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*Br J Sports Med* 2010 44: 731-735 originally published online December 2, 2008

doi: 10.1136/bjasm.2008.051888

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# Volatile organic compounds in runners near a roadway: increased blood levels after short-duration exercise

C Blair,<sup>1</sup> J Walls,<sup>2</sup> N W Davies,<sup>3</sup> G A Jacobson<sup>1</sup>

<sup>1</sup> School of Pharmacy, University of Tasmania, Hobart, Tasmania, Australia

<sup>2</sup> School of Medicine, University of Tasmania, Hobart, Tasmania, Australia

<sup>3</sup> Central Science Laboratory, University of Tasmania, Hobart, Tasmania, Australia

## Correspondence to

Dr G A Jacobson, School of Pharmacy, University of Tasmania, Private Bag 26, Hobart, Tasmania 7001, Australia; [glenn.jacobson@utas.edu.au](mailto:glenn.jacobson@utas.edu.au)

Accepted 11 November 2008  
Published Online First  
2 December 2008

## ABSTRACT

**Objective** To determine if non-elite athletes undertaking short duration running exercise adjacent to a busy roadway experience increased blood levels of common pollutant volatile organic compounds (benzene, toluene, ethylbenzene and xylene (BTEX)).

**Design and setting** The study was observational in design. Participants (nine males/one female non-elite athletes) ran for 20 min, near a busy roadway along a 100 m defined course at their own pace. Blood levels of BTEX were determined both pre- and post-exercise by SPME-GC-MS. Environmental BTEX levels were determined by passive adsorption samplers.

**Results** Subjects completed a mean (range) distance of 4.4 (3.4 to 5.2) km over 20 min (4.5 (3.8 to 5.9) min/km pace), with a mean (SD) exercise intensity of 93 (2.3)% HR<sub>max</sub>, and mean (SD) ventilation significantly elevated compared with resting levels (86.2 (2.3) vs 8.7 (0.9) l/min;  $p < 0.001$ ). The mean (SD) environmental levels (time weighted average) were determined as 53.1 (4.2), 428 (83), and 80.0 (3.7)  $\mu\text{g}/\text{m}^3$  for toluene, ethylbenzene and xylenes, respectively, while benzene was below the detectable limit due to the short exposure period. Significant increases in blood BTEX levels were observed in runners between pre- and postexercise for toluene (mean increase of 1.4 ng/ml;  $p = 0.002$ ), ethylbenzene (0.7 ng/ml;  $p = 0.0003$ ), *m/p*-xylene (2.0 ng/ml;  $p = 0.004$ ) and *o*-xylene (1.1 ng/ml;  $p = 0.002$ ), but no change was observed for benzene.

**Conclusions** Blood BTEX levels are increased during high-intensity exercise such as running undertaken in areas with BTEX pollution, even with a short duration of exercise. This may have health implications for runners who regularly exercise near roadways.

Benzene, toluene, ethylbenzene and xylene (BTEX) are volatile organic compounds (VOCs) commonly found in crude petroleum and petroleum products such as petrol. The main sources of urban VOC pollution are road transport, industrial sources, wood smoke and landfill sites.<sup>1-5</sup> Individuals are also exposed to VOCs indoors at levels often exceeding health benchmarks for outdoor exposure,<sup>6,7</sup> with smoking a particular risk.<sup>8</sup> Typical daily exposure has been reported with geometric means in the order of 0.80, 2.8, 0.5 and 2.4  $\mu\text{g}/\text{m}^3$  for benzene, toluene, ethylbenzene and xylenes, respectively, but there is a large variation in these figures with ranges of up to 23.8, 2120, 119 and 697  $\mu\text{g}/\text{m}^3$ , respectively, in a sample of 204 subjects from a cross-sectional study in non-occupationally exposed non-smokers.<sup>9</sup>

Exposure to VOC air pollution points to an elevated risk of developing chronic respiratory illness.<sup>10,11</sup> It is possible that endurance athletes may have a greater than average exposure and uptake of air pollutants due to exercise induced increases in ventilation and capillary blood volume.<sup>12,13</sup>

To date, several studies have been undertaken to evaluate the exposure to BTEX in on-road cyclists focusing on ambient air concentrations.<sup>14-18</sup> Increases in blood BTEX levels postexercise compared with baseline levels have been reported, even at low exposure levels.<sup>15,16</sup> Although exposure levels have been reported to be lower in cyclists compared with other modes of commuter transport such as bus transport, when taking into account respiration rate and travel times, inhaled weights of pollutants have the potential to be higher.<sup>14,18</sup>

