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Toxic equivalency factors study of polycyclic aromatic hydrocarbons (PAHs) in Taichung City, Taiwan

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Airborne particles and polycyclic aromatic hydrocarbons (PAHs) in industrial, background and urban atmosphere environments were investigated using toxic equivalent factors (TEFs) in central Taiwan during the period of August–December 2002. Concentrations of airborne particles were 93.4, 81.3 and 102.4 $\mu\text{g}/\text{m}^3$ for industrial, background and urban sites, respectively. Concentrations of 21 gaseous PAHs were 1530, 759 and 1030 ng/m^3 for industrial, background and urban sites, respectively; for carcinogenic activity of gaseous PAHs, the benzo[a]pyrene (BaP) equivalent concentrations were 17.0, 7.29 and 12.6 ng/m^3 for industrial, background and urban sites, respectively. Twenty-one particle-bound PAHs were only 10% of the 21 gaseous PAHs. Dibenzo(a,h)anthracene (DBA) serves as a surrogate to explain the carcinogenic activity of PAH mixtures in central Taiwan because its carcinogenicity is a high percentage of the total carcinogenic activity. During the sampling period, temperature inversion from a cold front from China occurred, leading to average daily temperatures of 16°C. These cold fronts caused atmospheric particles and pollutants to accumulate in the troposphere, leading to extremely high concentrations of airborne particles and both gaseous and particle-bound PAHs in central Taiwan. *Toxicology and Industrial Health* 2002; **18**: 279–288.

Key words: *airborne particles; health risk assessment; PAHs; TEFs*

Introduction

Polycyclic aromatic hydrocarbons (PAHs) are formed during incomplete combustion or pyrolysis of organic material and are often produced in connection with the worldwide use of oil, gas, coal and wood in energy production. Additional contributions to ambient air levels are from tobacco smoking. The use of heating sources can

increase PAH concentration in indoor air. Because of such widespread sources, PAHs are present almost everywhere. PAHs are complex mixtures of hundreds of chemicals, including derivatives of PAHs, such as nitro-PAHs and oxygenated products, and also heterocyclic PAHs. The biological properties of the majority of these compounds are as yet unknown. Benzo[a]pyrene (BaP) is the PAH most widely studied, and the abundance of information on toxicity and occurrence of PAHs is related to this compound. Current annual mean concentrations of BaP in major European urban areas are in the range 1–10 ng/m^3 . In rural areas, the concentrations are < 1 ng/m^3 (WHO, 1987).

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Binkova *et al.* (1999) found that organic compounds such as PAHs are highly correlated with DNA adducts, causing mutation of human cells. Extrapolation from occupational exposure and risk data suggests that, of the potential carcinogens present in polluted urban air, PAHs may be major contributors to air pollution-associated lung cancer risk (Georgiadis and Kyrtopoulos, 1999).

BaP is by far the most intensively studied PAH in experimental animals. It produces tumours of many different tissues, depending on the species tested and the route of application. BaP is the only PAH that has been tested for carcinogenicity following inhalation, and it produced lung tumours in hamsters, the only species tested. Induction of lung tumours in rats and hamsters has also been documented for BaP and several other PAHs following direct application. Lung carcinogenicity of BaP can be enhanced by co-exposure to other substances, such as cigarette smoke, asbestos and probably also airborne particles. Several studies have shown that the benzene-soluble fraction, containing 4- to 7-ring PAHs of condensates from car exhausts (petrol, diesel), domestic coal-stove emissions and tobacco smoke, contains nearly all the carcinogenic potential of PAHs from these sources (IARC, 1987).

Particle-bound PAHs are highly correlated with heavy duty vehicles ($r = 0.67-0.86$) and light duty vehicles ($r = 0.43-0.59$) (Junker *et al.*, 2000). The ultra fine particles ($< 0.1 \mu\text{m}$) generated by those vehicles occupied 82% of the total suspended fine particles ($< 0.421 \mu\text{m}$). Diesel exhaust usually consists of a complex mixture of chemicals, including known genotoxicants, some of which are PAHs (Muzyka *et al.*, 1998). Nielsen (1996) indicated that the BaP concentration in Denmark street air was three times higher than in park air. Lung cancer and skin cancer risks of workers in carbon black manufacturing factories of Taiwan (Tsai *et al.*, 2001a) are higher than the designated significant risk level for exposure to airborne PAHs ($= 10^{-3}$) defined by the US Supreme Court in 1980. Biomass burning, such as forest fires, is a major source of PAHs in South Asia (Okuda *et al.*, 2002).

Highways and industrial work environments for carbon black manufacturing, incineration process and petroleum refining are major sources of PAHs. We chose three different sampling sites (industrial

park, background and urban traffic) to measure concentrations of PAHs and toxic equivalency factors (TEFs).

