Aerosol and Air Quality Research, 11: 120–127, 2011

ISSN: 1680-8584 print / 2071-1409 online
doi: 10.4209/aaqr.2010.09.0074

Estimating Cancer Risk Increment from Air Pollutant Exposure for Sewer Workers Working in an Industrial City

Shu-Hsing Yeh[1], Chin-Hsing Lai[2*], Ching-Ho Lin[2], Ming-Jen Chen[3], Hui-Tsung Hsu[4], Gui-Xiang Lin[2], Tzong-Tzeng Lin[5], Yuh-Wen Huang[2]

[1] *Department of Leisure and Recreation Industry Management, Fooyin University, 151 Ching-Hsueh Road, Ta-Liao District, Kaohsiung City 831, Taiwan*
[2] *Department of Environmental Engineering and Science, Fooyin University, 151 Ching-Hsueh Road, Ta-Liao District, Kaohsiung City 831, Taiwan*
[3] *Department of Occupational Safety and Hygiene, Fooyin University, 151 Ching-Hsueh Road, Ta-Liao District, Kaohsiung City 831, Taiwan*
[4] *Department of Health Risk Management, China Medical University, 91 Hsueh-Shih Road, Taichung City 404, Taiwan*
[5] *Department of Civil Engineering, National Kaohsiung University of Applied Science, 415 Chien Kung Road, Kaohsiung City 807, Taiwan*

ABSTRACT

Sewer construction in Taiwan lags other developed nations, and the authorities are undertaking major sewerage system construction projects in several cities. In Kaohsiung City, sewerage networks pass through residential, commercial and industrial areas. The composition of sewage thus is highly complicated. Eight target monitoring positions are chosen to analyze the compounds and concentrations of hazardous air pollutants. Pollutant concentrations are used to evaluate the cancer risk increment based on inhalation intake for sewer workers under using exhaust ventilation and wearing personal gas filtering equipment. GC/MS analysis confirmed that concentrations of benzene and trichloromethane compounds in sewer air for all the monitoring positions exceeded the minimum risk levels (MRLs) of 0.009 ppm benzene and 0.1 ppm trichloromethane, and the maximum concentrations reached 148.4 and 327.3 ppm, respectively. The cancer risks of benzene and trichloromethane for workers without personal protection approached $2.77–3.98 \times 10^{-3}$ and $29.74–42.70 \times 10^{-3}$, respectively. Through ventilation for 15 minutes and the wearing of gas filtering equipment, the cancer risks for benzene and trichloromethane were reduced to $0.0003–0.0004 \times 10^{-3}$ and $0.0029–0.0041 \times 10^{-3}$, respectively. The authorities thus must order all workers to follow a strict code of practice for sewer entry before entering sewer systems. This code of practice should include a minimum time for general exhaust ventilation and the use of personal protection equipment.

Keywords: Cancer risk; Hazardous air pollutant; Sewer; Benzene; Trichloromethane.

INTRODUCTION

Sanitary sewer system air is influenced by regional environment type and sewage exhaust characteristics (Matos and Aires, 1995; Matthijs *et al*., 1995; Muezzinoglu, 2003; Paxeus, 1996; Veldkamp and Wiggers, 1997; Gostelow *et al*., 2001). Besides, sewer pipe environments are characterized owing to being enclosed and poorly ventilated. Consequently, complicated air pollutants may be produced through the physical, chemical or biological reactions in sewers, and the accumulation of hazardous air pollutants may harm the health of sewer workers (Paxeus *et al*., 1992; Haas and Herrmann, 1996; Watt *et al*., 1997; Haas and Herrmann, 1998; Devai and DeLaune, 1999; Lee *et al*., 2002; Huisman *et al*., 2004; Ohuraa *et al*., 2006; Choosong *et al*., 2010). Many studies have examined fatalities occurring in sewerage chambers and pipes, with sewer workers suffering injury or death from chemicals released into sewerage system or from explosions in sewer systems (Veldkamp *et al*., 1998; Bordado and Comes, 2001; Bridges, 2003; Padosch *et al*., 2005). Several toxic volatile organic compounds (VOCs) have been identified, and these compounds are classified as hazardous air pollutants and/or carcinogens (Chien *et al*., 2007). Hass and Herrmann (1996; 1998) reported hazardous air pollutants of trichloroethylene, tetrachloroethylene and trichloromethane were detected from sewer atmosphere. The 2009 survey data from the Environmental Protection Bureau, Kaohsiung City

* Corresponding author. Tel.: 886-7-7828717;
Fax: 886-7-7860780
E-mail address: chlai@mail.fy.edu.tw

Government of Taiwan indicated that the substances of benzene and trichloromethane were detected in sewer air (Environmental Protection Bureau, Kaohsiung City Government, 2009). The impact of hazardous air pollutants on health and cancer risk for sewer workers has recently attracted considerable attention in industrialized countries (Chinery and Gleason, 1993; Kuo *et al*., 1998; Hinwood *et al*., 2007). The local authorities must understand the composition of sewer air and implement robust plans or preparations, as well as training staff appropriately to deal with these emergencies (Haas and Herrmann, 1996; Watt *et al*., 1997; Lyons *et al*., 2002).