There is a surprising paucity of data on uptake of BTEX in runners, despite runners often running in close proximity to traffic along pedestrian routes. The main objective of this study was to determine if environmental respiratory exposure in exercising non-elite athletes in the field increases blood BTEX levels by using an established method of headspace solid-phase microextraction gas chromatography-mass spectrometry (SPME-GC-MS) for determination. Ventilation parameters were determined from a follow-up laboratory-based exercise protocol. This protocol replicated each individual workload recorded during the field test and enabled average respiratory rate and volume to be determined for the test duration.

## METHODS

### Study design

The study was observational in design with the primary outcome measures of blood BTEX concentration and environmental levels of BTEX. Participants ran for 20 min, near a busy roadway out and back along a 100 m defined course at their own pace ( $>12$  km/h). Observers were matched for each runner, positioned along the running route, and assisted in recording data in the exercising phase. The experiment start time was staggered so that participants began every 5 min. This study was approved by the Tasmania Health & Medical Human Research Ethics Committee in accordance with the standards laid down in the 1964 Declaration of Helsinki.

### Subjects

Study participants (one female and nine males aged 18-26) were regularly exercising non-elite athletes and were capable of running 5 km in less

than 25 min. The volunteers were not occupationally exposed to VOCs and were required to avoid exposure to petrol fumes (ie, filling cars with petrol) or cigarette smoke in the 48 h prior to the study. Subjects were recruited from the University of Tasmania undergraduate population by word of mouth.

### Study site and environmental conditions

The study was carried out at the Risdon Road intersection in Hobart, Tasmania (42°51'03.92" S, 147°18'49.00" E) during evening peak hour traffic (17:00 to 19:00) beside a four-lane dual carriageway. The site was chosen because of the proximity of a safe running route to a busy roadway (a source of VOCs). Typical winter meteorological conditions produce the highest levels of VOCs in the ambient air,<sup>19</sup> but adverse weather conditions delayed the field experiment until September (early spring, southern hemisphere). During the field experiment, site conditions were sampled at 15 min intervals during evening peak hour traffic between 17:00 and 19:00. Wind speed, temperature and relative humidity were measured using a combined anemometer, thermometer and hygrometer (Kestrel 3000, Nielsen-Kellerman, Chester, Pennsylvania). Traffic data were obtained from the Transport Infrastructure Branch of the Department of Infrastructure, Energy and Resources in Hobart, Tasmania.

### BTEX air monitoring

The ambient levels of VOCs along the running route were monitored using activated charcoal radial diffusion passive air samplers (Radiello, Sigma-Aldrich, Sydney) to assess time-weighted average (TWA) concentrations of VOCs. Three Radiello samplers were placed at equal distances (start, middle and end) along the course 2 m above the ground and approximately 15 m from the side of the roadway. Two Radiello samplers were attached to runners as they completed the field study. Two unexposed control samplers were also brought to the field site.

After the end of exposure period, the Radiello tubes were stored in sealed glass vials until analysis. The passive sampling gas badges were analysed by thermal desorption methods with a detection limit of 6 µg/m<sup>3</sup> of air over the study period in accordance with USEPA method TO-17 VOCs. This analysis was conducted by Leeder Consulting Pty (Mitcham, Australia), a NATA (National Association of Testing Authorities; Silverwater, Australia) accredited laboratory.

### Plasma BTEX

Prior to the exercise phase, all participants had approximately 5 ml of venous blood taken to determine the baseline concentrations of VOCs in their blood. Subjects were seated at the time of collection, and blood was collected in sterile heparinised BD Vacutainer tubes. After the exercise phase was complete, all participants had a second 5 ml blood sample taken. Blood samples contained in the heparinised BD Vacutainer tubes were stored in ice in the field, and then transferred to -30°C storage before analysis. Analysis of the VOC concentration in blood was undertaken at the Central Science Laboratory at the University of Tasmania using a solid-phase microextraction gas chromatography-mass spectrometry (SPME GC-MS) method.