Experimental methods

Sampling program

Three sampling sites, Taichung Industrial Park (IND), Tunghai University (BACK) and National Chung-Hsing University (URB) were selected to characterize ambient air PAH concentration in central Taiwan from August 2002 to December 2002. Table 1 indicates the sampling information and meteorological conditions during the sampling period.

A typical large-scale multiple industry area in Taiwan, the IND was developed on 580 hectares of land. There are > 800 factories at IND, including chemical, petroleum, plastic and electronics industries. The IND sampling site was on the roof of a pharmaceutical factory (15 m in height) and located in the centre of the IND.

The BACK sampling site was selected to provide background levels of PAHs to compare with IND levels. Located between Taichung City and Taichung County, BACK is surrounded by trees. Tunghai University has about 15000 students and faculty. Taichung Veterans General Hospital Incinerator (a combustion source) and Taichung Kong Road (the main route in Taichung City) are opposite Tunghai University. The sampling heights were at 1.5 m above ground level to represent the human breathing zone.

The URB sampling site was in downtown Taichung City. There is a residential area and a major highway surrounding the site on the campus of Chung Hsing University. The site was about 10 m above ground on the roof of the Environmental Engineering building.

The choice of sampling sites is described in Fang *et al.* (2002a,b, 2003), Wu *et al.* (2002). These studies selected different sampling sites at different altitudes to measure recent atmospheric pollution concentrations in central Taiwan. These sampling sites, with sampling height varied, are thought to be the most representative of the ambient air particle concentrations important to our living environment. This study further extends the importance of

Table 1. Sample information and meteorological conditions in three sites of central Taiwan.

Sampling date	Temperature (°C)	Relative humidity (%)	Wind speed (m/s)	Wind direction
1–3 August	33	65	1.6	NW
13–15 August	39	63	1.3	N
19–21 August	38	63	0.9	N
25–27 September	28	65	1.8	NE
7–9 October	25	54	5.2	NW
9–11 October	31	57	2.0	NNE
28–30 October	28	58	1.7	N
1–3 November	27	71	2.3	N
4–6 November	24	44	1.3	N
4–6 December	25	64	0.7	NNW
9–11 December	16	59	3.5	N
11–13 December	20	68	3.5	N
Mean	27.8	60.9	2.2	–
Standard deviation	6.7	7.2	1.3	–

these data. We transfer them into BaP concentration, a widely used index for a carcinogenicity study.

PAH sampling and analysis

Samples were collected using three PS-1 samplers (GPS1 PUF Sampler, General Metal Work, OH, USA). A pump was used to draw air through a tissue quartz filter (2500 QAT-UP, dimension 102 mm, Gelman Sciences, MI, USA) and a PM_{2.5}/PM₁₀ specific sampler (Model 310 Universal Air Sampler™, MSP Corporation, MN, USA). Particles in the 2.5–10 µm range were collected on 62 mm × 165 mm filters (tissue quartz filters, Gelman Sciences, MI, USA). Particles <2.5 µm were collected on 200 mm × 250 mm filters. Gas phase PAHs were sampled using a glass cartridge, filtered with a 5 cm long polyurethane foam plug, packed 3 cm thick XAD-16 resin (Amberlite) and finally filtered with a 2 cm long polyurethane foam plug. During sample transportation and storage, the plugs and resins were stored in clean jars wrapped with aluminium foil. Quartz filters were sealed in a CD box. Quartz filters were weighed before and after sampling to determine the amounts of particulate matter collected. Before sampling, quartz filters were baked in an oven at 450°C for 8 hours to remove organic impurities. Glass cartridges were cleaned by sequential Soxhlet extraction with distilled-deionized water, methanol, dichloromethane (DCM) and a mixture of DCM/n-hexane (50/50, v/v) for 24 hours before being dried in an oven at 45°C.

After collecting, PAHs were extracted from the quartz filters and glass cartridges separately placed in appropriate Soxhlet extractors and soaked in DCM/n-hexane mixture (50/50, v/v) for 24 hours. The extract was concentrated under a rotary evaporator, cleaned and reconcentrated with ultra-pure nitrogen to exactly 1 mL using a procedure described by Lee *et al.* (1995). Extracts were analysed using a gas chromatograph/mass selective detector (GC/MSD) (GC3800 Varian with MS2000 Saturn, Varian Inc., CA, USA) with a GC capillary column (30 m × 0.25 mm × 0.25 µm, DB-5) and a computer-controlled automatic sampler (Model 8200). All injections were splitless and volume was 1 µL. Injector and transfer line temperatures were 310°C and 300°C, respectively. The temperature program totalled 70 minutes: 35°C for 3 minutes, increasing to 180°C at 25°C/minute intervals, 180°C for 2 minutes, increasing to 200°C at 20°C/minute intervals, 200°C for 2 minutes, then increasing to 300°C at 2°C/minute intervals and 300°C for 6.4 minutes.

