Benzene Exposure During Tunnelling—Using Biological Monitoring to Assess Control Measures and Working Practice

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This paper reports the assessment of worker exposure to high levels of benzene (up to 18 p.p.m. 8 h time weighted average, weekly average) during tunnelling on a contaminated land site (former gas works). Although respiratory and personal protection was used, biological monitoring results indicated that workers had urinary S-phenylmercapturic acid levels in excess of that expected following exposure to the UK workplace exposure limit. Factors such as environmental conditions (high temperature and humidity, confined workspace), respiratory and personal equipment providing insufficient protection, human behaviour (removing protective equipment, using mobile phones), and work practices (12-h shifts, too few and too short breaks, lack of drinking water) were identified as contributing to the exposure. A thorough review of control measures and working practice led to significant improvements, resulting in workers’ exposure (as measured by biological monitoring) being kept below the 90th percentile value (8 μmol mol⁻¹ creatinine, 17 μg g⁻¹ creatinine) of data from a good cross section of UK industry (N = 2600) despite the continuing high environmental levels.

Keywords: behaviour; benzene; biological monitoring; contaminated land; personal protective equipment; PPE; S-PMA; tunnelling

INTRODUCTION

The Belfast Sewers Project is a multimillion pound investment to improve and upgrade the wastewater and sewers infrastructure in the city of Belfast. The existing network of 1300 km of sewers was built in Victorian times and is in urgent need of repair and/or replacement. The work is in two parts, the Sewer Rehabilitation Works (which will upgrade 500 sewers) and the Stormwater Management Works. This will involve the construction of a number of new tunnels, the main one of which is a 9.4-km tunnel that is ~4 m in diameter. A number of other tributary tunnels join the main tunnel at various points around the city. This paper reports a study conducted during the construction of the main tunnel.

Initial soil samples taken at the site (a redundant Gas Works) indicated that there could be some risk of pollution once tunnelling began, although this was believed to be low. Soil analysis indicated the presence of various volatile organic compounds with benzene being of greatest concern due to its toxicity and low workplace exposure limit (WEL) [1 p.p.m. 8 h time weighted average (TWA) (HSE, 2007)]. As benzene has a skin notation and control of exposure relied on personal protective equipment (PPE such as gloves and overalls and including respiratory protection, RPE), biological monitoring, in addition to air monitoring, was considered appropriate. S-phenylmercapturic acid (S-PMA) is a sensitive and specific metabolite of benzene. Biological monitoring based on urine analysis of S-PMA is well established and there are biological exposure indices
(ACGIH, 2009; DFG, 2009) to aid interpretation. Using the correlation data published by DFG (2009), a post-shift urinary S-PMA level of 21 µmol mol\(^{-1}\) creatinine (44 µg g\(^{-1}\) creatinine) could be expected following an 8-h exposure at the UK WEL and this value was used to interpret results in this study (referred to here as an ‘exposure limit equivalent’). Although the exposure limit equivalent relates to an 8-h exposure and the initial work in this study was in 12-h shifts, the exposure limit equivalent is still a useful indicator of exposure control because the total absorbed dose of benzene over the shift should be equivalent between shift systems if the WEL had been reduced appropriately to account for 12-hour shifts (HSE, 2007).

**METHODS**

**Description of work**

The tunnel was accessed via a large shaft. Workers entered and exited the shaft via scaffolding and steps. Inside the tunnel, a small electric train was used to remove soil and debris and as a mode of transport. A Tunnel Boring Machine (TBM) was used to excavate the tunnel. As the TBM moved forward, the labourers and train driver removed the waste material from the tunnel. Grouters then positioned and secured 3-m high concrete ‘panels’ to the tunnel walls. A crane operator removed the material from the pit bottom.

The work was carried out by an experienced multinational workforce.

**Control measures and PPE**

The tunnel was ventilated using forced air ventilation. Workers were initially provided with chemical suits (splash protection), gloves, and boots. Half-masks with a protective factor of 10 were provided for those working inside the tunnel. Pit bottom and surface workers were not required to wear respiratory protection.

**Informed consent**

The workers were informed of the potential risks associated with this particular work environment. Each person was spoken to individually. The biological monitoring sampling procedure and confidentiality were explained according to HSE guidance (HSE, 1997). Each individual was asked to sign that he understood the study, that he agreed to provide a urine sample, and that he also agreed to the results being made known to the company. All data were stored as ‘medical-in-confidence’ and in compliance with data protection requirements.

Baseline sampling was carried out pre-shift on the Monday and post-shift samples were on the following Friday. Two shifts (12-h shifts—day and night) were in operation at the time and a total of 70 workers provided samples. All workers were male with a mean age of 38 years (range 20–64 years). Thirty-one workers (44%) were smokers.

