal codes. The inclusion criteria were men and women aged 20–50 years; without diagnoses of cancer, liver illness or kidney illness; and, residing at their current address for at least three months. Of the 2682 residences contacted, 624 persons were willing to participate. Ultimately, 200 eligible volunteers (107 females and 93 males) living in different houses or buildings were recruited and signed consent forms. The study was approved by the Queen's University Health Sciences Research Ethics Board and the Ethics Committee of Research on Health Sciences of the Université de Montréal.

2.2. Data collection

Participants completed a self-administered questionnaire recording age, sex, weight, height, ethnicity, alcohol consumption, household income, and potential sources of traffic and PAH exposure including PAH related jobs, proximity of residence to industry sites, and types of stoves at home. They were also asked about potential PAH exposures specific to a 48-hour period, and provided a complete first morning void urine sample at home at the end of this observation period. Once collected, samples were kept in the refrigerator by participants and picked up within 24 h by a staff member and kept in a cooler with ice packs during transport. Once at Dr. Michèle Bouchard's laboratory at the Université de Montréal, they were frozen at −20 °C until analysis. Urinary volume was measured prior to freezing at −20 °C. Twenty-one female participants and 19 male participants were randomly selected to collect repeated urine sample measures in the same month as major data collection for quality control purposes. Thus, in total, 240 samples including 200 in major data and 40 for repeated measures were collected.

2.2.1. 1-OHP and 1-OHPG analysis

The method used for the processing and analysis of total 1-OHP (sum of free and conjugated metabolites) and 1-OHPG is a modification of a published method (Bouchard and Viau, 1999). Both 1-OHP and 1-OHPG levels were adjusted for creatinine normalization (Viau et al., 2002). Briefly, urine samples (10 ml each) were prepared for 1-OHP and 1-OHPG analysis separately, were subjected to an enzymatic hydrolysis for 1 h, and then 1-OHP or 1-OHPG was extracted using C18 cartridges. Urine samples were then analyzed with an Agilent 1290 series Ultra-high-performance liquid chromatography system coupled to fluorescence. Finally, for each batch of urine analysis, quality control samples of pools of urine from exposed individuals (casual smoker (Q1) and consumer of PAH-rich food (Q2)) and blank samples spiked with authentic reference standard of 1-OHP and 1-OHPG at two levels were analyzed. Intra-day ($n = 10$ replicates) and inter-day coefficients of variation ($n \geq 10$ days) of 1-OHP and 1-OHPG were <10%. The analytical limit of detection (LOD) was 0.016 and 0.022 pmol/ml for 1-OHP and 1-OHPG, respectively.

2.2.2. Traffic density in the 48 h before urine collection

Since the island of Montreal is an urban area, we assumed homogeneity of this area. The time and length of travel for each participant from home on roads to the workplace and other locations (if ≥0.5 h) during the 48-hour observation period were obtained in the questionnaire. Each location was geocoded based on its postal code and street addresses using ArcGIS software (ESRI, 2011) and then was overlaid with the DMTI road data layer for Montreal. Annual average daily traffic (AADT) volume data on highways, major roads and local roads in two directions were compiled from two sources: AADT data on local highways, major roads and local roads in 2011 were from the municipalities of Montreal, and as a proxy for 2011 AADT data in 2010 on provincial highways were collected from Transport Quebec.

We constructed a 1000-foot (304.8-meter) radius buffer for the location of each participant to capture traffic exposure variation in and beyond 500 ft (152.4 m) of highways or major roads based on a modified dispersion model (Pearson et al., 2000). Fig. 1 illustrates the buffer zone of a location and the near distances to the roads within the buffer zone used in the traffic impact calculation. A distance-weighted traffic density (DWTD) variable was defined based on the assumption that "96% of the vehicles' pollutants disperse at 152.4 m (500 ft) with a Gaussian probability distribution on a windless day" (Pearson et al., 2000). The DWTD for each address was calculated as described in Eqs. (1) and (2) (Huen et al., 2006):

$$\mathrm{DWTD}_l = \sum_i \left[\left(\frac{1}{\sum \mathrm{Y}_{li}} \right) \times \mathrm{Y}_{li} \right] \times \mathrm{AADT}_{li} \quad \text{where } i = 1, \ldots, n; \tag{1}$$

$$\mathrm{Y}_{li} = \left(\frac{1}{0.4\sqrt{2\pi}} \right) \times \exp \left[\frac{(0.5) \times \left(\frac{\mathrm{D}_{li}}{500} \right)^2}{(0.4)^2} \right] \quad \text{where } l = 1, \ldots, j; \tag{2}$$

$$\text{Time Weighted DWTD} = \frac{\sum_l (\mathrm{A}_l \times \mathrm{B}_l)}{48} \tag{3}$$