Taiwan has a low sewerage connection rate, lagging other advanced countries. Therefore, the Taiwanese government is attempting to construct sanitary sewerage systems in several cities. In Kaohsiung City (in the south of Taiwan), the networks of domestic sewerage collection system serve residential, commercial and industrial areas, and consequently are extremely complicated (Lin, 2001; Dong *et al*., 2002; Environmental Protection Bureau, Kaohsiung City Government, 2009; Wang *et al*., 2010). Unfortunately, Taiwan recently suffered an accident in which sewerage workers were injured after a manhole explosion. Analysis revealed that the sewer air contained a high concentration of VOCs. This explosion accident might have resulted from high concentrations of VOCs or methane in the sewer system.

Previous studies have emphasized that the health and cancer risk of workers in sewer system is worth investigating and evaluating. However, previously little attention has been devoted to hazardous air pollutants and evaluating the cancer risk for sewer workers in Taiwan. To understand the concentration of hazardous air pollutants in sewers, this study used the monitoring and sampling instruments to analyze the compounds and concentrations of hazardous air pollutants. Worker safety is also essential for these pollutants from a health risk perspective since these pollutants are also carcinogenic. Therefore, the concentrations of hazardous air pollutants are compared with minimum risk levels (MRLs), and cancer risk assessment is used to evaluate the degree of risk using the equation of cancer risk and the Integrated Risk Information System (IRIS) of the U.S. Environmental Protection Agency. Besides, methods to reduce concentrations of hazardous air pollutants in sewer workspaces are assessed, including general exhaust ventilation and protective breathing equipment.

MATERIAL AND METHODS

Sampling and Analysis

Eight target monitoring positions were chosen in the Kaohsiung City area. The manholes of the city sewerage system were adopted as the monitoring sites. As shown in Fig. 1, the eight manholes of monitoring and sampling positions were conducted at the Cheng-Kung and Kai-Suan sewers passing the city area. Both of them were two main sewers of sewerage system in Kaohsiung City. The manholes of the Kaohsiung City sewerage system were adopted as the monitoring sites. Eight target monitoring positions were chosen in the city area. Owing to the depth of the manhole from the ground level to the bottom of sewer pipe was 10 m, it was quite dangerous for sewer maintenance personnel to enter the sewer pipe and conducted monitoring, and thus the monitoring and sampling devices were arranged and shown in Fig. 2. Monitoring and sampling equipment included a personal pump, sampling tubes, mixing chamber and tubes. NMHC monitor (FOXBORO TVA-1000B) was used to continuously measure the NMHC concentration of sewer air over 8 hr. When the NMHC monitor appeared to be nearly stable during the monitoring period, the hazardous air pollutants of sewer air were collected on sampling tubes, consisting of stainless steel tubes packed with 0.6 g Carboxen 569 (Supelco, PA). Besides, the adsorption efficiency of Carboxen 569 for benzene and

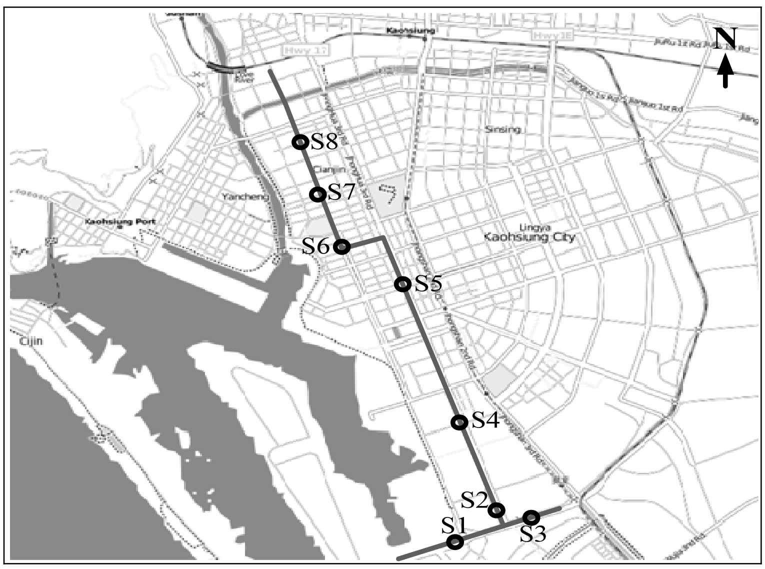

Fig. 1. The eight monitoring and sampling positions were arranged in the Kaohsiung City area.

