Urinary Polycyclic Aromatic Hydrocarbons and Childhood Obesity: NHANES (2001–2006)

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Background: Polycyclic aromatic hydrocarbons (PAHs) are known carcinogens and suspected endocrine disruptors. Prenatal exposure to PAHs has been associated with obesity in early childhood.

Objective: We examined the association of urinary PAH metabolites with adiposity outcomes [body mass index (BMI) *z*-score, waist circumference (WC), and rate of obesity] in children and adolescents.

Methods: We performed whole-sample analyses of 3,189 individuals 6–19 years of age who participated in the 2001–2006 National Health and Nutrition Examination Survey. We performed multivariate linear and logistic regression to analyze the association of BMI *z*-score, WC, and obesity with concentrations of single urinary PAH compounds and the sum of PAHs. Furthermore, the analyses were stratified by developmental stage [i.e., children (6–11 years) and adolescents (12–19 years)].

Results: BMI *z*-score, WC, and obesity were positively associated with the molecular mass sum of the PAHs and the total sum of naphthalene metabolites. Most associations increased monotonically with increasing quartiles of exposure among children 6–11 years of age, whereas dose–response trends were less consistent for adolescents (12–19 years of age). Neither total PAHs nor total naphthalene metabolites were associated with overweight in either age group, and there was little evidence of associations between the outcomes and individual PAHs.

Conclusions: Total urinary PAH metabolites and naphthalene metabolites were associated with higher BMI, WC, and obesity in children 6–11 years of age, with positive but less consistent associations among adolescents.

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Introduction

Childhood obesity has become an increasingly prevalent problem in the United States, with the rate of obesity in children and adolescents increasing from 6.1% in the 1972–1974 National Health and Nutrition Examination Survey I (NHANES I) to 18.1% in NHANES 2007–2008 (Ogden and Carroll 2010). The causes associated with this accelerating rate are being investigated, and an emerging hypothesis is that exposure to ubiquitous environmental toxicants may play a role in these childhood growth patterns (reviewed by Newbold 2010). Polycyclic aromatic hydrocarbons (PAHs) are a family of chemicals that are created through the incomplete combustion of organic materials [Agency for Toxic Substances and Disease Registry (ATSDR) 1995, 2005]. They are pervasive in our environment and distributed widely in the atmosphere. Nearly 100% of urinary samples collected through NHANES contain metabolites of naphthalene, fluorene, phenanthrene, and pyrene (Huang et al. 2006; Li et al. 2008). Humans can be exposed to PAHs through inhalation of cigarette smoke, vehicle exhaust, and processed fossil fuels, or through ingestion of grilled and charred meats, contaminated flour and bread products, processed and pickled foods, and contaminated water and cow's milk (ATSDR 1995, 2005). Contact with air, water, or soil near hazardous waste sites also poses a threat for exposure; nursing infants whose mothers live near these sites are an especially susceptible population to exposure through their mothers' milk. PAHs consist of two or more fused aromatic rings. Low-molecular-weight PAHs that have two or three aromatic rings are emitted in the gaseous phase, whereas high-molecular-weight PAHs, with five or more rings, are emitted in the particulate phase (ATSDR 1995, 2005).

PAHs are known carcinogens and suspected endocrine disruptors. Hydroxylated PAHs, the main metabolic product of PAHs, are structurally similar to estrogen and have been shown to have estrogenic activities (Schultz and Sinks 2002; Wenger et al. 2009). There is evidence that PAHs may act either antiestrogenically or estrogenically through disrupting estrogen-mediated pathways (Gozgit et al. 2004; Sievers et al. 2013). Some PAHs, such as phenanthrene and to a lesser extent fluoranthene, show antiandrogenic effects (Chang and Liao 1987; Vinggaard et al. 2000). Sun et al. (2008) showed that 1-naphthol and 2-naphthol may act as thyroid hormone receptor antagonists. Additionally, PAHs are transported into all tissues of the human body containing fat and have strong lipophilic properties. They can be stored in fat cells, the liver, and the kidneys and can accumulate by repeated and long-term exposures (Laher et al. 1984; Shu and Nichols 1979). Furthermore, experiments done in mice have shown that benzo[*a*]pyrene, a high-molecular-weight PAH, impairs adipose tissue lipolysis and leads to increased weight gain, increased fat mass, and changes in food intake (Irigaray et al. 2006).