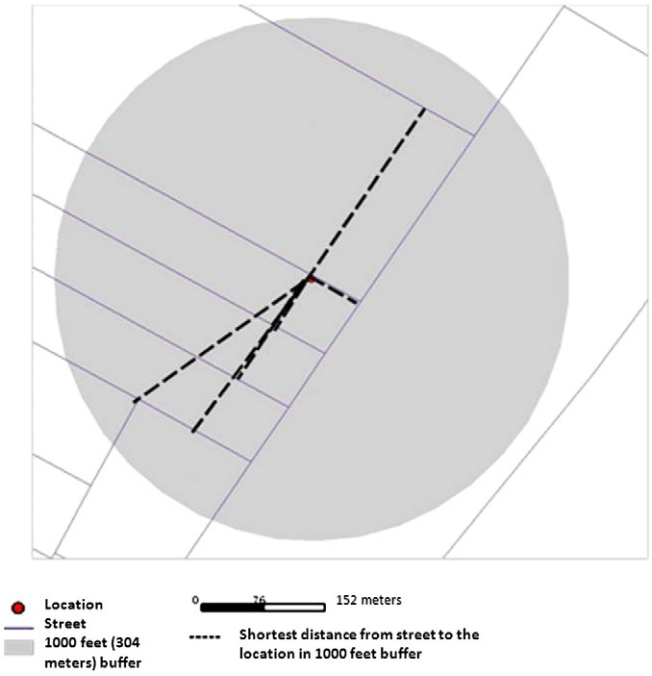

Fig. 1. An example of a location's buffer zone and the shortest distances to the roads within the buffer zone. Illustration: This is an example of a location's buffer zone and the shortest distances to the roads within the buffer zone.

where n is the total number of roads at location l, j is the number of locations where participants stayed in the 48 h before urine collection, $AADT_{li}$ is the annual average daily traffic volume on the ith road within 1000 ft of the location l, Y_{li} is a weight parameter calculated according to expression (2) that is used to weight the average daily traffic density from the ith road within 1000 ft of the location l, $\frac{Y_{li}}{\sum Y_{1i}}$ is a weighting constant, and D_{li} is the shortest distance in feet from ith road within 1000 ft of the location l.

The time-weighted DWTD (TDWTD) in Eq. (3) accounted for time spent on every location by each participant during the 48-hour period (Pearson et al., 2000), where A_l is traffic density for location l in the 48-hour and B_l is time spent on location l in the 48 h before urine collection. The traffic density on roads was estimated by the AADT on each road type (highway/major road vs. local road) and weighted by the length of time participants spent on each road type. The median AADT from all highways/major roads and local roads in Montreal, 23,978 cars/day and 669 cars/day respectively, was used to estimate the AADT values for each highway/major road and local road. The AADT value for a road was assigned as 0 if the road was in a park or on a mountain.

Age and BMI may influence the kinetics of pyrene elimination, and thus influence the level of urinary 1-OHP and 1-OHPG (Hansen et al., 2008). Therefore, we kept these two potential confounders into all models. In addition, sex, alcohol consumption, ethnicity and household income were assessed as potential confounders (Hansen et al., 2008; Crouse et al., 2009).

2.3. Statistical analysis

Pearson partial correlation analysis controlling for age, sex and BMI was used to assess the correlation between two biomarkers and log transformed traffic density. Multivariable linear mixed effects regression models were used to assess the determinants of 1-OHP and 1-OHPG in urine, and inter-person and intra-person variance of each biomarker, with subject variable as random effect to account for presumed compound symmetry covariance structure among repeated measurements. Tests for trend across levels of ordinal variables were calculated by treating levels of variables as continuous. Since the assumption of homogeneity and normality was not met through residual analysis, 1-OHP and 1-OHPG were natural log transformed, and residuals generated from the multivariable linear mixed effects regression models showed near normal distribution with constant variance.

Determinants of PAH biomarkers were assessed using the following strategy. First, the variables were placed into groups: 1) smoking and passive smoking in the past 48 h; 2) dietary factors, including consumption of smoked, BBQ and/or overdone meat, fruit, and green leafy vegetables; 3) indoor sources of PAH including the type of oven, frequency of cooking, and having the window open when cooking in the past 48 h; 4) industrial exposures due to occupation; and, 5) traffic density and time spent on roads in the past 48 h. Next, except groups 1 and 5, each of these groups, the relevant potential determinants and all potential confounders were put into four step 1 models predicting 1-OHP and 1-OHPG in the whole population, and the same biomarkers among non-smokers only. The strongest predictors ($p \leq 0.10$) from the step 1 models for each group were then forwarded to the next level of modeling where variables from the different groups were combined into four step 2 models. For the dietary exposure group, BBQ meat and fruit consumption met the criterion for inclusion. For indoor PAH pollution, oven type was selected into the step 2 models. Smoking and passive smoking were both forced into the step 2 models because they are important covariates according to the scientific literature. The variable of occupational exposure to PAH was also forced into the step 2 models for the same reason. Finally, we included the traffic variables into the next level of models because these factors represented our primary research interest.

For the next level of modeling (step 2), we included all potential confounders as well as the potential PAH determinants above. After using a 10% change-in-estimate approach to select confounders (Rothman et al., 2008), all confounders were included in the final models except household income. For each of the four models (two biomarkers in whole population, and two among non-smokers only), the determinants that had a p-value of ≤ 0.10 were selected into the final models. In order to find all potential predictors, we used the criteria of $p \leq 0.10$ instead of $p \leq 0.05$. All statistical analyses were performed using SAS (version 9.2, SAS Institute, Cary, North Carolina).