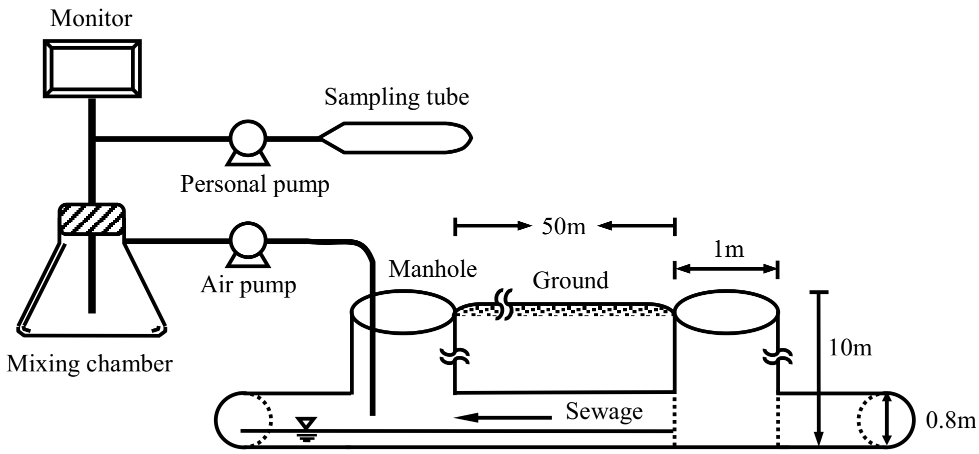

Fig. 2. Setup for monitoring and sampling equipments.

trichloromethane exceeded 98%. During the monitoring period, the sampling flow rate was set to a constant, and the sampling time was set to last 20 minutes. Samples were analyzed using thermal desorption (Model ATD400, Perkin Elmer, USA) coupled with GC/MS (Model 6890 plus GC and 5973 MSD, Hewlett Packard, USA) detection. The instruments were set as follows; the samples were desorbed at 250°C for 10 min and the transfer-line between the thermal desorption unit and GC was set to 220°C, with the aid of an additional heater. The thermal desorption instrument houses a cold trap (set at –30°C), which can concentrate desorbed chemicals from the sample and release them into GC via prompt heating (to 300°C). The GC oven temperature program was as follows; initial temperature of 35°C, held for 10 min, rising to 220°C at a rate of 10 °C/min, held for another 8 min. A capillary analytical column (Model GsBP-624, 60 m × 0.25 mm, 1.4 µm thickness, General Separation, USA) was used for separation, with helium as the carrier gas, running at 1.0 ml/min. The MSD was set to 250°C, and 70 eV was used in electron ionization. The interface between GC and MSD was also 250°C. The condition of MSD was checked daily with the manufacturers' auto-tune settings before it was used, while the thermal desorption unit automatically tested for leakage and correct functioning. The mean desorption efficiency of the protocol for common aromatic organics exceeded 95%. The minimum detection limits (MDLs) for benzene and trichloromethane were 2.00 ppb and 0.94 ppb, respectively.

The quality assurance and quality control procedure included field blanks and duplicate measurements of samples. During the sampling procedure, one sampling tube was used at the sampling site and then the ends capped, which served as a blank. The blank sample was transported along with the sampling tubes to the sampling positions, stored in the laboratory during the exposure period, and then analyzed to ensure that there was no contamination during sampling, transportation and storage. Duplicate samples were obtained at 8 sampling sites. Concentrations of hazardous air pollutants measured in duplicate samples were in good agreement, with a relative standard deviation of less than 15%.

Cancer Risk Assessment

The main hazardous air pollutants for sewer workers came from sewerage system air, and the cancer risk assessment was focused on inhalation intake for the duration of working in sewer. Therefore, the cancer risk increment was calculated based on the route from inhalation intake for sewer workers. This study identified the major compounds of hazardous air pollutants including benzene and trichloromethane.