In brief, 1 ml of blood sample was quantitatively transferred into a 7 ml glass vial using a micropipette and capped with a Teflon-lined silicon septum. Twenty microlitres of a methanolic solution containing deuterated standards (0.25 µg/ml D10-ethylbenzene, D6-benzene, D10-oxylen and D8-toluene internal

standard; Sigma-Aldrich) was added to the phial with a micropipette. Vials were heated to 50°C and stirred on a combination hotplate/stirrer. BTEX analytes were adsorbed onto a 100 µm polydimethylsiloxane SPME syringe needle (Supelco, Sigma-Aldrich), and the fibre extraction was carried out for 12 min. The fibre was then removed from the phial and immediately inserted into the GC-SPME injector port for 3 min. GC-MS analyses were undertaken using a Varian 3800 GC connected to a Varian 1200 triple quadrupole MS operated in selected ion-monitoring (SIM) mode with a 30 m×0.25 mm internal diameter 0.25 µm film VF5-ms (Varian) column. Quantitation was based on the peak area response of the analyte to the known level of internal standard over the linear calibration range 0.5–5 ng/ml with calibration tolerance to 7.5 ng/ml (150%).

### Respiratory parameters

Participants were fitted with a wireless heart-rate monitor (Polar Vantage NV, Kempele, Finland), and their heart rates were recorded each time they passed an observer on each lap throughout the experiment. Heart rate was monitored to allow estimation of the ventilation in the field experiment by replicating the heart rate and average speed in the laboratory-based exercise protocol where ventilation could be measured accurately without interfering with the individual ventilatory pattern. Estimates of exercise intensity were also made using heart rate as a percentage of maximum heart rate (HR<sub>max</sub>) where HR<sub>max</sub> was estimated using the formula HR<sub>max</sub> = 220 – age.<sup>20</sup>

One week after the completion of the field experiment, the participants had their respiratory parameters measured in the Physiology Laboratory at the University of Tasmania. Respiratory parameters were measured during a treadmill exercise set at an intensity that elicited the recorded heart rates measured during the field trial. This allowed for an estimation of the volume of air the subject inhaled during the field trial part of the study.

Each participant was fitted with a heart rate monitor (Polar Vantage NV) and began warming up by performing a 5 min walk on the treadmill. The speed of the treadmill was increased every 30 s over approximately 10 min to bring the subject's average heart rate up to a similar average steady-state heart rate and running pace as was observed from the field experiment. While continuing to run, subjects were fitted with a nose plug and breathed for 1 minute into a 100 l Douglas collection bag through a non-rebreathing valve. The amount of air expired was measured by withdrawing the air from the bag through a 3 l calibrated syringe. The subject was kept at a steady-state heart rate, and the procedure was repeated in duplicate. Comparisons were made with resting levels.

### Statistical analysis

Differences between pre- and post-exercise individual BTEX levels were assessed using a two-tailed paired Student t test. Differences in respiratory intake between exercise and rest were assessed by a two-tailed unpaired t test. Results with *p* < 0.05 were considered statistically significant.

## RESULTS

### Subjects

Nine runners (nine males, one female) were enrolled in the trial with a mean (SD) age of 21.1 years and covered a mean (range) distance of 4.4 (3.4 to 5.2) km over 20 min equivalent to a pace of 4.5(3.8 to 5.9) min/km.

### Environmental conditions

The mean (SD) wind velocity at 2 m height was 10.2 (2.4) km/h and remained relatively constant throughout the field experiment. The temperature was 20.0°C at the onset of the field experiment (17:00) and decreased to 15.6°C (19:00) by the completion of the field study. The mean (SD) relative humidity was 34.0% (2.2%) and remained relatively constant throughout the field study. The two-way vehicle count during the experiment was 4179 (17:00 to 18:00 h) and 2958 (18:00 to 19:00 h).

### BTEX air monitoring

The results of the BTEX ambient air concentration measurements are given in table 1. The benzene level based on the time period of the study and the ethylbenzene results are semi-quantitative because the analyte was detected at a level above the linear response of calibration curve.

### Blood BTEX

The detection limits of the assay were estimated at 0.5 ng/ml based on a signal:noise ratio of 3. Precision, estimated using the ratio between D8 toluene:D10 ethylbenzene and D10 ethylbenzene:D10 *o*-xylene from all samples, was 6.9% RSD and 4.9% RSD respectively. Accuracy at 0.5 ng/ml was +2.3%, -3.5%, -5.6%, -7.5% and -4.2% for benzene, toluene, ethylbenzene, *m/p*-xylene and *o*-xylene, respectively. A GC-MS chromatogram of an exercising subject is shown in fig 1 containing BTEX and deuterated standards. Chromatographic conditions did not allow resolution of *m*- and *p*-xylene, and these peak areas were combined. The blood BTEX results are shown in table 2. Significant increases in blood BTEX level were observed in runners between pre- and post-exercise for toluene ( $p = 0.002$ ), ethylbenzene ( $p = 0.0003$ ), *m/p*-xylene ( $p = 0.004$ ) and *o*-xylene ( $p = 0.002$ ), but no change was observed for benzene.