Filter and glass cartridges were stored at 4°C and analysed within 15 days of collection. Quantification of PAHs was according to the retention times and peak areas of the calibration standards. The instruments were calibrated using at least five standard concentrations covering the concentration of interest for ambient air work. The correlation coefficient of the calibration curve was >0.995 for linear least-squares fit of the data.

Twenty-one PAHs were analysed from the three sites in central Taiwan: naphthalene (Nap), acenaphthylene (AcPy), acenaphthene (Acp), fluorene

(Flu), phenanthrene (PA), anthracene (Ant), fluoranthene (FL), pyrene (Pyr), cyclopenta(c,d)pyrene (CYC), benzo(a)anthracene (BaA), chrysene (CHR), benzo(b)fluoranthene (BbF), benzo(k)fluoranthene (BkF), benzo(e)pyrene (BeP), benzo(a)pyrene (BaP), perylene (PER), indeno(1,2,3,-cd)pyrene (IND), dibenzo(a,h)anthracene (DBA), benzo(b)chrycene (BbC), benzo(ghi)perylene (BghiP) and coronene (COR). The elution

Table 2. QA/QC of 21 PAHs in this study.

Compounds	Elution order (<i>m/z</i>)	Recovery (%)	Method detection limit (mg/L)
Naphthalene (Nap)	128	88	0.059
Acenaphthylene (AcPy)	152	93	0.091
Acenaphthene (Acp)	154	89	0.084
Fluorene (Flu)	166	91	0.072
Phenanthrene (PA)	178	85	0.171
Anthracene (Ant)	178	94	0.095
Fluoranthene (FL)	202	98	0.091
Pyrene (Pyr)	202	99	0.095
Cyclopenta(c,d)pyrene (CYC)	226	99	0.117
Benzo(a)anthracene (BaA)	228	95	0.116
Chrysene (CHR)	228	101	0.531
Benzo(b)fluoranthene (BbF)	252	92	0.110
Benzo(k)fluoranthene (BkF)	252	101	0.329
Benzo(e)pyrene (BeP)	252	77	0.047
Benzo(a)pyrene (BaP)	252	86	0.183
Perylene (PER)	252	86	0.046
Indeno(1,2,3,-cd)pyrene (IND)	276	89	0.074
Dibenzo(a,h)anthracene (DBA)	278	91	0.054
Benzo(b)chrycene (BbC)	278	90	0.067
Benzo(ghi)perylene (BghiP)	276	95	0.093
Coronene (COR)	300	99	0.117

Table 3. Proposed TEFs for individual PAHs.

Compound ^a	CAS-No.	USEPA (1984)	Nisbet and LaCoy (1992)
Nap	91-20-3	0	0.001
AcPy	208-96-8	0	0.001
Acp	83-32-9	0	0.001
Flu	86-73-7	0	0.001
PA	5801-8	0	0.001
Ant	120-12-7	0	0.01
FL	206-44-0	0	0.001
Pyr	129-00-0	0	0.001
BaA	56-55-3	1	0.1
CHR	219-01-9	1	0.01
BbF	205-99-2	1	0.1
BkF	207-08-9	1	0.1
BaP	50-32-8	1	1
IND	193-39-5	1	0.1
DBA	53-70-3	1	1
BghiP	191-24-2	0	0.01

^a Full names of compounds are indicated in the text.

orders, recoveries and method detection limits for the 21 analysed PAHs are displayed in Table 2.

Toxic equivalency factors

The development and establishment of TEFs for PAHs are listed in Table 3 to help characterize the carcinogenic properties of PAH mixtures. Individual PAHs can be separated into two subclasses, consisting of carcinogenic and noncarcinogenic compounds. BaP is used as a reference compound. All carcinogenic PAHs were given toxic equivalency factors of 1, and 0 to the noncarcinogenic PAHs (USEPA, 1984). The available information indicates that the other carcinogenic PAHs have lower potency than BaP. Previous to the USEPA approach led to an overestimation of risk. Nisbet and LaGoy (1992) completed a new list of TEFs which seems to better reflect the actual state of knowledge on the relative potency of individual PAHs (Petry *et al.*, 1996). We used the Nisbet and LaGoy (1992) approach to evaluate the human health risk resulting from inhalatory exposure to PAHs in Taichung City, Taiwan.

Results and discussion

Airborne particle concentrations

The concentrations for airborne particles in the IND, BACK and URB sampling sites are shown in Table 4. As can be seen in Table 2, the concentrations of total suspended particles were 53.7–156.2, 43.4–130.2 and 54.1–189.6 $\mu\text{g}/\text{m}^3$, with an average value of 93.4, 81.3 and 102.4 $\mu\text{g}/\text{m}^3$ for IND,

Table 4. Airborne particle concentrations in the three sampling sites.