3. Results

Table 1 describes the characteristics of the study population. The mean age (±SD) of participants was 37 ± 8.31 years. Among 200 urine samples in the major data collection, 2 (1%) and 9 (4.5%) samples were below the detection limit for 1-OHP and 1-OHPG analysis respectively. Four (2%) and 1 (0.5%) samples for 1-OHP and 1-OHPG analysis were too dirty, thus the urine concentrations of these two biomarkers were not accurate and were removed from the analysis. Among the 40 repeated samples, one sample (2.5%) was under the detection limit for 1-OHPG.

As only 10 participants reported living within 100 m of industry sites, we did not include this variable in all multiple regression models. We performed a simple Kruskal–Wallis test and did not detect an association between levels of biomarkers and living within 100 m of industrial sites.

The intra-class correlation coefficients (ICC) of 1-OHP and 1-OHPG were 0.49 and 0.84 in the full study population, and 0.65 and 0.80 among non-smokers. The distribution of both biomarkers was skewed; however, following log transformation, the distribution of log 1-OHP and 1-OHPG showed a near normal distribution with a geometric mean (GM) of 78.69 nmol/mol creatinine and geometric standard deviation (GSD) of 2.67, and GM 42.21 nmol/mol creatinine with GSD 3.11, respectively among the entire population. Among non-smokers, we

Table 1
Characteristics of study population in major data collection.

Variables	Total (N = 200) N (%)	1-OHP[a] (nmol/mol creatinine) (N = 196)				1-OHPG[b] (nmol/mol creatinine) (N = 199)			
		Arith. mean	Median	Geo. mean	Geo. SD	Arith. mean	Median	Geo. mean	Geo. SD
Age (mean: 37, SD: 8.31)									
20–30	57 (29)	119.58	87.20	82.37	2.44	70.37	56.80	45.22	3.27
31–40	71 (36)	120.96	78.50	74.66	3.46	67.84	45.30	38.96	3.52
41–53	72 (36)	105.30	84.30	79.84	2.12	62.78	49.70	43.27	2.62
Sex									
Male	93 (47)	101.36	78.20	68.86	2.81	57.35	45.00	36.98	3.23
Female	107 (54)	127.01	86.90	88.54	2.53	75.02	50.40	47.40	2.99
BMI (mean = 24.8, SD = 5.0)									
<25	113 (57)	129.27	90.10	88.91	2.55	72.45	52.30	45.21	3.12
25–29.9	53 (27)	92.20	70.75	61.98	3.14	55.12	48.90	33.97	3.55
30+	27 (14)	107.91	95.20	85.45	2.06	69.26	50.00	51.89	2.28
Missing	7 (4)	83.53	42.70	49.12	2.74	53.83	27.20	33.48	2.54
Ethnicity									
European	138 (69)	119.46	87.20	80.97	2.81	68.21	50.60	40.78	3.48
Others	61 (31)	103.63	77.65	72.71	2.39	62.22	44.40	44.69	2.30
Missing	1 (1)	–	–	–	–	–	–	–	–
Household income									
<$30,000	38 (19)	115.92	91.65	76.32	2.85	63.69	51.30	45.68	2.58
$30,000 to $49,000	61 (31)	124.12	100.20	78.96	3.41	70.11	57.35	43.12	3.56
$50,000 to $79,000	44 (22)	104.63	86.30	80.68	2.15	61.65	46.80	38.71	3.14
≥80,000	54 (27)	114.99	70.80	78.89	2.30	69.47	47.50	40.97	3.12
Missing	3 (2)	–	–	–	–	–	–	–	–
Alcohol consumption									
<1 drink/mth	76 (38)	110.44	90.10	80.35	2.64	62.79	51.45	47.11	2.42
1 drink/mth-5 drinks/wk	64 (32)	117.08	76.10	81.14	2.33	69.42	48.05	39.15	3.77
>5 drinks/wk	59 (30)	119.90	82.90	74.64	3.18	69.55	49.25	39.82	3.38
Missing	1 (1)	–	–	–	–	–	–	–	–
Smoking in 48 h (# of cigarettes)			$p < 0.0001$*				$p < 0.0001$*		
0	133 (67)	88.92	65.20	64.42	2.37	52.77	41.90	34.69	2.85
1–20	32 (16)	150.73	97.70	90.96	3.89	85.38	57.00	42.87	4.72
>20	26 (13)	188.70	145.55	157.77	1.86	109.27	103.50	95.57	1.76
Missing	9 (5)	170.46	161.40	135.30	2.27	89.19	77.20	75.09	1.93
Secondhand smoking in 48 h (# of hours)			$p = 0.002$*				$p = 0.006$*		
0	113 (56)	106.37	67.80	67.53	2.91	61.89	40.20	35.72	3.35
>0–1	39 (19)	106.74	84.50	75.86	2.64	62.23	55.90	39.45	3.44
>1	34 (17)	153.77	124.90	126.51	1.88	84.60	67.50	68.72	1.95
Missing	14 (7)	114.65	95.30	97.10	1.79	76.69	53.10	62.23	1.97
Cooking fried or grilled food in 48 h									
No	77 (39)	117.66	83.70	74.44	3.02	72.04	45.30	41.93	3.45
Yes	112 (56)	113.12	85.50	80.79	2.50	62.93	50.60	41.58	2.97
Missing	11 (6)	114.69	78.50	88.92	2.13	68.45	48.90	51.52	2.38
Window open in 48 h									
No	49 (25)	132.81	93.70	93.05	2.28	74.72	45.30	42.11	3.52
Yes	138 (69)	106.93	83.10	76.06	2.63	63.50	49.60	42.30	2.92
Missing	13 (7)	132.60	64.20	58.11	4.90	71.14	50.20	41.67	3.93
Type of oven at home							$p = 0.09$*		
Electricity	188 (94)	112.86	83.10	77.25	2.69	64.45	48.90	40.74	3.14
Natural gas	12 (6)	150.46	100.20	107.36	2.41	102.71	76.35	73.47	2.33
TDWTD (cars/day) in 48 h (mean: 6663; median: 4785; 1st tertile: ≤3827; 3827 < 2nd tertile ≤ 6626; upper tertile: >6626)									
1st tertile (lowest; mean 2791; median 2897)	67 (34)	97.86	76.60	70.03	2.51	60.54	51.40	39.42	3.10
2nd tertile (mean 5096; median 4811)	67 (34)	134.57	91.00	92.92	2.75	82.29	56.75	53.33	2.80
3rd tertile (highest; mean 12,186; median 9420)	66 (33)	112.18	83.10	74.67	2.75	57.55	44.65	35.81	3.36
Time spent on road in 48 h							$p = 0.06$*		
<3 h	88 (44)	117.02	95.00	85.93	2.39	73.88	54.50	49.83	2.83
≥3 h	112 (56)	137.37	79.40	73.45	2.89	61.12	45.00	37.01	3.30
Smoked food in 48 h									
No	153 (77)	112.15	83.80	77.57	2.75	64.41	49.50	42.10	3.10
Yes	44 (22)	124.15	88.25	82.46	2.45	74.36	52.9	42.52	3.16
Missing	3 (2)	–	–	–	–	–	–	–	–
BBQ meat in 48 h									
No	131 (66)	111.10	84.50	75.05	2.76	62.66	49.65	42.07	2.94
Yes	69 (35)	122.42	87.20	86.19	2.51	74.48	48.90	42.48	3.46
Overdone meat in 48 h									
No	171 (86)	114.81	80.05	76.63	2.77	68.58	49.65	41.86	3.29
Yes	29 (15)	115.94	103.3	92.20	2.11	56.12	48.90	44.33	2.08
Green leaves in 48 h									
No	85 (43)	110.58	89.70	77.11	2.74	66.17	55.30	41.16	3.44
Yes	115 (58)	118.13	80.05	79.84	2.64	67.19	48.60	43.00	2.89
Fruit intake in 48 h									
No	29 (15)	113.11	91.65	65.62	3.98	67.69	43.65	32.12	5.14
Yes	171 (86)	115.28	83.80	81.11	2.47	66.61	49.70	44.14	2.80
Living within 100 m of industry sites									
No	187 (94)	115.36	85.50	78.69	2.70	67.11	49.65	42.03	3.18
Yes	10 (5)	112.71	58.70	75.35	2.63	69.45	51.75	49.17	2.43