### Respiratory parameters

The mean (SD) heart rate (beats per minute) measured during the field experiment was significantly elevated compared with resting values (185.3 (3.2) vs 69.4 (4.5);  $p < 0.001$ ). The average ventilation (l/min) during exercise was significantly elevated (86.2 (2.3) vs 8.7 (0.9);  $p < 0.001$ ). Based on BTEX exposure levels (benzene was not detected), the cumulative inhaled mass over the period of exercise in the field was estimated at 92 µg, 738 µg and 138 µg for toluene, ethylbenzene and xylenes, respectively. The cumulative inhaled mass over the same period at rest was estimated at 9 µg, 74 µg and 14 µg for toluene, ethylbenzene and xylenes, respectively. The mean (SD) exercise intensity (%HR<sub>max</sub>) was estimated at 93(2.3)%.

### DISCUSSION

The BTEX environmental levels detected in this microenvironment were in general agreement with other international

reports of traffic-related emissions. Environmental BTEX levels associated with transport related pollution vary widely and depend on many factors including traffic density and the microenvironment. Recent reports of total BTEX levels in Australia at traffic intersections have been reported at around 6.2–6.5 µg/m<sup>3</sup>,<sup>21</sup> but urban levels have been reported over a wide range of values that may be 10-fold higher or more.<sup>1 15 22 23</sup> The ethylbenzene levels were much higher than expected and could potentially be attributed to several different sources including relaying of an artificial turf playing surface approximately 200 m downwind of the study site, and several small commercial and light industries 1 km upwind including shower screen manufacture, plastics, spray painters and an aluminium supplier. In addition to the BTEX results, the environmental sampling also detected styrene at 1200 µg/m<sup>3</sup> (a semiquantitative result beyond the linear calibration range) and 1,2,4-trimethylbenzene and 1,3,5-trimethylbenzene at 26 and 21 µg/m<sup>3</sup>, respectively.

The blood BTEX results in this current study are higher than those expected based on previously suggested reference values in non-occupationally exposed non-smokers. Reference values have been reported at 0.13 ng/ml, 0.52 ng/ml, 0.11 ng/ml, 0.37 ng/ml and 0.14 ng/ml for benzene, toluene, ethylbenzene, *m/p*-xylene and *o*-xylene, respectively.<sup>24</sup> There are inherent and extensive difficulties associated with low-level VOC determinations,<sup>25</sup> particularly given the field environment and potential for further introduced contamination associated with decontamination and storage of Vacutainer tubes. BTEX are popular solvents, are highly evaporative, are found indoors including the laboratory, and outdoors from a variety of sources, and are found in the blood of non-occupationally exposed individuals at very low levels but above typical detection limits of modern analytical instrumentation. Hence, blank bloods cannot be used for calibration purposes, and other matrices such as water cannot be used, as SPME extraction efficiency varies between matrices. Trace BTEX levels in subjects at baseline may have been raised by environmental contamination, non-disclosed smoking or petrol station exposure, passive smoke, time in doors, car travel, unknown occupational exposure, as well as ethanol consumption.<sup>9 26 27</sup>

The blood toluene, ethylbenzene, *m/p*-xylene and *o*-xylene levels increased over the exercise period for all runners with an average increase of 1.4, 0.7, 2.0 and 1.1 ng/ml, respectively, over the exercise period of 20 min. This result is consistent with previous studies involving cyclists, but these studies were all of considerably longer duration. Both Andreoli *et al*<sup>15</sup> and Bergamaschi *et al*<sup>16</sup> have reported significant increases in benzene and toluene blood levels in cyclists over a 2 h period. From our current study, it appears that even a short duration of exercise has the potential to increase blood BTEX levels.