**Air monitoring**

Personal diffusive samplers were used to measure individual TWA exposures to benzene between April and June (the initial phase of the project).

**Urine analysis**

Aliquots of urine (2 ml) were acidified with 6 M HCl (200 µl); internal standard (d5-S-BMA) was added. Samples were then extracted by C18 solid-phase extraction (100 mg/1 ml cartridges). After conditioning with methanol and 10 mM HCl (1 ml of each), the sample was loaded and washed with 10 mM HCl and toluene (1 ml and 250 µl, respectively). The cartridge was dried with nitrogen and S-PMA was eluted with 1 ml dichloromethane (containing 1% acetic acid). The eluate was evaporated to dryness and reconstituted in 100 µl mobile phase (70:30, 20 mM ammonium acetate with 0.1% acetic acid:methanol).

Analysis was by negative ion electrospray liquid chromatography-tandem mass spectrometry using an Applied Biosystems 3200 Triple Quad mass spectrometer with a Shimadzu HPLC system. Injections (10 µl) were made onto a 150 × 2 mm Synergi 4 µ Hydro-RP 80A column (Phenomenex) using a flow rate of 0.2 ml min\(^{-1}\). A gradient elution was used from 70% 20 mM ammonium acetate with 0.1% acetic acid (30% methanol) to 95% methanol (5% 20 mM ammonium acetate with 0.1% acetic acid) from 1 to 5 min. Samples were introduced into the mass spectrometer at a temperature of 500°C with an ion spray voltage of −4500 V. A curtain gas of 10 p.s.i. was used with auxiliary gases of 45 and 35 p.s.i.; the collision cell had a pressure of 5 p.s.i. Lens voltages for S-PMA were as follows: −25 V (DP), −3.5 V (entrance potential), −14 V (CEP), −18 V (CE), and −2 V (CXP). The multiple reaction mode transitions monitored were 238→109 for S-PMA and 259→130 for the internal standard. The method was linear (least squares regression) to 500 nmol l\(^{-1}\) with a quantification limit of 10 nmol l\(^{-1}\) (detection limit 2 nmol l\(^{-1}\), 3 × signal:noise). The inter-assay coefficient of variation was 13% at 200 nmol l\(^{-1}\).

Creatinine was determined in all urine samples using a Cobas Mira (ABX France) and an automated alkaline picrate method (Bonsnes and TH, 1945).
The coefficient of variation for within-day analysis was 1.5% and for between-day analysis was 3% at 6 mM.

RESULTS

Personal air monitoring showed that weekly average 8 h TWA results for benzene rose from less than 0.6 p.p.m. in April to between 2.4 and 18 p.p.m. in May and June, significantly exceeding the UK WEL of 1 p.p.m. (8 h TWA).

Initial biological monitoring results for the first few weeks showed little change with ~75% of samples within the background range. However, during early May, the weather became very warm and the temperature within the tunnel increased significantly as work progressed. Air monitoring showed an increase in benzene exposure levels at this time. The men were complaining about the heat and were sweating profusely inside their suits. This was particularly problematic for the men using the TBM at the front of the tunnel and a small number exhibited signs of what was believed to be heat stress/dehydration. Additional bottled water was made available at this time, but the next series of biological monitoring results showed significant benzene exposure with 20% of samples exceeding the urinary S-PMA equivalent of the UK WEL as described in the Introduction (Fig. 1). There were statistically highly significant differences in the urinary S-PMA results between the different job categories (Kruskall–Wallis, \( P < 0.001 \)). Four of the job categories (fitter, miner, pit boss, and TBM driver) all had mean exposures in excess of this UK WEL ‘equivalent’ (Table 1) and maximum S-PMA levels at this time reached more than 10 times this UK WEL ‘equivalent’ [239 \( \mu \text{mol mol}^{-1} \text{ creatinine} \), 90th percentile was 26.9 \( \mu \text{mol mol}^{-1} \text{ creatinine} \) (57 \( \mu \text{g g}^{-1} \text{ creatinine} \)]. On investigation, it was found that due to the heat and the need to drink water more frequently, workers had been removing their PPE in the tunnel during work, when leaving the tunnel at break times, and at the end of their shifts. Some also reported taking off their respirators to answer their mobile phones.

As a result of these elevated S-PMA levels, a decision was taken to stop work immediately until control of exposure could be improved. This resulted in a week’s shutdown with no mining being undertaken. During this time, a chiller was added to the ventilation system to improve working comfort and thus improve PPE compliance. HSE Northern Ireland was informed and meetings were held with the Site Inspector and a Medical Inspector.

After the shutdown, PPE was upgraded to include chemical suits with a protection factor of 40 (Scotts Micro Chem 3000 professional disposable suit with double zips and cuffs), Scott Tornado T25 Chemical hoods with forced air ventilation, and three carbon filters for all workers in the tunnel, rubber gauntlets, and wellington boots. Half-masks were made available to the other workers at the pit top and bottom.