Table 1 (*continued*)

Variables	Total (N = 200) N (%)	1-OHP[a] (nmol/mol creatinine) (N = 196)				1-OHPG[b] (nmol/mol creatinine) (N = 199)			
		Arith. mean	Median	Geo. mean	Geo. SD	Arith. mean	Median	Geo. mean	Geo. SD
Living within 100 m of industry sites									
Missing	3 (2)	–	–	–	–	–	–	–	–
Potential occupational PAH exposure									
No	161 (81)	111.09	83.05	74.10	2.81	63.54	46.8	39.87	3.13
Yes	35 (18)	133.63	88.85	100.86	2.07	80.03	56.8	51.42	3.11
Missing	4 (2)	109.45	115.85	102.23	1.56	79.38	78.70	73.37	1.59
Overall	200 (100)	114.97	85.00	78.69	2.67	66.76	49.60	42.21	3.11

[a] 4 missing values.
[b] 1 missing value.
* p value from Kruskal–Wallis one-way ANOVA ranks test to evaluate the relationship between categorical variables (excluding missing values) and 1-OHP or 1-OHP; p value was greater than 0.10 if not specified in the table.

observed GM 64.42 nmol/mol creatinine (GSD 2.37) for 1-OHP and GM 34.69 nmol/mol creatinine (GSD 2.85) for 1-OHPG.