Van Wijnen *et al*<sup>14</sup> and O'Donoghue *et al*<sup>18</sup> have reported a respiratory intake 2.3–2.5 greater in cyclists than a car driver. In

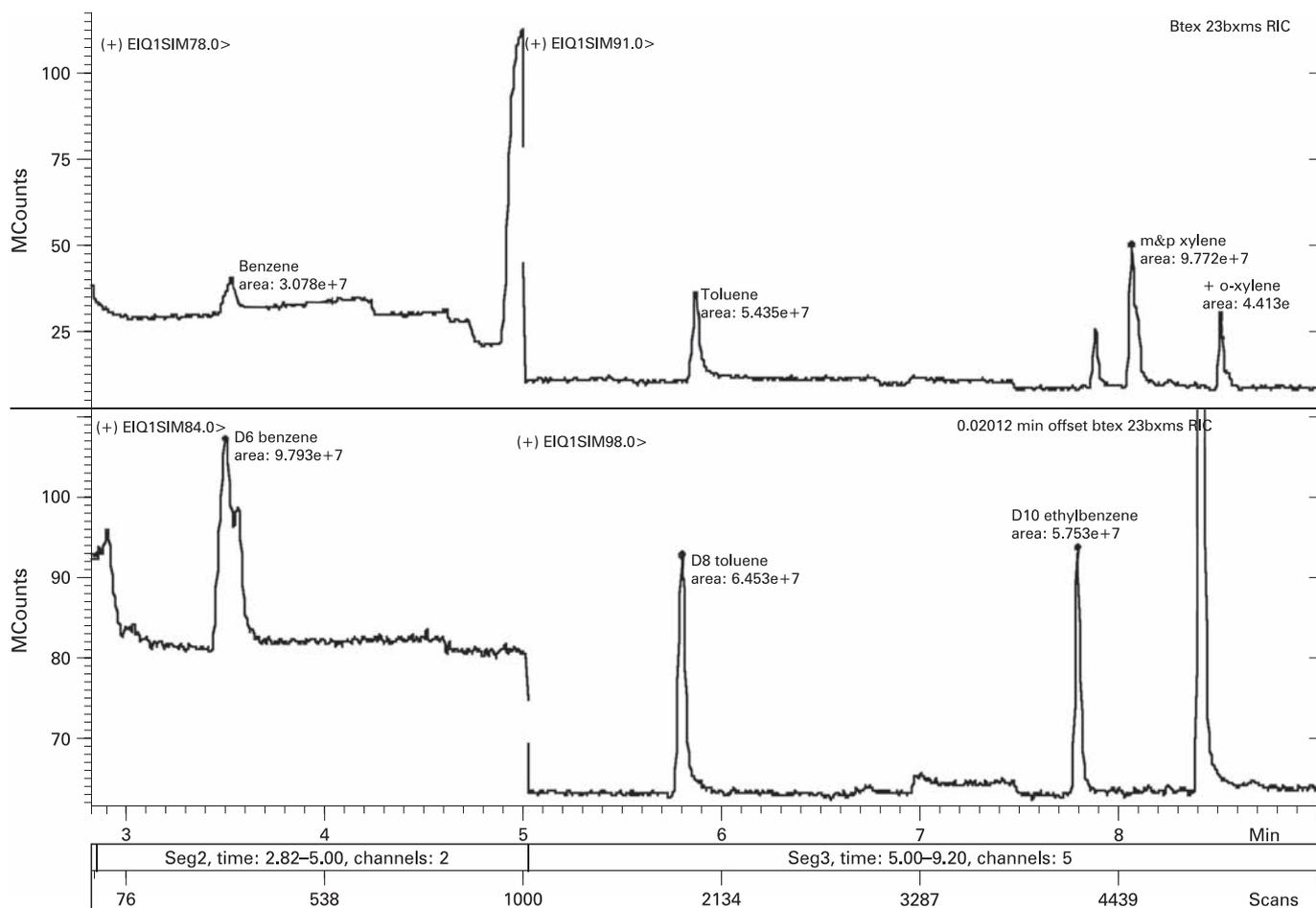
**Table 1** Environmental concentrations of blood benzene, toluene, ethylbenzene and xylene measured by radial diffusion Radiello passive samplers

Aromatic hydrocarbon	Mean (SD) concentrations	Start end of route				
		Middle of route	Distant end of route	Runner 1	Runner 2	
Benzene	ND	ND	ND	ND	ND	ND
Toluene	53.1 (4.2)	52	60	52	53	49
Ethylbenzene*	428 (83)	400	440	440	450	410
Xylenes	80.0 (3.7)	74	83	83	81	79

Mean (SD) time-weighted average (TWA) and individual sampler values during a 120 min period (µg/m<sup>3</sup>).