Sampling site	Sample size (<i>n</i>)	Range ($\mu\text{g}/\text{m}^3$)	Average ($\mu\text{g}/\text{m}^3$)	Percentage above the AQS ^a
Industrial (TSP)	12	53.7–156.2	93.4	0.0
Background (TSP)	12	43.4–130.2	81.3	0.0
Urban				
TSP	12	54.1–189.6	102.4	0.0
PM _{2.5}	6	24.5–43.2	32.3	–
PM ₁₀	6	45.2–126.3	65.5	16.7% ^b

^a AQS: air quality standard in Taiwan; 250 $\mu\text{g}/\text{m}^3$ 24 hours average for TSP and 125 $\mu\text{g}/\text{m}^3$ 24 hours average for PM₁₀.

^b The sampling day had temperature inversion due to a cold front from China with an average temperature of 16.0°C.

BACK and URB, respectively. The total suspended particle concentration for the URB site was higher than that of IND and BACK sampling sites. This is probably from the busy highway, with about 150 vehicles/minute near the sampling site.

Because of the higher total suspended particle concentrations in the URB site, this site was also equipped with a universal sampler to measure the PM_{2.5}/PM₁₀ (Table 4). The results indicated that the concentration of PM_{2.5} ranged from 24.5 to 43.2 µg/m³ with an average value of 32.3 µg/m³; PM₁₀ ranged from 45.2 to 126.3 µg/m³ with an average value of 65.5 µg/m³. PM_{2.5} and PM₁₀ contributed about 31.5% and 63.0%, respectively, of the total suspended particles at the URB sampling site. The high PM₁₀ values indicated that the source of airborne particles was from vehicular exhaust. The concentrations of the total suspended particles at each sampling site were below the Air Quality Standard (250 µg/m³ for 24 hours average) for Taiwan. One PM₁₀ sample had concentrations greater than the Air Quality Stan-

dard (125 µg/m³ for 24 hours average) for Taiwan (Table 4). This is probably due to a cold front being included in the temperature inversion, which yielded an average daily temperature of 16.0°C. This cold front may have caused accumulation in the troposphere, elevating PM₁₀ concentrations.

Ambient air gaseous PAH concentrations

The gaseous concentration of individual PAHs, including carcinogenic PAHs to BaP and the sum of each PAH for each sampling environment (IND, BACK and URB) are shown in Table 5. The 21 gaseous PAH concentrations in the IND ranged from 625 to 4620 ng/m³ with an average value of 1530 ng/m³ and was higher than that of BACK and URB, with average values of 759 ng/m³ (273–1510 ng/m³) and 1030 ng/m³ (547–3680 ng/m³), respectively. The industrial exhaust in the IND site from the chemical, petroleum, plastic and electronics industries yielded higher PAH concentrations than the BACK and URB sites. The highest 21 gaseous

Table 5. Concentrations and TEFs of 21 gaseous PAHs (ng/m³)

Compounds	IND		BACK		URB	
	Gas phase Avg. ±Std. n ^a = 12	TEFs BaP _{eq}	Gas phase Avg. ±Std. n = 12	TEFs BaP _{eq}	Gas phase Avg. ±Std. n = 12	TEFs BaP _{eq}
Nap	409 ± 332	0.41	223 ± 125	0.22	283 ± 186	0.28
AcPy	177 ± 131	0.18	126 ± 122	0.126	118 ± 128	0.12
Acp	196 ± 158	0.20	47.4 ± 83.1	0.047	137 ± 106	0.14
Flu	129 ± 126	0.13	73.3 ± 54.5	0.073	85.8 ± 63.1	0.086
PA	90.0 ± 83.2	0.09	33.2 ± 30.5	0.033	60.0 ± 53.2	0.060
Ant	158 ± 86.3	1.58	48.3 ± 22.5	0.48	105 ± 50.1	1.05
FL	80.5 ± 62.1	0.08	31.3 ± 20.3	0.031	53.7 ± 37.1	0.054
Pyr	79.9 ± 16.5	0.08	32.9 ± 15.3	0.033	53.3 ± 21.1	0.053
CYC	35.9 ± 28.1	–	30.8 ± 26.2	–	33.3 ± 21.6	–
BaA ^b	13.8 ± 6.8	1.38	26.5 ± 9.5	2.65	19.2 ± 3.1	1.92
CHR ^b	48.3 ± 16.1	0.48	22.6 ± 15.8	0.23	32.2 ± 14.3	0.32
BbF ^b	10.1 ± 3.3	1.01	3.3 ± 1.5	0.33	6.7 ± 2.2	0.67
BkF ^b	12.4 ± 3.8	1.24	4.6 ± 5.9	0.46	10.3 ± 12.2	1.03
PER	33.8 ± 20.6	–	24.6 ± 21.7	–	32.5 ± 31.8	–
BeP	35.3 ± 11.5	–	20.0 ± 15.5	–	23.5 ± 31.5	–
BaP ^b	8.3 ± 4.3	8.30	1.6 ± 2.1	1.60	5.5 ± 2.3	5.51
IND ^b	1.3 ± 2.1	0.13	3.4 ± 1.2	0.34	1.8 ± 1.0	0.18
DBA ^b	1.7 ± 0.8	1.70	0.6 ± 0.4	0.60	1.1 ± 0.8	1.12
BbC	7.6 ± 1.2	–	0.8 ± 1.3	–	5.1 ± 2.1	–
BghiP	2.1 ± 1.1	0.021	3.7 ± 2.5	0.037	2.4 ± 2.1	0.024
COR	3.4 ± 1.1	–	0.7 ± 1.5	–	2.3 ± 1.6	–
PAH (sum of 21 forms)	625–4620 (1530)	–	272–1510 (759)	–	547–3680 (1030)	–
Total BaP _{eq}	–	17.0	–	7.29	–	12.6