Recently, studies have shown that prenatal exposure to PAHs is associated with reduced birth weight and birth head circumference as well as smaller birth size for gestational age among African Americans (Choi et al. 2008; Perera et al. 2003). Moreover, a study done in New York City (USA) showed a positive association between maternal exposure to PAHs during pregnancy and increased rates of obesity in early childhood (Rundle et al. 2012). The objective of our study was to investigate whether low-molecular-weight PAHs are associated with adiposity outcomes [body mass index (BMI) *z*-score and rate of obesity] in children and adolescents (6–19 years of age) using data from NHANES 2001–2006.

Methods

Study population. The NHANES studies from 2001–2006 were conducted by the U.S. National Center for Health Statistics [NCHS; Centers for Disease Control and Prevention (CDC), Atlanta, GA] with biomonitoring data evaluated by the National Center for Environmental Health (NCEH). The studies are cross-sectional, multistage, nationally representative surveys of the noninstitutionalized civilian population of the United States (NCHS 2008a). NCHS maintains that institutional review board approval and informed

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consent was obtained from all participants in these surveys. The grouping we used consisted of three cycles (2001–2002, 2003–2004, and 2005–2006) that were combined using NCHS recommendations (NCHS 2008b). Interviews were conducted in participants' homes and extensive physical examinations, which included blood and urine collection, were conducted at mobile examination centers.

Measure of adiposity: BMI z-score, waist circumference, and obesity. BMI is calculated by the weight divided by height squared (kilograms per meter squared). However, because the relation between BMI and body weight in children depends on age and sex, it is more appropriate to calculate the BMI *z*-score. The BMI *z*-score is the number of standard deviations (SDs) by which a child differs from the mean BMI of children of the same age and sex. Thus, the BMI *z*-score allows comparison of children of different ages and both sexes. The age and sex independent BMI *z*-scores were calculated using the methodology provided by the CDC (2011).

Individuals were classified as overweight and obese by BMI *z*-score between the 85th and 94th percentile and ≥ 95th percentile, respectively, for age and sex. Waist circumference (WC) was measured by trained technicians to the nearest 0.1 cm using standardized protocol.

Covariates. We controlled for the following *a priori* confounders of the association between PAHs and BMI *z*-score and obesity: age, race/ethnicity, sex, urinary creatinine, poverty:income ratio (PIR), serum cotinine, serum C-reactive protein (CRP), calorie intake, and television, video game, and computer use. PIR is a measure of socioeconomic status and represents the calculated ratio of household income to the poverty threshold after accounting for inflation and family size.

Caloric intake was categorized as "normal" and "excessive" based on the U.S. Department of Agriculture (2010) calorie intake guidelines by age and sex. The individual cut-off caloric need was the highest value for the range by age and sex assuming a moderate physical activity level. Information on daily hours of television, video game, or computer use was obtained by questionnaire, and the covariate was categorized with a cut point of ≥ 2 hr/day.

Laboratory analysis. PAH metabolites were measured in spot urine samples obtained from a random subsample of one-third of subjects ≥ 6 years of age. The eight monohydroxy-PAHs (OH-PAHs) we investigated were measured using gas chromatography combined with high-resolution mass spectrometry, as detailed by Romanoff et al. (2006). Additionally, we created three other variables: the sum of the individually calculated molar mass of all PAH metabolites (∑molPAHs), the sum of the naphthalene metabolites (∑NAPHT), and the sum of the metabolites of the PAHs with three (fluorene and phenanthrene) or four (pyrene) benzene rings (∑mol3–4PAHs). To account for variation in dilution in spot urinary samples, urinary creatinine was entered in the analyses as an independent variable, as suggested by previous studies (Barr et al. 2005; Ikeda et al. 2003). Urinary creatinine was determined using a Jaffé rate reaction measured with a CX3 analyzer (Beckman Instruments, Inc., Brea, CA) (NCHS 2007).