The cancer risk equation was used to calculate the number of individuals likely to acquire cancer because of pollutant exposure from inhalation absorption (Wallace, 1991; Lee *et al*., 2001; Morello-Frosch *et al*., 2000; Guo *et al*., 2004; Lee *et al*., 2004; Tam and Neumann, 2004; Durmusoglua *et al*., 2010). The cancer risk equation is expressed as follows:

$$\text{Risk} = LADD \times SF = \frac{C \times 10^{-3} \times IR \times ET \times EF \times EW \times ED}{BW \times TL} \times SF \quad (1)$$

where LADD (mg/kg-day) denotes the lifetime average daily dose, SF (kg-day/mg) represents the slope factor, C (µg/m^3) is the concentration of pollutant, IR (m^3/hr) denotes the inhalation rate, ET (hr/time) is the average exposure time, EF (time/week) represents the average exposure frequency, EW (week/year) denotes the exposure weeks, ED (year) represents the average working exposure duration, BW (kg) is the average body weight, and TL (day) is the average life-span. The lifetime average daily dose from sewer system air could be estimated based on the general parameter data obtained from the Taiwanese city used as an example here. Furthermore, the slope factors of benzene and trichloromethane through inhalation could be obtained from the website of the Integrated Risk Information System of the American Environmental Protection Administration (USEPA, 1998).

Uncertainty Analysis

In order to quantify the uncertainty and variability and their impact on the estimation of expected cancer risk assessment, a Monte Carlo simulation was conducted. The software program Crystal Ball® (Version 7.3, Decisioneering, Inc., Denver, CO, USA) was used to analyze data and to estimate distribution parameters. The distribution type was selected based on statistical criteria. The result of Monte Carlo simulation provides a confidence interval (5th and 95th quartiles) of health risk for sewer workers exposed to hazardous air pollutants in sewer workplace. Table 1 shows the selected types of probability distribution for random variables including IR, ET, EF, ED and BW. A sensitivity analysis using Spearman rank correlations was performed to determine which probability density functions had the greatest effect on the cancer risk assessment.

RESULTS AND DISCUSSION

Hazardous Air Pollutants in the Monitoring Area

In this work, NMHC monitor was used to continuously measure the NMHC concentration of sewer air over 8 hr. During the monitoring period, the NMHC measuring concentration appeared to be nearly stable level, the sewer air was collected for 20 min by drawing air through sampling tubes. During the 20-minute sampling period, NMHC concentrations of eight monitoring positions were shown in Table 2. Among these eight target monitoring positions, the NMHC ranged of 126–1,347 ppm, and the maximum concentration of NMHC occurred at monitoring position S4. Besides, according to GC/MS analytical results, the species and concentrations for VOCs are trichloromethane (1.0–327.3 ppm), benzene (0.4–148.4 ppm), ethane + acetylene + ethane (7.9–315.3 ppm), acetone (4.7–252.3 ppm), tetrachloroethylene (0.6–223.9 ppm), toluene (1.6–86.2 ppm), xylene (0.9–81.0 ppm), isopentane (2.0–62.7 ppm), trichloroethylene (0.6–29.0 ppm), pentane (1.6–25.3 ppm), propene (0.7–18.9 ppm), 2-methylpentane (0.3–16.8 ppm), 3-methylpentane (0.5–14.1 ppm), 1,1-dichloroethylene (2.2–14.2 ppm), 1-butene (0.8–13.7 ppm), butane (1.0–12.4 ppm), cis-2-butene (0.6–3.1 ppm), trans-2-butene (0.8–2.3 ppm) and the other trace species. Both of benzene and trichloromethane were identified as major of carcinogenic air pollutants by the Integrated Risk Information System (IRIS) of US EPA, while the other compounds belonged to the non-carcinogenic air pollutants. This study analyzed the concentrations of carcinogenic air pollutants from sewer air in Kaohsiung City area, and the analytical results are listed in Table 3. Among these eight target monitoring positions, the detected concentrations of benzene and trichloromethane ranged of 0.4–148.4 ppm and 1.0–327.3 ppm, respectively. The maximum concentration of benzene and trichloromethane occurred at monitoring position S2. Recently, two carcinogenic pollutants were also measured by the Environmental Protection Bureau, Kaohsiung City Government (2009) which reported 9.50 ppm and 32.69 ppm for benzene and trichloromethane were found from sewer air, respectively. These results are consistent with this study.

From the measurement results, concentrations of hazardous air pollutants in sewer air were generally higher than those in ambient air. Hazardous air pollutants in sewer air were released from the sewage, and solvent containing wastewater could possibly be discharged to the sewer from business activities within the city. Concentrations of benzene and trichloromethane compounds in sewer air for all the monitoring positions exceeded the MRLs of 0.009 ppm benzene and 0.1 ppm trichloromethane (ATSDR, 2009). MRLs are only based on noncancer diseases, and the no observable adverse effects level (NOAEL) approach is used to determine MRLs for hazardous chemicals.

Table 1. Risk parameters considered as random variables for uncertainty analysis in this study.