In addition, changes were made to working practice including the replacement of suits, filters, and gloves after each meal break; provision of additional bottled water; introducing shorter working time between breaks and a third shift to reduce the men’s exposure time (3 \( \times \) 8-h shifts from 2 \( \times \) 12-h shifts).

Any worker with an elevated biological monitoring test result was interviewed by the Health and Safety Manager and asked about specific behaviours, breakdowns or non-compliance regarding PPE, or if they could recall any incident that could explain the result. The occupational health nurse spoke to each of the groups about the health risks and the importance of wearing PPE correctly, highlighting the need for prompt reporting of any system failures or health effects. Each worker was also spoken to individually to explain their own biological monitoring results and to answer any specific queries or concerns. There were regular reminders of the importance of PPE compliance at pre-shift briefings and toolbox talks and additional, non-operational, supervision was introduced to carry out regular air monitoring and enforce PPE compliance where necessary.

Once these improvements in control measures and working practice had been introduced, work resumed with at least weekly biological monitoring. Following these improvements, a dramatic reduction in S-PMA levels was seen (Fig. 2), with only three results out of 432 (0.7%) exceeding the UK WEL.
equivalent described earlier. One worker, with persistent elevated S-PMA levels (despite evidence of his compliance being reported by others and his own claims that he had complied with all the necessary controls), was removed from the tunnel.

DISCUSSION

This case study illustrates the value of biological monitoring in situations where control of exposure primarily relies on RPE and other PPE. It also highlights the impact of working conditions and working practice on workers’ exposure. Although air monitoring had identified ‘hot spots’ of contamination, the intermittent nature of these pockets of benzene contamination and the extensive use of PPE meant that it was not sufficient to assess the risk of exposure. Biological monitoring was able to give an integrated measurement of actual systemic exposure (despite the PPE) and highlight issues with both the PPE and its use. As well instances of removing PPE while still in contaminated areas, it is possible that some exposure was due to dermal absorption of vapours penetrating the initial suits. Dermal absorption of vapours has previously been demonstrated, particularly in hot and humid conditions (Jones et al., 2003). Absorption of benzene has also been suspected (Colman and Coleman, 2006) from contaminated overalls; changing of overalls more frequently led to reduced S-PMA levels.

This case study also draws attention to the potential problems of contaminated land (the main shaft was dug out on the site of a disused gas works) and tunnelling. The Health and Safety Laboratory have previously dealt with a similar incident where extremely high benzene exposures were occurring during tunnelling of contaminated land (HSL, unpublished data). Again ~20% of samples exceeded the urinary S-PMA equivalent of the UK WEL, with the maximum exposure over 100 times this UK WEL equivalent (3379 µmol mol⁻¹ creatinine, 7117 µg g⁻¹ creatinine), demonstrating that very high exposures can occur in these situations despite the high level of PPE usually provided. These exposures are likely to be exacerbated by hot and humid conditions and the contained environment. A study of oil shale mineworkers (Sorensen et al., 2004) showed that underground workers had higher levels of S-PMA than surface workers and that there was a significant increase in S-PMA throughout the working week in underground workers but not in surface workers. Davidoff et al. (1998) also studied

<table>
<thead>
<tr>
<th>Job</th>
<th>N (workers)</th>
<th>N (samples)</th>
<th>Mean (SD) S-PMA, range µmol mol⁻¹ creatinine</th>
<th>% samples &gt; UK WEL equivalent a</th>
</tr>
</thead>
<tbody>
<tr>
<td>TBM driver</td>
<td>4</td>
<td>13</td>
<td>45.1 (29.3), 13.4–99.2</td>
<td>77</td>
</tr>
<tr>
<td>Miner</td>
<td>5</td>
<td>22</td>
<td>32.4 (32.6), 0.1–113.4</td>
<td>55</td>
</tr>
<tr>
<td>Pit boss</td>
<td>3</td>
<td>14</td>
<td>24.0 (19.0), 0.1–66.2</td>
<td>50</td>
</tr>
<tr>
<td>Fitter</td>
<td>6</td>
<td>11</td>
<td>42.9 (75.5), 2.2–238.5</td>
<td>36</td>
</tr>
<tr>
<td>Belt man</td>
<td>3</td>
<td>14</td>
<td>18.2 (22.7), 0.1–73.2</td>
<td>21</td>
</tr>
<tr>
<td>Loco driver</td>
<td>7</td>
<td>30</td>
<td>14.6 (29.8), 0.1–157.9</td>
<td>20</td>
</tr>
<tr>
<td>Electrician</td>
<td>5</td>
<td>18</td>
<td>16.1 (32.2), 0.1–140.5</td>
<td>11</td>
</tr>
<tr>
<td>Pit bottom</td>
<td>7</td>
<td>31</td>
<td>12.1 (21.3), 0.1–121.2</td>
<td>10</td>
</tr>
<tr>
<td>Pit top</td>
<td>14</td>
<td>46</td>
<td>5.8 (7.0), 0.1–27.9</td>
<td>7</td>
</tr>
<tr>
<td>Grouter</td>
<td>4</td>
<td>16</td>
<td>7.0 (10.4), 0.1–41.1</td>
<td>6</td>
</tr>
<tr>
<td>Shift engineer</td>
<td>8</td>
<td>20</td>
<td>6.7 (7.4), 0.1–29.4</td>
<td>5</td>
</tr>
<tr>
<td>Manager</td>
<td>4</td>
<td>13</td>
<td>4.3 (6.6), 0.1–19.4</td>
<td>0</td>
</tr>
</tbody>
</table>