CRP is a marker of inflammation and has been associated with obesity (Dowd et al. 2010). Serum CRP was measured by a high-sensitivity assay using latex-enhanced nephelometry, with a lower limit of detection of the assay of 0.1 mg/L. CRP was categorized in weighted tertiles. Serum cotinine, a marker of exposure to environmental tobacco smoke, was categorized by weighted quartiles.

Statistical methods. We used sample weights for analyses to account for the complex sampling design and nonresponse of NHANES; these were calculated according to NHANES guidelines (NCHS 2008c). We estimated sampling errors using the Taylor series linearized method. We used separate linear regression models to estimate associations between BMI *z*-scores and WC (as dependent variables) and individual or grouped PAHs categorized according to quartiles (based on the weighted distributions in the study population). We used multinomial logistic regression models to simultaneously estimate adjusted odds ratios (ORs) for obesity and overweight status as distinct outcomes (compared with normal/underweight) in association with categorical PAH exposures. In addition to estimating associations for all observations combined, we performed separate analyses stratified by age (6–11 years and 12–19 years).

Table 1. Weighted characteristics of NHANES 2001–2006 participants 6–19 years of age.

Characteristic	6–19 years	6–11 years	12–19 years
n	3,189	1,081	2,108
1-naphthol (ng/L)	1604.55 (48.24)	1370.51 (59.58)	1804.98 (77.10)
2-naphthol (ng/L)	2530.30 (81.94)	2032.47 (74.13)	2979.43 (131.06)
2-fluorene (ng/L)	249.89 (7.25)	212.32 (6.92)	282.95 (10.35)
3-fluorene (ng/L)	105.58 (3.45)	89.35 (3.16)	119.97 (4.90)
1-phenanthrene (ng/L)	135.48 (3.75)	122.68 (3.82)	145.95 (4.90)
2-phenanthrene (ng/L)	50.10 (1.55)	42.74 (1.42)	56.49 (2.35)
3-phenanthrene (ng/L)	106.54 (3.46)	101.92 (4.00)	110.15 (4.17)
1-pyrene (ng/L)	98.91 (3.36)	95.58 (3.85)	101.49 (4.16)
∑PAHs (ng/L)	5704.66 (167.69)	4891.34 (189.24)	6417.88 (262.67)
Age (years)	11.81 (0.14)	8.37 (0.07)	15.23 (0.08)
BMI *z*-score	0.77 (0.02)	0.74 (0.04)	0.79 (0.03)
C-reactive protein (mg/dL)	0.05 (0.00)	0.04 (0.00)	0.05 (0.00)
Blood cotinine (ng/mL)	0.16 (0.02)	0.09 (0.01)	0.24 (0.03)
BMI	20.50 (0.13)	17.92 (0.14)	22.64 (0.16)
Urinary creatinine (mg/dL)	113.72 (2.46)	91.73 (2.07)	133.51 (3.11)
Sex			
Male	51.34 ± 1.25	51.14 ± 2.13	51.49 ± 1.48
Female	48.66 ± 1.25	48.86 ± 2.13	48.51 ± 1.48
Race/ethnicity			
Non-Hispanic white	62.18 ± 2.28	60.06 ± 2.71	64.74 ± 2.53
Non-Hispanic black	14.71 ± 1.48	15.00 ± 1.68	14.49 ± 1.52
Mexican American	11.79 ± 1.19	13.21 ± 1.30	10.75 ± 1.31
Other Hispanic	5.22 ± 0.81	4.59 ± 1.27	5.68 ± 0.97
Other	6.11 ± 0.75	7.14 ± 1.32	5.34 ± 0.82
Weight (*n*)			
Obese	608 (15.53 ± 0.98)	204 (14.17 ± 1.44)	404 (16.54 ± 1.14)
Overweight	510 (16.69 ± 0.89)	169 (16.60 ± 1.43)	341 (16.76 ± 1.53)
Normal and underweight	2,071 (67.78 ± 1.23)	708 (69.23 ± 1.99)	1,363 (66.70 ± 1.66)
Poverty income ratio (PIR)			
PIR ≤ 1	22.22 ± 1.43	22.55 ± 1.76	21.96 ± 1.87
PIR > 1	77.78 ± 1.43	77.45 ± 1.76	78.04 ± 1.87
TV and video games use			
≤ 2 hr	48.61 ± 1.63	52.46 ± 2.38	45.70 ± 1.89
> 2 hr	51.39 ± 1.63	47.54 ± 2.38	54.30 ± 1.89
Caloric intake			
Normal intake	53.95 ± 1.20	50.10 ± 1.91	56.78 ± 1.75
Excessive intake	46.05 ± 1.20	49.90 ± 1.91	43.22 ± 1.75
C-reactive protein			
Tertile 1, ≤ 0.01 mg/dL	28.76 ± 1.07	34.68 ± 1.89	24.69 ± 1.56
Tertile 2, > 0.01–0.07 mg/dL	38.26 ± 1.10	35.91 ± 2.03	39.88 ± 1.39
Tertile 3, > 0.07 mg/dL	32.98 ± 1.00	29.41 ± 1.99	35.43 ± 1.53