– No available TEFs.

^a Sample numbers.

^b These compounds are classified as possible or probable human carcinogens by the IARC.

PAH concentrations was 4620, 1510 and 3680 ng/m³, for IND, BACK and URB, respectively. The sampling period was consistent with the highest PM₁₀ concentrations mentioned above due to the temperature inversion. Extremely high PAH concentrations were all found in three different sites (Table 5). Two to three ringed PAHs were dominant in all sampling environments and occupied about 75% of the 21 PAH concentrations.

Table 5 indicates the toxic equivalency concentrations of the gaseous PAHs in different environments (IND, BACK and URB) as mated from BaP equivalents. About half of the total carcinogenic activity in IND and URB was dominated by BaP, which supplied 48.9% and 43.7% of the carcinogenic activity, respectively. The highest BaP equivalent compound in the BACK site was BaA, not BaP (Table 5), which supplied 21.9% of the total carcinogenic activity. Georgiadis and Kyrtopoulos (1999) found that the range of airborne PAH exposure in biomarker-based studies varied by several orders of magnitude. They found total PAH concentrations of <20, 20–200 and 100–1000 ng/m³ for rural, urban and workplace environments, respectively. They found BaP concentrations <5, 5–50 and 100 ng/m³ for rural, urban and workspace sites, respectively. Tsai *et al.* (2001b) examined a factory in a Taiwan industrial park to find the total gaseous PAHs and BaP concentrations of 1401 and 29.8 ng/m³, respectively. Petry *et al.*

(1996) found the total BaP equivalency was about 11 857.2, 1812.8, 305.95 and 0.96 ng/m³ for coke plants, anode plants, graphite plants and city environments, respectively. These studies suggest that the high gaseous PAH concentrations and BaP concentrations occurring in the IND site are due to industrial exhausts. The total gaseous PAH concentrations and BaP concentrations of the URB site probably were due to traffic exhaust. Although, the lowest total gaseous and BaP concentrations were found in the BACK site, the major source of PAH probably was the nearby industrial park and road traffic.

The considerable differences in the gaseous PAH profiles (Figure 1) among the three sites (IND, BACK and URB) are clearly reduced when the carcinogenic potency of each PAH is taken into account (Figure 2). The carcinogenic potency of BaP alone ranged from 21.9% to 48.9%. An important surrogate compound for gaseous PAH mixtures in the atmosphere is BaP for the IND and URB sites. However, BaA is the major carcinogenic compound in the BACK site. Other carcinogenic PAHs, such as DBA, BbF and BkF, which dominate various PAH mixtures, play only a minor role in the three sampling sites. Thus, the carcinogenic potency of the PAH mixtures can be represented by BaP concentration alone. This result is consistent with the findings of Petry *et al.* (1996).

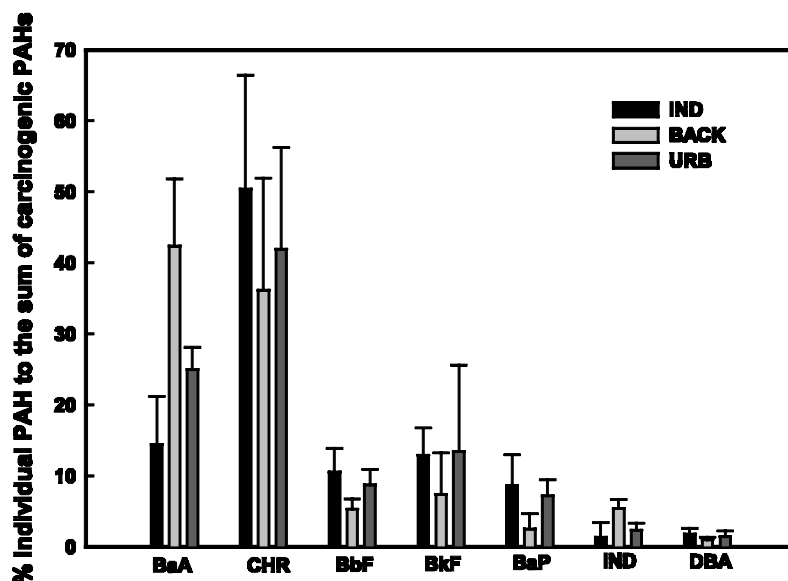


Figure 1. Percentage of the individual carcinogenic gaseous PAHs at the different environments to the total carcinogenic PAHs