Input parameters	Unit	Values (mean ± std)	Distribution	Range and Explanation
IR	m^3/hr	0.76 ± 0.15	Normal	Standard deviation (std) was taken as 20% of the mean; mean value is adapted from DOH Taiwan, 2008
EF	time/week	2.33 ± 1.66	Normal	(1, 5) this study
ET	hr/time	1.98 ± 2.56	Lognormal	(0.5, 5) this study
ED	year	14.07 ± 21.84	Lognormal	(1.1, 29) this study
BW	kg	70.61 ± 32.15	Lognormal	(49, 103) adapted from DOH Taiwan, 2008
AT	year	76.6	Point	Adapted from DOH Taiwan, 2008

Department of Health (DOH), Taiwan. 2008. Compilation of exposure factors (in Chinese).

Table 2. Concentrations of NMHC were monitored at different sampling positions, S1–S8, during the 20-minute sampling period.

Sites	S1	S2	S3	S4	S5	S6	S7	S8
NMHC (ppm)	628–680	950–1,050	1,100–1,116	1,145–1,347	150–159	1,055–1,073	343–351	126–133

Table 3. Concentrations of pollutants were detected at S1–S8 monitoring positions.

Monitoring compounds	S1	S2	S3	S4	S5	S6	S7	S8
Benzene (ppm)	1.7	148.4	59.9	0.9	0.6	0.6	0.7	0.4
Trichloromethane (ppm)	4.5	327.3	131.3	63.4	1.4	2.0	2.2	1.0

Estimate of Cancer Risk Increment for Sewer Worker

By searching the Integrated Risk Information System of US EPA, this study found that the slope factors of benzene and trichloromethane through inhalation intake were 2.9×10^{-2} and 8.1×10^{-2} kg-day/mg, respectively (Attias *et al.*, 1995; USEPA, 1998; Guo *et al.*, 2004; Lee *et al.*, 2004; Durmusoglua *et al.*, 2010).

This study administered a questionnaire on actual working time, sewer entry frequency, and ventilation time for sewer workers in Taiwan. All exposure parameters adopted were retrieved from the comprehensive domestic databank, i.e. Compilation of Exposure Factors, Department of Health (DOH), Taiwan, 2008 (in Chinese). The exposure-related parameters used in this work were summarizes in Table 1. The average ventilation time was 13.56 minutes before entering a manhole. Meanwhile, considering the 7 weeks of legal holiday date and annual vocation each a year in Taiwan, which leads to the exposure weeks for workers as 45 weeks annually. Furthermore, risk assessment calculations were based on two situations. The first situation was the actual case study of sewer workers in Taiwan (using the investigating data). Meanwhile, the second situation was a simulated case, with the working exposure time of 20 years, entry to the sewer to perform work 2.33 times per week, working time of 2 hours on each instance of sewer entry, and ventilation time before sewer entry of 13.56 and 15 minutes, respectively.

Based on the above method and the parameter data, the cancer risks associated with benzene and trichloromethane for sewer workers without any ventilation and personal protection equipment were calculated using information from eight monitoring positions, as shown in Figs. 3 and 4, respectively. The cancer risks of benzene and trichloromethane for actual case and simulated case through inhalation intake ranged from $2.77–3.98 \times 10^{-3}$and $29.74–42.70 \times 10^{-3}$, respectively. These ranges indicated high cancer risk increment from the sewer air exposure, and a consequent strong need for protection for workers.

Moreover, the equation for calculating general exhaust ventilation was employed to forecast the ventilation performance. The pollutant concentration in the sewer air could be described using the equation of general exhaust ventilation, as follows:

$$V\frac{dC}{dt} = QC_0 - QC + G \quad (2)$$

where C denotes the pollutant concentration at t (μg/m^3), C_0 represents the initial pollutant concentration at t_0 (μg/m^3), V is the sewer volume (actual measure, V = 32.98 m^3), Q denotes the ventilation rate (general use, Q = 16.8 m^3/min), G represents the generation rate of pollutant (μg/min), and t is the time (min). Eq. (3) can be obtained based on Eq. (2) by integration.

$$C = \frac{1}{Q}[G - (G - QC_0)\exp^{-\frac{Q}{V}(t-t_0)}] \quad (3)$$

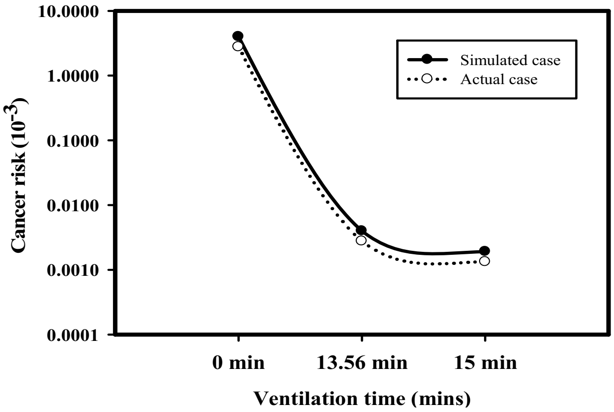

Fig. 3. Estimating cancer risk from benzene after various ventilation time without wearing protective equipment.