a21 µmol mol⁻¹ creatinine (44 µg g⁻¹ creatinine) based on correlation reported by (DFG, 2009). 1 µmol S-PMA mol⁻¹ creatinine equates to ~2.1 µg g⁻¹ creatinine.
workers exposed to high levels of benzene as a result of excavating a subway tunnel under a former gasoline station (no biological monitoring was conducted). Certainly, the exposures seen in the two UK tunnelling examples are far higher than in other industries in the UK (oil and gas, steel, coke works, chemical processing, etc.) where only about 3% of results \((N = 2600,\) data from this study not included) exceed the UK WEL equivalent (HSL, unpublished data). Based on these data from a wide range of industry, the 90th percentile value for urinary S-PMA of 8 \(\mu\)mol mol\(^{-1}\) creatinine \((17 \mu\text{g g}^{-1}\text{ creatinine})\) could be suggested as an action level above which controls should be investigated.

It is well known that smokers exhibit higher urinary levels of S-PMA than non-smokers in the general population and it has previously been stated (Maestri et al., 2005) that smoking status needs to be considered where low-level occupational exposures to benzene are expected. In the study reported here, there was no significant difference between smokers and non-smokers for the initial work [smokers: mean 7.3 \(\mu\)mol mol\(^{-1}\) creatinine \((15.4 \mu\text{g g}^{-1}\text{ creatinine})\), SD = 16.9 \(\mu\)mol mol\(^{-1}\) creatinine, \(n = 361\); non-smokers: mean 5.4 \(\mu\)mol mol\(^{-1}\) creatinine \((11.4 \mu\text{g g}^{-1}\text{ creatinine})\), SD = 16.9 \(\mu\)mol mol\(^{-1}\) creatinine, \(n = 488\); \(t\)-test \(P = 0.1057\)] due to the high exposures. However after the improvements, which reduced the exposures considerably, smoking status did become significant [smokers: mean 2.6 \(\mu\)mol mol\(^{-1}\) creatinine \((5.4 \mu\text{g g}^{-1}\text{ creatinine})\), SD = 4.4 \(\mu\)mol mol\(^{-1}\) creatinine, \(n = 121\); non-smokers: mean 1.4 \(\mu\)mol mol\(^{-1}\) creatinine \((2.9 \mu\text{g g}^{-1}\text{ creatinine})\), SD = 2 \(\mu\)mol mol\(^{-1}\) creatinine, \(n = 153\); \(t\)-test \(P = 0.0029\)]. Although some workers were still demonstrably occupationally exposed, mean results were now within the general population levels [smokers <10.2 \(\mu\text{g g}^{-1}\) creatinine \((4.8 \mu\text{mol mol}^{-1}\text{ creatinine}, n = 134)\); non-smokers <4.0 \(\mu\text{g g}^{-1}\) creatinine \((1.9 \mu\text{mol mol}^{-1}\text{ creatinine}, n = 102)\) (Maestri et al., 2005)]. Similar levels have also been reported in the UK (Aston et al., 2002).

The thorough review of control measures and working practice in light of the elevated biological monitoring results in this study led to significant improvements in the protection factors of PPE supplied, compliance with correct PPE use, and the working environment. These improvements resulted in significant reductions in actual worker exposure to benzene [95% of S-PMA results below the proposed action level, 90th percentile was 5.4 \(\mu\)mol mol\(^{-1}\) creatinine \((11 \mu\text{g g}^{-1}\text{ creatinine})\) despite continuing contamination, demonstrating that working safely in high ambient benzene concentrations in a hot, humid, confined environment is possible but that means of monitoring the efficacy of controls (and their use) is vital. Biological monitoring is a valuable tool in monitoring such exposures where control is highly reliant on PPE and skin absorption may also be an issue. A 90th percentile value for SPMA of 8 \(\mu\)mol mol\(^{-1}\) creatinine \((17 \mu\text{g g}^{-1}\text{ creatinine})\) is indicative of current UK industry practice.

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