\*Above the calibration range, and results are semiquantitative.

ND, not detected.



**Figure 1** Solid-phase microextraction gas chromatography–mass spectrometry (SPME-GC-MS) chromatogram of solid-phase microextraction derived blood sample from an exercising subject (upper chromatogram) with benzene at 1.6 ng/ml, toluene at 3.4 ng/ml, ethylbenzene at 2.3 ng/ml, *m/p*-xylene at 8.5 ng/ml and *o*-xylene at 3.8 ng/ml. Deuterated standards are shown in the lower chromatogram.

this current study, runners were found to have an average respiratory intake around 10-fold that of resting respiratory intake, and around fourfold greater than previous reports of cycling. Levels of inhaled mass of BTEX found in this study are much greater than those reported by O'Donoghue *et al* for benzene, 1,3-butadiene, ethylene and acetylene for bike or bus commuter journeys of a similar time.<sup>18</sup>

Although it may seem reasonable to assume that increased ventilation increases the potential for BTEX uptake, this should be interpreted with caution, as increased ventilation also increases the potential for respiratory elimination. BTEX inhalation pharmacokinetics is very complex and follows a four-compartment model with different parameters for each BTEX compound which can be influenced by various mixture

combinations of BTEX.<sup>28–29</sup> Uptake is greatest at the beginning of exposure before levelling off after longer exposures,<sup>30</sup> and hence is most relevant in short, intense exercise as observed in this current study. Exposure to hydrocarbon solvent mixtures in the range of 200–1000 µg/m<sup>3</sup> for 8 h while undertaking physical exercise demonstrated increased blood concentrations compared with controls (1.2 times at 50 W and 1.9 times at 75 W).<sup>31</sup>

Smoking is well known to be associated with increased blood levels of BTEX.<sup>32</sup> Typically there is around 10-fold greater exposure to benzene via cigarette smoke,<sup>33</sup> and blood benzene and toluene levels in smokers have been shown to be around double that in non-smokers.<sup>26</sup> While there was an approximate doubling of blood levels of toluene, ethylbenzene and xylene in this study during short intensive exercise, given the short exposure duration, there is the potential for more rapid elimination than would be expected from chronic inhalation of cigarette smoke. Additionally, it must be remembered that benzene was not observed in the environmental sampling or significantly increased in blood. Based on the environmental levels alone, apart from potential respiratory effects, the risk of other serious health effects due to toluene, ethylbenzene and xylene in this study appears low. The American Conference of Industrial Hygienists recommends a threshold limit value–time-weighted average (TLV-TWA) of 50 ppm for toluene based on subtle neurological impairment, a TLV-TWA of 100 ppm for ethylbenzene based on irritation and central nervous system

**Table 2** Mean (SD) blood benzene, toluene, ethylbenzene and xylene concentrations (ng/ml) in runners pre- and postexercise

	Subjects		Concentration change
	Pre-exercise	Postexercise	
Benzene	1.4 (0.3)	1.5 (0.5)	+0.1
Toluene	1.4 (0.7)	2.8 (0.9)	+1.4*
Ethylbenzene	1.2 (0.4)	1.9 (0.4)	+0.7*
<i>m/p</i> -Xylene	3.5 (1.1)	5.5 (1.6)	+2.0*
<i>o</i> -Xylene	1.6 (0.6)	2.7 (0.7)	+1.1*

\**p*<0.05.

## What is already known on this topic

- ▶ Volatile organic compounds (VOCs) including benzene, toluene, ethylbenzene and xylene (BTEX) are common atmospheric pollutants from road transport and industrial sources.
- ▶ VOCs can be taken up into the body via inhalation, and increased exposure has been associated with an increased risk of chronic respiratory illness.

## What this study adds

- ▶ High-intensity exercise of short duration (20 min) undertaken in areas with high levels of environmental BTEX, such as running near roadways, can lead to measurable increases in blood levels of BTEX.
- ▶ Regular, intense exercise near busy roadways may potentially have respiratory health implications and warrants further study.

effects and a TLV-TWA of 100 ppm for xylene isomers (*o*-, *m*-, *p*-) based on irritation to the respiratory tract, eyes and skin.<sup>34</sup> Toluene, ethylbenzene and xylene are not listed as known or anticipated human carcinogens by the US National Toxicology Program,<sup>35</sup> but ethylbenzene is listed by the International Agency for Research on Cancer (IARC) as a possible human carcinogen based on evidence in animals.<sup>36</sup> This is in stark contrast to benzene with a TLV-TWA of 0.5 ppm and classification as a carcinogen in humans.<sup>34 35</sup>

In conclusion, high-intensity roadside running, although of short duration, has the potential to expose runners to relatively high amounts of BTEX mass which can be observed in increased blood concentrations. This may have health implications for runners who regularly exercise near roadways.