Values are geometric mean (SE) or percent ± SE.

SAS version 9.2 (SAS Institute Inc., Cary, NC) was used for all statistical analyses, and SAS-Callable SUDAAN 10 (Research Triangle Institute, Research Triangle Park, NC) was used to account for the NHANES complex sample design. *p*-Values from Satterthwaite statistics were presented at the significance level ≤ 0.05.

Results

Table 1 illustrates the weighted characteristics and geometric mean concentrations (SE) of urinary PAH metabolites among participants 6–19 years of age from NHANES 2001–2006 included in this study (n = 3,189). The geometric mean age of the participants was 11.8 years and 51.3% were male. Non-Hispanic whites accounted for 62.2% of the total study group; 14.7% were non-Hispanic blacks, and 11.8% were Mexican American. Approximately 22.2% of the participants were from families with income at or below the poverty level (PIR ≤ 1). The geometric mean (SE) BMI *z*-score was 0.77 (0.02); 15.5% of the individuals were classified as obese and 16.7% as overweight. Approximately 14.2% of children 6–11 years of age were obese, whereas the percentage of obese individuals among adolescents (12–19 years) was 16.5%. Estimated mean values for BMI *z*-score and WC increased monotonically with increasing quartiles of ∑molPAHs in the population as a whole, and among children ages 6–11 years (Table 2). Positive associations were also estimated for the older age group, though adjusted mean values were similar for all exposure quartiles above the reference exposure group, without a consistent increasing trend. BMI *z*-score and WC also increased monotonically with increasing quartiles of ∑NAPHT among children 6–11 years of age, whereas associations in adolescents and the overall population were positive but not monotonic (Table 2).

ORs from adjusted multinomial logistic regression models indicated positive associations with obesity for ∑molPAHs and ∑NAPHT in the population as a whole and in both age groups, although monotonic increases with exposure were estimated for ∑molPAHs in children 6–11 years of age only (Table 3). Neither exposure was associated with overweight in the population as a whole or in either age group.

Associations with individual PAH metabolites and with ∑mol3–4PAHs were less precise than those estimated for ∑molPAHs and ∑NAPHT, but 2-naphthol was positively associated with BMI *z*-score, WC, and obesity (overall and in both age groups), and 1-phenanthrene and 2-phenanthrene were positively associated with BMI *z*-score and WC (overall and in both age groups) (see Supplemental Material, Tables S1 and S2).

Table 2. Multivariate linear regression β coefficient (95% CI)[a] association between BMI *z*-score, waist circumference, and quartile[b] of ∑molPAHs, or ∑NAPHT.