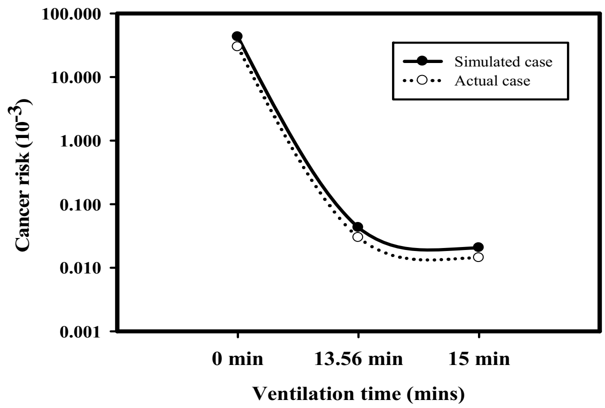

Fig. 4. Estimating cancer risk from trichloromethane after various ventilation time without wearing protective equipment.

Due to the ventilating time being short, this study assumed that the amount of pollutant generated during exhaust ventilation approached zero (G = 0). According to these parameters, the concentrations of hazardous air pollutants in the sewer could be calculated using Eq. (3) after ventilating for 13.56 and 15 minutes, respectively. Figs. 3 and 4 show that the cancer risks of benzene and trichloromethane were reduced from $2.77–3.98 \times 10^{-3}$, $29.74–42.70 \times 10^{-3}$ to $0.003–0.004 \times 10^{-3}$, $0.030–0.043 \times 10^{-3}$ and $0.001–0.002 \times 10^{-3}$, $0.014–0.021 \times 10^{-3}$ after ventilating for 13.56 and 15 minutes, respectively. The analytical results demonstrated that ventilation was an effective strategy for reducing the degree of cancer risk for sewer workers.

Moreover, sewer workers who wore breathing protection equipment were also evaluated. Owing to the high cancer risk associated with breathing workspace air, gas filtering equipment should be used, in which the inhaled air passes through a filter where the gas contaminants were eliminated, such as gas and vapor filtering equipment (Cheng, 2008; Zuo *et al.*, 2010). Full-face masks generally described masks in which the filtering chamber was attached directly to the chin area of the mask. The filters could be either dual cartridges or single canisters. Canisters contained granular adsorbents that filtered the air by adsorption, absorption or chemical reaction. Generally, the filter containing activated carbon medium was used as the personal breathing protection equipment to adsorb the hazardous air pollutants for sewer workers. Based on our results of risk assessment, we suggested that the removal efficiency of activated carbon respirator for benzene or trichloromethane should be ≥ 80% for workers. Therefore, cancer risk was also assessed when sewer workers wore gas filtering equipment following ventilation, and the results were shown in Figs. 5 and 6, respectively. By ventilating for 13.56 and 15 minutes and wearing protective equipment, the cancer risks for benzene and trichloromethane were reduced from 2.77–3.98 × 10^{-3}, 29.74–42.70 × 10^{-3} to 0.0006–0.0008 × 10^{-3}, 0.0059–0.0085 × 10^{-3} and 0.0003–0.0004 × 10^{-3}, 0.0029–0.0041 × 10^{-3} respectively. The analytical results indicated that the protective equipment could also reduce cancer risk to an acceptable level for sewer workers. Workspace safety for sewer worker thus can be achieved through ensuring good ventilation and wearing protective equipment. The government should require sewer workers to wear breathing equipment and ensure good exhaust ventilation.

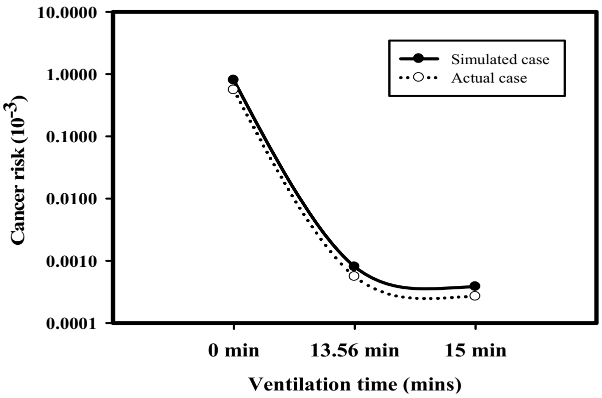

Fig. 5. Estimating cancer risk from benzene after various ventilation time with wearing protective equipment.