**Acknowledgements** M Russell, School of Geography and Environmental Studies at the University of Tasmania, for equipment and advice on environmental monitoring; J Fell, School of Human Life Sciences at the University of Tasmania, for providing heart rate monitors; B Howell and R Dyer, Transport Infrastructure Branch of the Department of Infrastructure Energy and Resources, for providing traffic data; E Peacock (Central Science Laboratory, University of Tasmania) and P Harvey (Australian Antarctic Division), for providing deuterated BTEX samples; L Tyrell and N Young, for blood sample collection.

**Funding** This project was funded by the School of Pharmacy Research Committee.

**Competing interests** None.

**Ethics approval** Ethics approval was provided by Tasmanian Health and Medical Research Ethics Committee.

**Patient consent** Obtained.

## REFERENCES

1. **Fernandez-Villarreal V**, Lopez-Mahia P, Muniategui-Lorenzo S, *et al*. C1 to C9 volatile organic compound measurements in urban air. *Sci Total Environ* 2004;**334**:5:167–76.
2. **Kwon J**, Weisel CP, Turpin BJ, *et al*. Source proximity and outdoor-residential VOC concentrations: results from the RIOPA study. *Environ Sci Technol* 2006;**40**:4074–82.
3. **Conley FL**, Thomas RL, Wilson BL. Measurement of volatile organic compounds in the urban atmosphere of Harris County, Texas, USA. *J Environ Sci Health A Tox Hazard Subst Environ Eng* 2005;**40**:1689–99.
4. **Hellen H**, Hakola H, Haaparanta S, *et al*. Influence of residential wood combustion on local air quality. *Sci Total Environ* 2008;**393**:283–90.
5. **Kim KH**, Baek SO, Choi YJ, *et al*. The emissions of major aromatic VOC as landfill gas from urban landfill sites in Korea. *Environ Monit Assess* 2006;**118**:407–22.
6. **Adgate JL**, Church TR, Ryan AD, *et al*. Outdoor, indoor, and personal exposure to VOCs in children. *Environ Health Perspect* 2004;**112**:1386–92.
7. **Kim YM**, Harrad S, Harrison RM. Concentrations and sources of VOCs in urban domestic and public microenvironments. *Environ Sci Technol* 2001;**35**:997–1004.
8. **Lin YS**, Egeghy PP, Rappaport SM. Relationships between levels of volatile organic compounds in air and blood from the general population. *J Expo Sci Environ Epidemiol* 2008;**18**:421–9.
9. **Hinwood AL**, Rodriguez C, Runnion T, *et al*. Risk factors for increased BTEX exposure in four Australian cities. *Chemosphere* 2007;**66**:533–41.
10. **Rumchev K**, Spickett J, Bulsara M, *et al*. Association of domestic exposure to volatile organic compounds with asthma in young children. *Thorax* 2004;**59**:746–51.
11. **Ware JH**, Spengler JD, Neas LM, *et al*. Respiratory and irritant health effects of ambient volatile organic compounds. The Kanawha County Health Study. *Am J Epidemiol* 1993;**137**:1287–301.
12. **Fisher JT**, Cerny FJ. Characteristics of adjustment of lung diffusing capacity to work. *J Appl Physiol* 1982;**52**:1124–7.
13. **Stokes DL**, MacIntyre NR, Nadel JA. Nonlinear increases in diffusing capacity during exercise by seated and supine subjects. *J Appl Physiol* 1981;**51**:858–63.
14. **van Wijnen JH**, Verhoeff AP, Jans HW, *et al*. The exposure of cyclists, car drivers and pedestrians to traffic-related air pollutants. *Int Arch Occup Environ Health* 1995;**67**:187–93.
15. **Andreoli R**, Manini P, Bergamaschi E, *et al*. Solid-phase microextraction and gas chromatography-mass spectrometry for determination of monoaromatic hydrocarbons in blood and urine: application to people exposed to air pollutants. *Chromatographia* 1999;**50**:168–72.
16. **Bergamaschi E**, Brustolin A, De Palma G, *et al*. Biomarkers of dose and susceptibility in cyclists exposed to monoaromatic hydrocarbons. *Toxicol Lett* 1999;**108**:241–7.