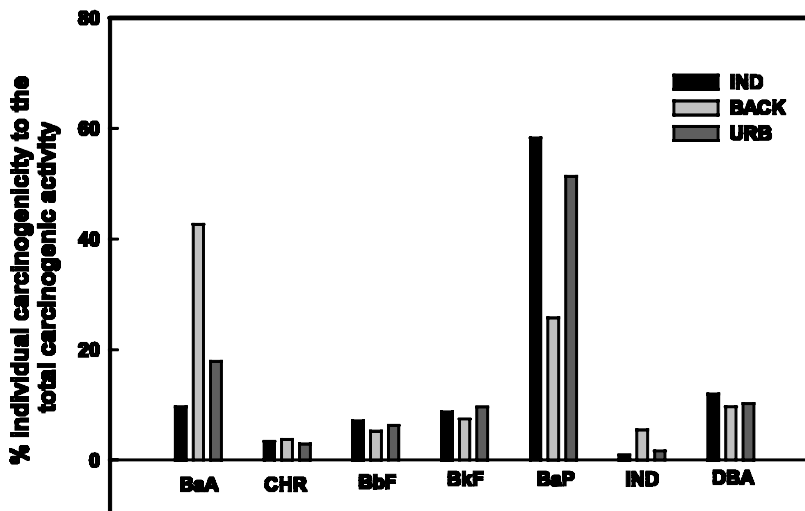


Figure 2. Relative contribution in carcinogenic activity of the individual gaseous PAHs at the different environments to the total carcinogenic potential PAHs

Particle-bound PAHs in ambient air

The comparison of the particle-bound concentration of individual PAHs and carcinogenic PAHs with BaP as well as with the sum of individual PAHs for the three sampling sites (IND, BACK and URB) are shown in Table 6. The 21 particle-bound PAHs concentrations of the IND site ranged from 65.2 to 341 ng/m³ (average of 118 ng/m³), and was higher than the BACK and URB sites, which averaged 75.3 ng/m³ and 115 ng/m³, respectively. In all three sites, the particle-bound PAHs concentrations were only a tenth the magnitude of the gaseous PAH concentrations, because of the lower concentrations of two- and three-ring PAHs. The 21 particle-bound PAHs concentrations for PM₁₀ and PM_{2.5} contributed 65.0% and 31.9%, respectively, of the total suspended particles in the URB site. Therefore, about a third the total suspended carcinogenic particles were small enough to pass through the human respiration system and caused serious health problems.

Particle-bound BaP concentrations contributed only 16.5%, 16.7% and 19.7% to the total carcinogenic activity in the IND, BACK and URB sampling sites, respectively. Figures 3 and 4 show the relative carcinogenic concentrations of PAHs and BaP equivalencies in the three sites. DBA was the most important compound in all sampling sites. These results were different from the gaseous PAH mixtures. BaP had the second highest concentration

in all sampling sites. Thus, DBA and BaP compounds may be used to identify the presence of carcinogenic activity for particle-bound PAHs in central Taiwan.

Comparison of BaP concentration with other studies

The particle phase and total (particle+gas phases) BaP concentrations in different countries and different sampling sites are in Table 7. The average BaP particle phase concentration in the URB site was 2.5 ng/m³. This is comparable with values obtained in Korea (Park *et al.*, 2002). The BaP concentration at the IND site was 2.7 ng/m³; the same as the finding of Caricchia *et al.* (1999). For the BACK site, the BaP particulate concentration was 1.5 ng/m³; an average higher than that found by Caricchia *et al.* (1999) and Omar *et al.* (2002). The high values at the BACK site were probably due to that the emissions of vehicles on the nearby road and incinerators in the adjacent industrial park.

Table 7 also shows the total (particle+gas phase) BaP concentration compared with other studies. The BaP concentration at the URB site was 6.4 ng/m³, which was higher than that found in previous studies (Li and Ro, 2000; Lee *et al.*, 2001; Park *et al.*, 2002). This higher BaP concentration was probably due to the nearby traffic. In the IND site, the average BaP concentration was 9.0 ng/m³, which was lower than another industrial factory

Table 6. Particle-bound concentrations and TEFs of 21 particle-bound PAHs (ng/m³).