	BMI *z*-score		Waist circumference	
Exposure	β coefficient (95% CI)	*p*-Value	β coefficient (95% CI)	*p*-Value
ALL (6–19 years)	n = 3,189		n = 3,189	
∑molPAHs Q1	Referent		Referent	
∑molPAHs Q2	0.18 (0.04, 0.32)	0.01	1.37 (–0.11, 2.85)	0.07
∑molPAHs Q3	0.18 (0.01, 0.35)	0.04	1.34 (–0.28, 2.96)	0.10
∑molPAHs Q4	0.25 (0.08, 0.43)	0.01	2.24 (0.25, 4.23)	0.03
∑NAPHT Q1	Referent		Referent	
∑NAPHT Q2	0.22 (0.06, 0.39)	0.01	1.79 (0.15, 3.43)	0.03
∑NAPHT Q3	0.24 (0.08, 0.40)	< 0.01	1.78 (0.24, 3.32)	0.02
∑NAPHT Q4	0.31 (0.15,0.50)	< 0.01	2.68 (0.88, 4.49)	< 0.01
Children (6–11 years)	n = 1,081		n = 1,081	
∑molPAHs Q1	Referent		Referent	
∑molPAHs Q2	0.20 (–0.04, 0.44)	0.09	1.08 (–0.85, 3.00)	0.27
∑molPAHs Q3	0.24 (–0.02, 0.49)	0.07	1.36 (–0.83, 3.56)	0.22
∑molPAHs Q4	0.41 (0.04, 0.77)	0.03	3.30 (0.24, 6.35)	0.03
∑NAPHT Q1	Referent		Referent	
∑NAPHT Q2	0.25 (–0.03, 0.52)	0.07	1.56 (–0.68, 3.80)	0.17
∑NAPHT Q3	0.31 (0.04, 0.56)	0.02	1.95 (–0.44, 4.34)	0.11
∑NAPHT Q4	0.37 (0.03, 0.70)	0.03	3.07 (0.19, 5.96)	0.04
Adolescents (12–19 years)	n = 2,108		n = 2,108	
∑molPAHs Q1	Referent		Referent	
∑molPAHs Q2	0.20 (0.01, 0.39)	0.04	2.37 (–0.07, 4.82)	0.06
∑molPAHs Q3	0.12 (–0.14, 0.38)	0.35	2.01 (–1.16, 5.17)	0.21
∑molPAHs Q4	0.18 (–0.06, 0.43)	0.13	2.65 (–0.16, 5.45)	0.06
∑NAPHT Q1	Referent		Referent	
∑NAPHT Q2	0.24 (0.04, 0.45)	0.02	2.83 (0.35, 5.31)	0.03
∑NAPHT Q3	0.21 (–0.01, 0.45)	0.08	2.53 (–0.07, 5.12)	0.06
∑NAPHT Q4	0.32 (0.07, 0.59)	0.02	3.66 (1.15, 6.17)	0.01

[a]Adjusted for age, race/ethnicity, sex, urinary creatinine, PIR, serum cotinine, serum C-reactive protein, calorie intake, and television, video game, and computer usage. [b]Quartiles (Q) ∑molPAHs (nmol/L): Q1: ≤ 19.90; Q2: 19.91–34.89; Q3: 34.90–64.48; Q4: > 64.48. Quartiles ∑NAPHT (ng/L): Q1: ≤ 2404.34; Q2: 2404.35–4259.03; Q3: 4259.04–8256.64; Q4: > 8256.64.

Discussion

To our knowledge, this is the first report of an association of environmental PAH exposures with childhood obesity using a nationally representative sample.

In the present study, we found that ∑NAPHT and ∑molPAHs were positively and significantly associated with BMI *z*-score, WC, and obesity. These associations were evident in the younger age group (6–11 years), but not in the older age group (12–19 years). It is worthwhile to note that the main source of exposure for naphthalene is through inhalation (mostly ambient pollution), whereas for the larger PAHs (fluorene, phenantrene, and pyrene), the main source of exposure is

Table 3. OR (95% CI)[a] from multinomial logistic regression models of association between urinary quartile[b] PAHs and obesity and overweight versus normal/underweight.