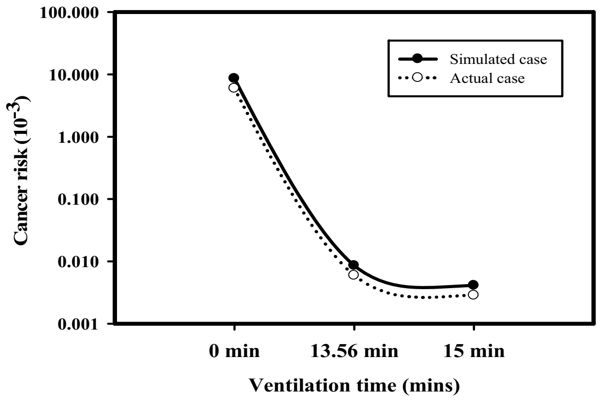

Fig. 6. Estimating cancer risk from trichloromethane after various ventilation time with wearing protective equipment.

Uncertainty and Sensitivity Analysis

The Monte Carlo simulation is performed to quantify the uncertainty and its impact on the estimation of sewer workers exposed to carcinogens in the sewer workplace. Table 4 shows the percentile predictions of excess lifetime cancer risks for workers exposed to benzene or trichloromethane at different air concentrations. Our results showed that the 95th percentile for workers exposed to benzene and trichloromethane ranged from 2.61 × 10^{-5} to 9.52 × 10^{-3} and 2.75 × 10^{-4} to 9.01 × 10^{-2}, respectively. Under most regulatory program, an excess lifetime cancer risk between 10^{-6} and 10^{-4} indicates potential risk; while larger than 10^{-4} indicates high potential health risk. Our simulation showed that for sewer workers exposed to high benzene or trichloromethane concentrations at monitoring position S2 and S3, 95% probability excess lifetime cancer risk were much higher than 10^{-4}, indicating high potential health risk.

In this study, we conducted a quantitative sensitivity analysis to evaluate the variability and uncertainty of parameters that contributed most significantly to the excess lifetime cancer risk. Fig. 7 presented the results of sensitivity analysis of excess lifetime cancer for sewer workers exposed to (a) benzene and (b) trichloromethane, respectively. The results showed that the most influential variable in risk estimate is exposure duration (ED). It contributes 64% of variance in health risk estimation. The second most important parameter that contribute to the

Table 4. Estimated range of excess lifetime cancer risk for sewer workers exposed to benzene and trichloromethane.

	S1	S2	S3	S4	S5	S6	S7	S8
Benzene								
5%	3.65E-06	3.20E-04	1.29E-04	1.96E-06	1.28E-06	1.28E-06	1.49E-06	8.78E-07
25%	1.22E-05	1.07E-03	4.31E-04	6.54E-06	4.28E-06	4.28E-06	4.96E-06	2.93E-06
50%	2.59E-05	2.27E-03	9.15E-04	1.39E-05	9.10E-06	9.10E-06	1.05E-05	6.22E-06
75%	5.01E-05	4.39E-03	1.77E-03	2.69E-05	1.76E-05	1.76E-05	2.04E-05	1.21E-05
95%	1.09E-04	9.52E-03	3.84E-03	5.83E-05	3.82E-05	3.82E-05	4.42E-05	2.61E-05
Trichloromethane								
5%	4.17E-05	3.03E-03	1.21E-03	5.86E-04	1.30E-05	1.85E-05	2.04E-05	9.24E-06
25%	1.39E-04	1.01E-02	4.05E-03	1.96E-03	4.34E-05	6.17E-05	6.80E-05	3.08E-05
50%	2.96E-04	2.14E-02	8.60E-03	4.15E-03	9.23E-05	1.31E-04	1.44E-04	6.55E-05
75%	5.73E-04	4.16E-02	1.67E-02	8.05E-03	1.79E-04	2.54E-04	2.80E-04	1.27E-04
95%	1.24E-03	9.01E-02	3.61E-02	1.74E-02	3.87E-04	5.50E-04	6.06E-04	2.75E-04