Female participants had higher 1-OHP and 1-OHPG levels (exp β: 1.56, 95% CI: 1.17 to 2.09 for 1-OHP; exp β: 1.49, 95% CI: 1.05 to 2.11 for 1-OHPG) than males. Pearson partial correlation analysis controlling for age, BMI and sex did not find significant correlation between traffic density and the two biomarkers ($r = 0.04$, $p = 0.59$ for log transformed 1-OHP and 48-hour traffic density and $r = -0.009$, $p = 0.91$ for log

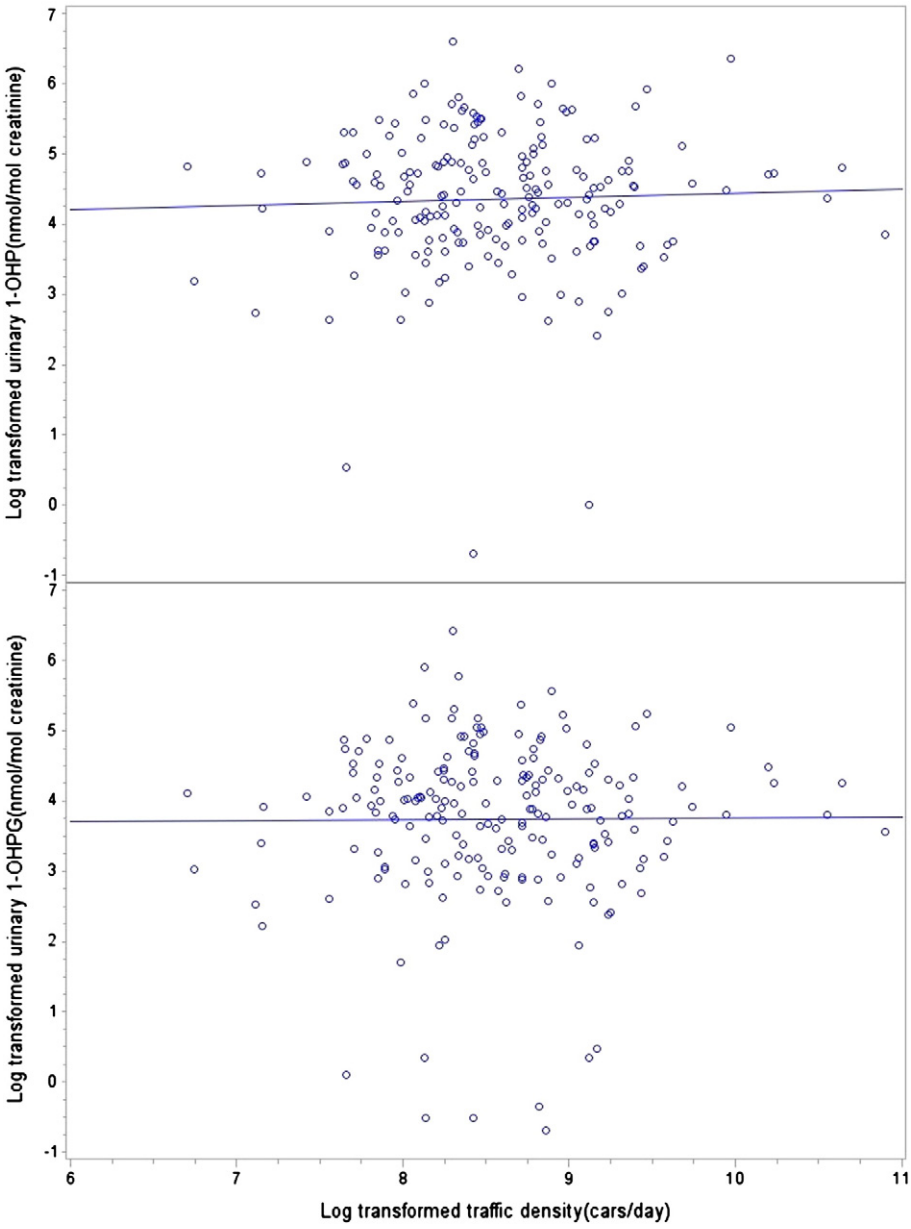

Fig. 2. Relationships between log 1-OHP and log 1-OHPG in urine and log TDWTD. Illustration: This is a scatter plot to show the relationships between log 1-OHP and log 1-OHPG in urine and log TDWTD.

transformed 1-OHPG and 48-hour traffic density) (Fig. 2). Fig. 3 illustrates how these two biomarkers are highly correlated after controlling for age, BMI and sex (Pearson partial correlation r = 0.79, p < 0.001 for log transformed 1-OHP and 1-OHPG).

Tables 2 and 3 show predictors of 1-OHP and 1-OHPG levels using multivariable linear mixed effect regression models. Compared to non-smokers, smoking more than one pack (20 cigarettes) in the 48 h before urine collection significantly predicted levels of both biomarkers (exp β: 2.83, 95% CI: 1.83 to 4.37 for 1-OHP and exp β: 3.11, 95% CI: 1.89 to 5.11 for 1-OHPG). Compared to non-smokers, those who smoked 20 cigarettes or less in the 48 h before urine collection had higher urinary 1-OHP levels (exp β: 1.42, p = 0.06, 95% CI: 0.99 to 2.05). No association was detected for other PAH sources including traffic density, time spent on the road, having a window open, cooking fried or grilled food, and dietary factors in the past 48 h.

Tables 4 and 5 present the results of predictors of 1-OHP and 1-OHPG from the multivariable linear mixed effect regression analysis among non-smokers. Participants who consumed grilled or BBQ meat in the 48 h before urine collection had higher 1-OHP levels (exp β: 1.45, 95% CI: 1.07 to 1.98). Compared to participants who were not exposed to smokers in 48 h before urine collection, those who had been exposed to smokers more than 1 h tended to have an increased urinary 1-OHP levels (exp β: 1.49, p = 0.06, 95% CI: 0.99 to 2.25).