	6–19 years		6–11 years		12–19 years	
Exposure	Obese vs. normal	Overweight vs. normal	Obese vs. normal	Overweight vs. normal	Obese vs. normal	Overweight vs. normal
∑molPAHs Q1	1.00	1.00	1.00	1.00	1.00	1.00
∑molPAHs Q2	2.08 (1.21, 3.56)	1.12 (0.75, 1.67)	1.99 (0.83, 4.75)	1.45 (0.73, 2.89)	2.37 (1.18, 4.77)	0.95 (0.58, 1.56)
∑molPAHs Q3	1.74 (1.00, 3.05)	0.96 (0.61, 1.52)	1.78 (0.81, 3.90)	1.30 (0.60, 2.81)	1.76 (0.71, 4.35)	0.70 (0.37, 1.33)
∑molPAHs Q4	2.56 (1.40, 4.69)	0.87 (0.53, 1.41)	4.42 (1.57, 12.42)	1.12 (0.43, 2.92)	2.16 (0.94, 4.98)	0.67 (0.33, 1.35)
∑NAPHT Q1	1.00	1.00	1.00	1.00	1.00	1.00
∑NAPHT Q2	1.99 (1.12, 3.53)	1.47 (0.94, 2.31)	1.52 (0.61, 3.79)	1.96 (0.96, 4.00)	2.58 (1.24, 5.40)	1.24 (0.72, 2.14)
∑NAPHT Q3	1.70 (1.02, 2.81)	1.00 (0.66, 1.50)	1.77 (0.77, 4.06)	1.27 (0.55, 2.90)	1.83 (0.79, 4.23)	0.80 (0.48, 1.35)
∑NAPHT Q4	2.53 (1.40, 4.56)	0.89 (0.59, 1.39)	3.24 (1.27, 8.28)	0.78 (0.28, 2.12)	2.54 (1.14, 5.68)	0.88 (0.47, 1.67)

[a]Adjusted for age, race/ethnicity, gender, urinary creatinine, poverty income ratio (PIR), serum cotinine, serum c-reactive protein, calorie intake, and television, videogame and computer usage. [b]Quartiles (Q) ∑molPAHs (nmol/L): Q1: ≤ 19.90; Q2: 19.91–34.89; Q3: 34.90–64.48; Q4: > 64.48. Quartiles ∑NAPHT (ng/L): Q1: ≤ 2404.34; Q2: 2404.35–4259.03; Q3: 4259.04–8256.64; Q4: > 8256.64.

dietary (Li et al. 2008). Our results are in agreement with previous studies done both in animals and in humans. Irigaray et al. (2006) reported that PAH exposure impaired adipose tissue lipolysis and led to increased weight gain and fat mass in mice.

Recently, Rundle et al. (2012), in a longitudinal birth cohort of African Americans and Dominican mothers (18–35 years of age) residing in New York City, investigated the effect of prenatal exposure to airborne PAHs on the child's body size at 5 (n = 422) and 7 (n = 341) years of age. The authors reported that exposure to ambient high-molecular-weight PAHs was associated with higher BMI z-scores and obesity at both 5 and 7 years of age (Rundle et al. 2012).

PAHs are suspected endocrine-disrupting chemicals (EDCs) (Gozgit et al. 2004; Sievers et al. 2013). Using a *Saccharomyces cerevisiae* system, Schultz and Sinks (2002) reported estrogenic gene activity of the hydroxylated metabolites of naphthalene such as 1-naphthol and 2-naphthol, but not of the parent compound. Estrogenic activity was also reported for 2-fluorene and 1-pyrene (Schultz and Sinks 2002). It has been proposed that exposure to EDCs and other chemicals is an important risk factor for childhood obesity (Grun and Blumberg 2006). These chemicals can act on adipocytes by altering the metabolism or lipid homeostasis through activation of the peroxisome proliferator–activated receptor (PPAR), which differentiates the pre-adipocyte cells in fat tissue (Grun and Blumberg 2006). Chemicals that have been reported to act through this mechanism in experimental models are organotins, such as tributyltin, perfluoroalkyl acids, and certain phthalates (Grun and Blumberg 2006). In an *in vitro* system, Kim et al. (2005) reported activation of both PPARα and PPARβ/δ after exposure to several PAHs. Both naphthalene and phenanthrene significantly increased PPAR expression, though more weakly than benz[*a*]anthracene. Experimental animal studies show that other EDCs such as bisphenol A (Rubin and Soto 2009) and polybrominated diphenyl ethers (Hoppe and Carey 2007) may promote adipogenesis through a secondary metabolic imbalance instead of through PPAR. Coplanar polychlorinated biphenyls, for example, increased adipogenesis through the binding of the aryl hydrocarbon receptor in adipocytes (Arsenescu et al. 2008).