17. **Rank J**, Folke J, Jespersen PH. Differences in cyclists and car drivers exposure to air pollution from traffic in the city of Copenhagen. *Sci Total Environ* 2001;**279**:131–6.
18. **O'Donoghue RT**, Gill LW, McKeivitt RJ, *et al*. Exposure to hydrocarbon concentrations while commuting or exercising in Dublin. *Environ Int* 2007;**33**:1–8.
19. **Chung CW**, Morandi MT, Stock TH, *et al*. Evaluation of a passive sampler for volatile organic compounds at ppb concentrations, varying temperatures, and humidities with 24-h exposures. 2. Sampler performance. *Environ Sci Tech* 1999;**33**:3666.
20. **Antonacci L**, Mortimer LF, Rodrigues VM, *et al*. Competition, estimated, and test maximum heart rate. *J Sports Med Phys Fitness* 2007;**47**:418–21.
21. **Hinwood AL**, Berko HN, Farrar D, *et al*. Volatile organic compounds in selected micro-environments. *Chemosphere* 2006;**63**:421–9.
22. **Iovino P**, Salvestrini S, Capasso S. Background atmospheric levels of aldehydes, BTEX and PM10 pollutants in a medium-sized city of southern Italy. *Ann Chim* 2007;**97**:597–604.
23. **Deole S**, Phadke KM, Kumar A. Benzene, toluene and xylene (BTX) pollution in ambient air: a case study. *J Environ Sci Eng* 2004;**46**:15–20.
24. **Ashley DL**, Bonin MA, Cardinali FL, *et al*. Blood concentrations of volatile organic compounds in a nonoccupationally exposed US population and in groups with suspected exposure. *Clin Chem* 1994;**40**:1401–4.
25. **Ashley DL**, Bonin MA, Cardinali FL, *et al*. Measurement of volatile organic compounds in human blood. *Environ Health Perspect* 1996;**104**(5 Suppl):871–7.
26. **Hajmiragha H**, Ewers U, Brockhaus A, *et al*. Levels of benzene and other volatile aromatic compounds in the blood of non-smokers and smokers. *Int Arch Occup Environ Health* 1989;**61**:513–18.
27. **Wallen M**, Naslund PH, Nordqvist MB. The effects of ethanol on the kinetics of toluene in man. *Toxicol Appl Pharmacol* 1984;**76**:414–19.
28. **Dennison JE**, Andersen ME, Yang RS. Characterization of the pharmacokinetics of gasoline using PBPK modeling with a complex mixtures chemical lumping approach. *Inhal Toxicol* 2003;**15**:961–86.
29. **Tardif R**, Plaa GL, Brodeur J. Influence of various mixtures of inhaled toluene and xylene on the biological monitoring of exposure to these solvents in rats. *Can J Physiol Pharmacol* 1992;**70**:385–93.
30. **Wallace L**, Buckley T, Pellizzari E, *et al*. Breath measurements as volatile organic compound biomarkers. *Environ Health Perspect* 1996;**104**(5 Suppl):861–9.
31. **Zimmer H**, Uhlich H, Knecht U, *et al*. Biological monitoring of experimental human exposure to hydrocarbon solvent mixtures. *Toxicol Lett* 2006;**162**:263–9.
32. **Churchill JE**, Ashley DL, Kaye WE. Recent chemical exposures and blood volatile organic compound levels in a large population-based sample. *Arch Environ Health* 2001;**56**:157–66.
33. **Wallace L**, Pellizzari E, Hartwell TD, *et al*. Exposures to benzene and other volatile compounds from active and passive smoking. *Arch Environ Health* 1987;**42**:272–9.
34. **ACGIH**. *Threshold limit values for chemical substances and physical agents and biological exposure indices*. Cincinnati, Ohio, USA: American Conference of Governmental Industrial Hygienists; 2001.
35. **NTP**. *United States Department of Health and Human Services, Public Health Service, National Toxicology Program*. Research Triangle Park, North Carolina, USA: National Institute of Environmental Health Sciences; 2001.
36. **IARC**. International Agency for Research on Cancer. IARC monographs on the evaluation of carcinogenic risks to humans. *Ethylbenzene* 2000;**77**:227–66.