Table 2
Predictors of natural log transformed 1-OHP in urine among all populations using mixed effects model (N = 210).

Variables	Adjusted estimate[a,b] Exp β, (95% CIs)	p-value	p_{-trend}
Age (year)	1.00 (0.98–1.02)	0.90	
BMI (kg/m^2)	1.01 (0.98–1.04)	0.49	
Sex			
Male	Referent		
Female	1.56 (1.17–2.09)	0.004	
Ethnicity			
European	Referent		
Others	0.98 (0.71–1.36)	0.92	
Alcohol consumption ($p_{overall}$ = 0.86)			
Less than one per month	Referent		*0.70*
1 drink per month — 5 drinks per week	1.06 (0.75–1.50)	0.74	
>5 drinks per week	0.96 (0.65–1.42)	0.83	
Smoke in 48 h (packs), 1 pack = 20 cigarettes ($p_{overall}$ = 0.0001)			
0	Referent		*<0.0001*
>0–1	1.42 (0.99–2.05)	0.06	
>1	2.83 (1.83–4.37)	<0.0001	
Potential occupational PAH exposure			
No	Referent		
Yes	1.41 (0.98–2.03)	0.06	

Note: 1) Inter-person variance (estimate ± SE): 0.40 ± 0.12, p = 0.0005.
2) Intra-person variance (estimate ± SE): 0.41 ± 0.10, p < 0.0001.
3) Repeated data were included in the analysis.
[a] All variables were from one model.
[b] Estimates including β and 95% CI were back transformed from log transformed values.

4. Discussion

In this study in Montreal, over 95% participants had PAH levels above the detection limit. This level of sensitivity is higher than that reported in previous studies, and suggests that both biomarkers can be widely used in general population studies where lower PAH exposure would be expected compared to occupational settings. Consistent with previous studies, we show that smoking has a significant effect on urinary 1-OHP/1-OHPG (Fagundes et al., 2006; Gunier et al., 2006; Hansen et al., 2008). Barbecue and grilled meat consumption was not associated with 1-OHP or 1-OHPG concentrations in the overall study population, although an association was found with 1-OHP in non-smokers. There are some inconsistencies in the literature. Three studies conducted in Italy, the USA and South Korea (Cocco et al., 2007; Gunier et al., 2006; Yang et al., 2003) found an association between grilled meat consumption and 1-OHP or 1-OHPG concentrations, while two other studies from Brazil and South Korea did not find any association (Fagundes et al., 2006; Hong et al., 1999).

Our study demonstrates no relationship between the time and distance weighted traffic density in the 48 h before urine collection and two urinary PAH biomarkers. This is consistent with a previous study conducted in the USA (Gunier et al., 2006). While GIS-based traffic density can accurately measure traffic exposure, recent traffic exposures represent only a portion of the total PAH exposure, and compared to that of smoking, the impact of 48-hour traffic exposure on PAH biomarkers appears to be relatively small in the general population.

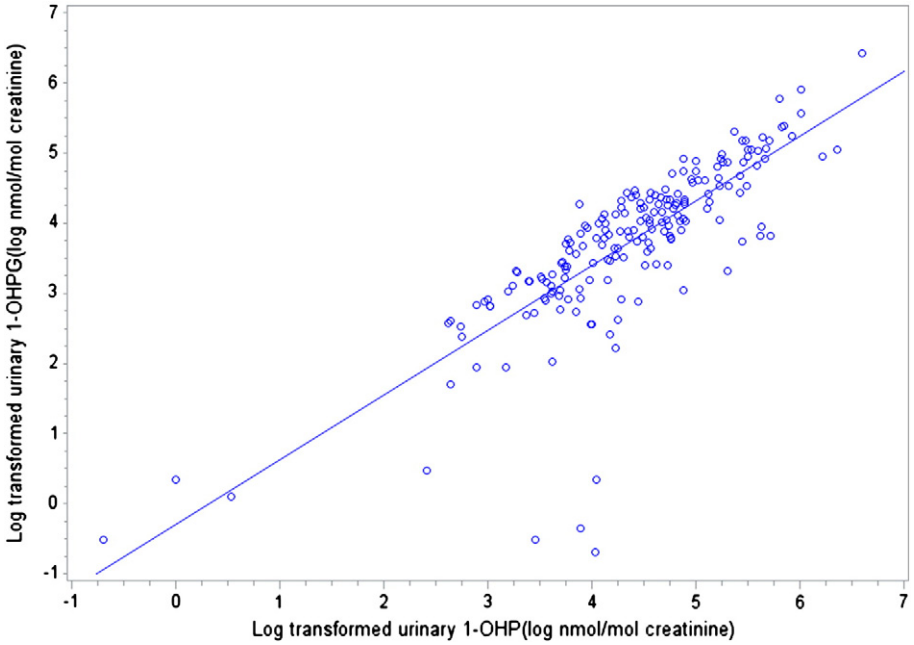

Fig. 3. Relationship between log 1-OHP and log 1-OHPG in urine. r = 0.79 and p < 0.001 from partial Pearson correlation adjusted for age, sex, and BMI in major data collection. Illustration: This is a scatter plot to show the relationship between log 1-OHP and log 1-OHPG in urine.