Chang and Liao (1987) studied the effect of phenanthrene in castrated rats. They found that the compound bound weakly to the AR of rat prostate but did not bind to the estrogen receptor or the glucorticoid receptor. Higher activity was reported for the phenanthrene metabolite. Also, both phenanthrene and its metabolite reduced the androgen-dependent growth of the ventral prostate, seminal vescical, and coagulating gland (Chang and Liao 1987).

A slight antiandrogenic effect of phenanthrene was similarly reported by Vinggaard et al. (2000) in an *in vitro* system. The authors also reported antiandrogenic effect of fluorantene (Vinggaard et al. 2000).

EDCs may also influence adipogenesis through effects on thyroid hormone. Thyroid hormone inhibits lipogenesis (Viguerie et al. 2002) and stimulates lipolysis in adipocytes (Smith et al. 1991; Van Inwegen et al. 1975), possibly through crosstalk with the PPARs (reviewed in Lu and Cheng 2010). In animal models, thyroid hormone receptor (TR) agonists induced fat loss and decreased plasma cholesterol and triglyceride levels (Baxter et al. 2004; Grover et al. 2003). There is evidence that 1-naphthol and 2-naphthol act as EDCs through thyroid hormone receptor antagonist activity (Sun et al. 2008). Using an *in vitro* system based on the thyroid hormone receptor (TR)-luciferase reporter gene, Sun et al. (2008) tested carbaryl, 1-naphthol, and 2-naphthol for their TR activities. 1-naphthol, 2-naphthol, and carbaryl showed TR antagonist activities, indicating that they could disrupt the normal function of the thyroid hormones. Whereas 2-naphthol is an important metabolite of naphthalene, 1-naphthol is a metabolite of both carbaryl and naphthalene. Therefore, it may be possible that 1-naphthol and 2-naphthol may increase adipocyte lipid accumulation through TR antagonism and by reducing circulation levels of thyroid hormones in children.

Li et al. (2008), using the NHANES 2001–2002 survey, reported that the eight PAH metabolites correlate to each other to some degree (r = 0.4–0.8), which in some cases suggests a common source of exposure. Naphthalene metabolites, as a group, correlate better with the fluorene group than with the phenanthrene and pyrene groups. This may be explained by the difference in exposure source: exposure through inhalation for naphthalene, and by diet for the larger PAHs (fluorene, phenantrene, and pyrene). Although these metabolites have a good correlation with each other, our analyses show a difference in association between individual PAH metabolites and obesity and body weight outcomes. Our finding may be explained, for example, by the different action on the estrogen-responsive genes by the different PAHs, as shown by Gozgit et al. (2004).

The temporal relations between exposures and outcomes cannot be determined given the cross-sectional study design. Although we controlled for several factors associated with obesity, exposure to other chemicals such as bisphenol A (Trasande et al. 2012) and phthalates (Teitelbaum et al. 2012; Trasande et al. 2013) might have confounded associations. Another important limitation is that PAHs have a short half-life, and exposure values are based on single spot urine analyses. Low-molecular-weight PAHs are ubiquitous in the environment, so it may be reasonable to assume that exposure is continuous. If so, urinary PAHs may be a good proxy for typical PAH exposures. Although no studies link short-term PAH exposure to long-term exposure, there are examples of other lipophilic chemicals, such as phthalates, for which a single urine sample may represent exposure over the previous 3 months (Hauser et al. 2004). We do not know whether this would apply to the PAHs, but our results merit further investigation.

Conclusion

We found that the total molar sum of the PAHs was associated with higher BMI, WC, and obesity in children 6–11 years of age. However, this association was less consistent among adolescents (12–19 years of age) in the same survey. We found that urinary naphthalene was associated with higher BMI z-score, WC, and obesity in both children and adolescents.

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