Compounds	IND		BACK		URB			TSP BaP _{eq}
	Particle phase	TEFs BaP _{eq}	Particle phase	TEFs BaP _{eq}	Particle phase			
					TSP	PM ₁₀	PM _{2.5}	
Nap	7.8±11.2	0.0078	0.9±2.3	0.0009	10.2±12.5	6.6±10.3	3.3±5.2	0.0102
AcPy	7.1±6.3	0.0071	3.3±3.1	0.0033	8.3±6.6	5.4±4.9	2.6±4.8	0.0083
Acp	6.2±8.1	0.0062	1.1±0.9	0.0011	6.1±6.1	4.0±3.3	2.0±1.7	0.0061
Flu	9.8±13.1	0.0098	3.4±3.1	0.0034	9.9±8.1	6.4±5.1	3.2±1.6	0.0099
PA	4.2±5.1	0.0042	1.9±2.2	0.0019	3.2±2.2	2.1±2.3	1.0±1.4	0.0032
Ant	5.6±6.2	0.056	0.9±1.8	0.009	4.1±3.1	2.7±2.8	1.3±1.9	0.041
FL	3.9±4.2	0.0039	4.7±3.6	0.0047	5.2±1.9	3.4±1.1	1.7±3.1	0.0052
Pyr	1.7±2.3	0.0017	0.7±1.3	0.0007	1.2±0.4	0.8±0.2	0.4±0.5	0.0012
CYC	2.0±2.3	– ^a	2.6±3.5	–	1.5±0.9	1.0±0.4	0.5±0.4	–
BaA ^b	0.4±1.6	0.04	1.8±2.2	0.18	1.1±2.1	0.7±0.3	0.4±0.6	0.11
CHR ^b	2.4±3.5	0.024	3.6±2.5	0.036	2.1±1.9	1.4±1.1	0.7±0.4	0.021
BbF ^b	2.7±3.5	0.27	1.9±2.6	0.19	2.4±3.2	1.6±2.1	0.8±0.6	0.24
BkF ^b	2.1±5.2	0.21	3.3±4.1	0.33	2.3±3.8	1.5±2.0	0.7±0.6	0.23
PER	23.3±18.8	–	10.9±8.8	–	21.5±10.3	14.0±5.1	6.9±3.3	–
BeP	6.9±7.8	–	4.9±2.1	–	7.8±6.6	5.1±2.3	2.5±3.1	–
BaP ^b	0.7±2.1	0.7	1.5±0.9	1.5	0.9±1.3	1.6±1.2	0.8±0.6	2.5
IND ^b	2.6±2.5	0.26	1.9±0.6	0.19	2.4±3.2	1.6±1.1	0.8±0.6	0.24
DBA ^b	2.6±3.3	2.6	6.5±3.1	6.5	1.8±2.1	1.2±0.8	0.6±0.5	1.8
BbC	10.5±8.2	–	8.0±3.3	–	8.5±3.5	5.5±1.2	2.7±1.3	–
BghiP	4.6±3.2	0.046	2.0±1.0	0.02	3.1±3.0	2.0±0.9	1.0±1.0	0.031
COR	10.8±12.2	–	9.6±4.5	–	9.7±8.1	6.3±3.5	3.1±2.2	–
PAH (sum of 21 forms)	117.9	–	75.3	–	113.3	74.7	36.7	–
Total BaP _{eq}	–	4.24	–	8.97	–	–	–	3.66

– No available TEFs.

^a Sample numbers.

^b These compounds are classified as possible or probable human carcinogens by the IARC.

site (Yang *et al.*, 2002). Yang *et al.* (2002) analysed the BaP concentration within an industrial factory, but we measured the BaP concentration in the ambient air of an industrial park.

Conclusions

We focused on the TEFs exposure profiles of PAHs in three different environments (industrial, back-

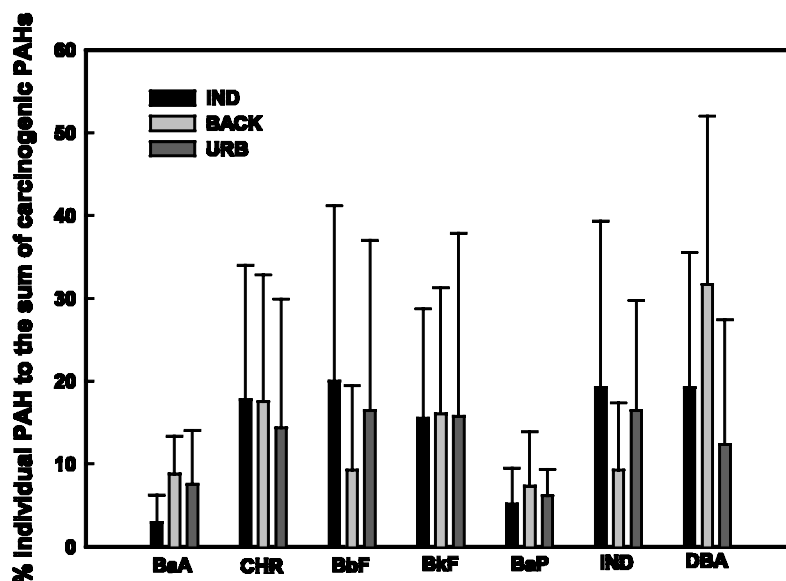


Figure 3. Percentage of the individual carcinogenic particle-bound PAHs at the different environments to the total carcinogenic PAHs