Table 3
Predictors of natural log transformed 1-OHPG in urine among all populations using mixed effects model (N = 218).

Variables	Adjusted estimate[a,b] Exp β, (95% CIs)	p-value	p-*trend*
Age (year)	1.00 (0.98–1.02)	0.94	
BMI (kg/m^2)	1.02 (0.98–1.06)	0.33	
Sex			
Male	Referent		
Female	1.49 (1.05–2.11)	0.03	
Ethnicity			
European	Referent		
Others	1.18 (0.79–1.76)	0.40	
Alcohol consumption ($p_{overall}$ = 0.81)			
Less than one per month	Referent		*0.40*
1 drink per month — 5 drinks per week	0.89 (0.58–1.36)	0.57	
>5 drinks per week	0.87 (0.54–1.40)	0.57	
Smoke in 48 h (packs), 1 pack = 20 Cigarettes ($p_{overall}$ = 0.0002)			
0	Referent		*<0.0001*
>0–1	1.36 (0.87–2.11)	0.17	
>1	3.11 (1.89–5.11)	<0.0001	
Type of oven at home			
Electricity	Referent		
Natural gas	1.84 (0.91–3.71)	0.09	

Note: 1) Inter-person variance (estimate ± SE): 1.01 ± 0.14, p < 0.0001.
2) Intra-person variance (estimate ± SE): 0.19 ± 0.05, p < 0.0001.
3) Repeated data were included in the analysis.
[a] All variables were from one model.
[b] Estimates including β and 95% CI were back transformed from log transformed values.

Other factors may also dilute the relationship between traffic density and the two biomarkers in the current study. For example, AADT data only includes annual average daily traffic volumes, which cannot reflect the difference in traffic volumes between peak and non-peak hours, and weekdays and weekends (Gunier et al., 2006). For some locations without associated AADT data, we had to use the AADT values from nearby roads. We also used the median levels of AADT to estimate traffic on highways, major roads, and local roads. Thus, the proposed weighted traffic density measure based on GIS may randomly misclassify the true traffic exposure to some extent. The GIS approach also does not take into account factors affecting dispersion of pollutants (wind direction, wind speed, atmospheric conditions and height of buildings), and variations between vehicles, such as the type of engine (gasoline or diesel engines) (Gunier et al., 2006; Phuleria et al., 2006). Previous studies have shown variation in air pollution levels by season (Fanou et al., 2006), which could be due to the slowing of air pollutant dispersion in winter (Hansen et al., 2008). Since our data collection took place during the summer, we were unable to identify a seasonal difference, and thereby determine whether the null association between traffic density and biomarkers is due to seasonal variation although two studies failed to find different 1-OHP levels by season (Cocco et al., 2007; Pastorelli et al., 1999). The above possible non-differential misclassification errors may have moved the results toward the null. Actual individual traffic exposure may be different from our estimation of air pollution exposure through the use of traffic density, which is a possible reason that we did not find the correlation between traffic density and the PAH biomarkers (Von Behren et al., 2008). It is difficult to address the magnitude of this possible misclassification of traffic exposure since many potential factors can influence traffic exposure levels. Nevertheless, recent studies have reported that simple traffic density (without considering wind, sky types and vehicle types of AADT etc.) is a valid method for traffic exposure measurement (Lai et al., 2004; Rioux et al., 2010; Rose et al., 2009) and similar traffic density methods have been widely used in previous epidemiological studies (Gunier et al., 2006; Huen et al., 2006; Pearson et al., 2000; Rioux et al., 2010).

In the present study, we initially intended to use time spent on the road in the 48 h before urine collection as an indicator of traffic exposure as one previous study conducted in the USA found nonsmokers who reported traveling on roads 3 h or more during the 48-hour period had significantly higher 1-OHPG levels than those who traveled less than 3 h (Gunier et al., 2006). However, we did not observe the relationship between time spent on the road and 1-OHP and 1-OHPG levels. It is possible that time spent on the road may not represent true traffic levels, because some participants may have run/walked on local roads with low traffic, and different transportation vehicles during commutes can also influence traffic exposure levels (Gunier et al., 2006).

Residential heating systems including gas oven, open wood/coal burning fireplaces and inappropriate operating of furnaces and stoves are also sources of PAH exposure (Environment Canada, 2005; Maliszewska-Kordybach, 1999). We found only a weak relationship between natural gas oven at home and levels of urinary 1-OHPG using

Table 4
Predictors of natural log transformed 1-OHP in urine among non-smokers using mixed effects model (N = 137).

Variables	Adjusted estimate[a,b] Exp β, (95% CIs)	p-value	p-*trend*
Age (year)	1.00 (0.98–1.02)	0.82	
BMI (kg/m^2)	1.00 (0.97–1.04)	0.85	
Sex			
Male	Referent		
Female	1.54 (1.08–2.19)	0.02	
Ethnicity			
European	Referent		
Others	1.14 (0.75–1.74)	0.52	
Alcohol consumption ($p_{overall}$ = 0.16)			
Less than one per month	Referent		*0.16*
1 drink per month — 5 drinks per week	1.42 (0.93–2.16)	0.10	
>5 drinks per week	1.03 (0.62–1.70)	0.91	
Environmental smoking in 48 h (# hours) ($p_{overall}$ = 0.15)			
0	Referent		*0.15*
>0–1	1.14 (0.78–1.67)	0.48	
>1	1.49 (0.99–2.25)	0.06	
BBQ meat consumption in 48 h			
No	Referent		
Yes	1.45 (1.07–1.98)	0.02	

Note: 1) Inter-person variance (estimate ± SE): 0.44 ± 0.12, p = 0.0001.
2) Intra-person variance (estimate ± SE): 0.24 ± 0.08, p = 0.0011.
3) Repeated data were included in the analysis.
[a] All variables were from one model.
[b] Estimates including β and 95% CI were back transformed from log transformed values.

Table 5
Potential predictor of natural log transformed 1-OHPG in urine among non-smokers using mixed effects model (N = 138).

Variables	Adjusted estimate[a,b] Exp β, (95% CIs)	p-value	p-*trend*
Age (year)	0.99 (0.97–1.02)	0.58	
BMI (kg/m^2)	1.01 (0.96–1.06)	0.79	
Sex			
Male	Referent		
Female	1.33 (0.84–2.11)	0.21	
Ethnicity			
European	Referent		
Others	1.22 (0.71–2.08)	0.45	
Alcohol consumption ($p_{overall}$ = 0.73)			
Less than one per month	Referent		*0.64*
1 drink per month — 5 drinks per week	1.05 (0.61–1.81)	0.86	
>5 drinks per week	0.84 (0.44–1.61)	0.59	
Environmental smoking in 48 h (# hours) ($p_{overall}$ = 0.43)			
0	Referent		*0.21*
>0–1	1.06 (0.66–1.71)	0.79	
>1	1.34 (0.85–2.13)	0.20	

Note: 1) Inter-person variance (estimate ± SE): 0.89 ± 0.17, p < 0.0001.
2) Intra-person variance (estimate ± SE): 0.23 ± 0.08, p = 0.001.
3) Repeated data were included in the analysis.
[a] All variables were from one model.
[b] Estimates including β and 95% CI were back transformed from log transformed values.

multivariable regression models; this may be due to the small number of participants (6%) who used natural gas ovens at home and small effect size. Future studies with large sample sizes are needed to confirm the above relationship and to further examine the relationships between fireplace/furnace and biomarkers in the winter season.

In the current study, females tended to have higher 1-OHP and 1-OHPG levels even after adjustment for creatinine levels, which is consistent with previous studies (Chen et al., 2007; Huang et al., 2012). A possible reason for this finding may be that the process of endogenous metabolism may vary between females and males (Huang et al., 2012; Kure et al., 1996), and future studies should explore the mechanism of differences in endogenous metabolism of PAH by sex.

We have demonstrated that the two PAH biomarkers used in this study are reliable. With respect to our methods for measuring traffic density, the fact that we found that traffic density in the 48 h before urine collection is not related to the two urinary PAH biomarkers does not mean that traffic density is not a good means of traffic measurement. However, traffic density during the 48-hour period prior to urine collection does not represent total PAH exposure as estimated by urinary PAH biomarkers. Due to cost constraints, we were unable to compare this method with other 48-hour traffic exposure measurements. In the future, use of personal monitors in the 48 h before urine collection could be applied to examine the correlation between traffic densities and traffic related air pollution levels.

Strengths of this study include that sampling occurred within different stratified zones of traffic levels, thus increasing potential exposure variability. In addition, non-invasive biomarkers with high detection of PAHs and fair to moderate ICC value (0.49) for 1-OHP and the fair to almost perfect ICC value (0.80) for 1-OHPG confirmed that both are appropriate biomarkers to measure low levels of PAH exposure in the general population.

Limitations include that in this cross-sectional study, subjects were volunteers; it is possible that these individuals are more health conscious (or perhaps, more “health hazard aware”) than the general population. However, because the major objective of the study was to examine a biological mechanism, and the exposure variables were heterogeneous, potential volunteer bias likely would not bias the associations per se, although generalizability could be affected. Interestingly, the external validity could also be influenced due to that there are more smokers (around 33%) in this study population, compared to smokers (around 26%) in the general population of Montreal (Statistics Canada Survey, 2005). Due to the cross-sectional study design, we were unable to test the exact temporality of potential determinants in relation to biomarkers. Finally, we were not able to examine potential gene–environment interactions of genetic polymorphisms influencing the variation of 1-OHP/1-OHPG, although we controlled for ethnicity in the multivariate analyses (Gunier et al., 2006; Mez et al., 2009).

5. Conclusions

Both 1-OHP and 1-OHPG are PAH biomarkers that can be widely used in studies of the general population. Smoking has a large impact on biomarker levels, and differences between female and male levels of biomarkers require further investigation. Among non-smokers, barbecued meat consumption is a predictor of 1-OHP concentration in urine. GIS-based TDWTD during the 48-hour period prior to urine collection represents only a small contribution to total PAH exposure as estimated by urinary PAH biomarkers in this population. Larger studies will further clarify associations between potential PAH sources and levels of biomarkers.

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