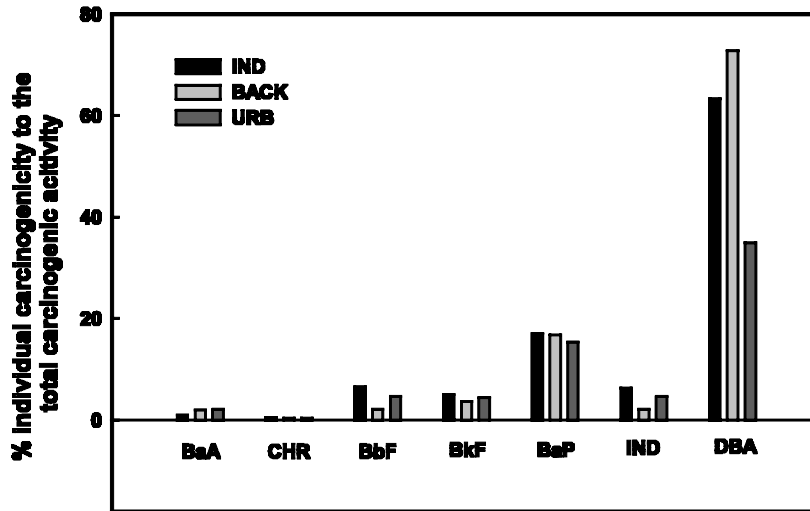


Figure 4. Relative contribution in carcinogenic activity of the individual particle-bound PAHs at the different environments to the total carcinogenic potential PAHs

Table 7. Comparison of BaP concentrations in ambient air particle and gas in the world.

References	Location	BaP concentration (ng/m ³)
Ambient air PAHs in particles		
Caricchia <i>et al.</i> (1999)	Residential	0.9 (0.03–3.8)
	Traffic	3.0 (0.19–6.9)
	Industrial	2.8 (0.1–12.3)
Omar <i>et al.</i> (2002)	Urban	0.5
	Rural	0.05
Park <i>et al.</i> (2002)	Urban	2.6
This study (2002)	IND	2.7
	BACK	1.5
	URB	2.5
Ambient air total PAHs in gas-phase and particle-bound		
Li and Ro (2000)	Urban	1.7 ± 2.4
Yang <i>et al.</i> (2002)	Steel and iron plants	0.38 ± 110
Lin <i>et al.</i> (2002)	Temple	102.1 (71.5–124.2)
	Suburban	10.3
	Urban	–
Park <i>et al.</i> (2002)	Urban	2.6 ± 3.3
Lee <i>et al.</i> (2001)	Urban	0.49 (0.05–1.34)
This study (2002)	IND	9.0
	BACK	3.0
	URB	6.4

7.29 and 12.6 ng/m³ for IND, BACK and URB, respectively. For gaseous PAHs in central Taiwan, carcinogenic activity can be explained by individual BaP concentrations, because they represent a high proportion of the total carcinogenicity. The 21 particle-bound PAHs concentrations were 118, 75.3 and 115 ng/m³ for IND, BACK and URB, respectively. They contributed about 10% of the 21 gaseous PAHs. For carcinogenic activity of particle-bound PAHs, the BaP equivalent concentrations were 4.24, 8.97 and 4.56 ng/m³ for IND, BACK and URB, respectively. The contribution of DBA concentration to the total carcinogenic activity in three sampling sites suggests that DBA could serve as a surrogate compound to measure particle phase PAHs mixtures. During the December 2002 sampling period, a temperature inversion due to a cold front from China yielded an average daily temperature of 16°C, causing atmospheric particles and pollutants to accumulate in the troposphere, resulting in extremely high concentrations of airborne particles, both gaseous and particle-bound PAHs.

ground and urban) in central Taiwan. The airborne particle concentrations were 93.4, 81.3 and 102.4 µg/m³ for IND, BACK and URB, respectively. The 21 gaseous PAHs concentrations were 1530, 758 and 1030 ng/m³ for IND, BACK and URB, respectively; for carcinogenic activity of gaseous PAHs, the BaP equivalent concentrations were 17.0,

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