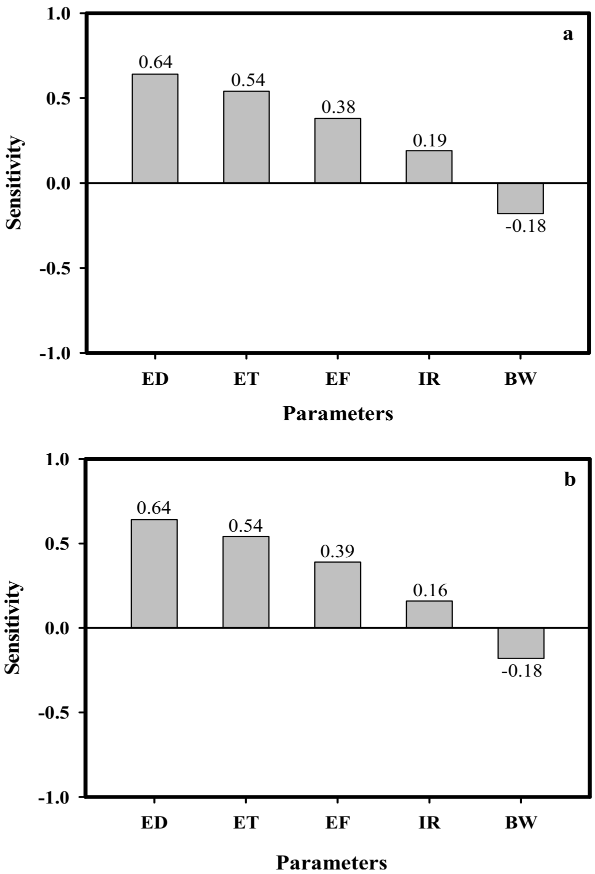

Fig. 7. Sensitivity analysis of excess lifetime cancer risk model for sewer workers exposed to (a) benzene and (b) trichloromethane.

variance in risk estimation is exposure time (ET) followed by exposure frequency (EF). They contribute 54% and 38%, respectively, to the variance in risk estimation. All these three parameters have positive correlation with excess lifetime cancer risk. Body weight is negatively correlated with cancer risk. Therefore, in order to protect sewer workers, it is suggested that reducing the working time or frequency under sewer environment are necessary. In addition, as mentioned earlier, asking workers to wear breathing equipment and ensuring good exhaust ventilation are risk management options.

CONCLUSIONS

GC/MS analysis confirmed that sewer gas in Kaohsiung contained hazardous air pollutants, including benzene and trichloromethane, and that the maximum concentrations of benzene and trichloromethane reached 148.4, and 327.3 ppm, respectively. The concentrations of benzene and trichloromethane in sewer air thus exceeded the MRLs. The analytical results indicate the likelihood of solvent containing wastewater being discharged to sanitary sewers. According to the cancer risk assessment, the cancer risks of benzene and trichloromethane for workers without protective equipment reached the ranges of 2.77–3.98 × 10^{-3} and 29.74–42.7 × 10^{-3}, respectively. General exhaust ventilation and the wearing of protective equipment are effective measures for reducing sewer worker cancer risk. Through ventilation for 15 minutes and the wearing of gas filtering equipment, the cancer risks for benzene and trichloromethane were reduced to 0.0003–0.0004 × 10^{-3} and 0.0029–0.0041 × 10^{-3}, respectively. The authorities thus must order all sewer workers to follow a strict code of practice for sewer entry before entering sewer systems. This code of practice should include a minimum time for general exhaust ventilation and the use of personal protection equipment.

ACKNOWLEDGMENTS

The authors would like to thank the National Science Council of the Republic of China, Taiwan for financially supporting this research under Contract No. NSC 97-2221-E-242-005. Sampling and analyzing assistance from Sewerage Systems Office Public Works Bureau Kaohsiung City Government, Prof. Chia-Wei Lee and Prof. Yeh-Chung Chien are also greatly appreciated.

REFERENCES

ATSDR (2009). Agency for Toxic Substances and Disease Registry, Minimal Risk Levels for Hazardous Substances (MRLs). URL: http://www.atsdr.cdc.gov/mrls/index.asp.

Attias, L., Contu, A. Loizzo, A. Massiglia, M., Valente, P. and Zapponi, G.A. (1995). Trihalomethanes in Drinking Water and Cancer: a Risk Assessment and Integrated Evaluation of Available Data, in Animals and Humans. *Sci. Total Environ.* 171: 61–68.

Bordado, J.C.M. and Comes, J.F.P. (2001). Characterization of Non-condensable Sulphur Containing Gases from Kraft Pulp Mills. *Chemosphere* 44: 1011–1016.

Bridges, O. (2003). Double Trouble: Health Risk of Accidental Sewage Release. *Chemosphere* 52: 1373–1379.

Cheng, W.H. (2008). Adsorption Characteristics of Granular Activated Carbon and SPME Indication of VOCs Breakthrough. *Aerosol Air Qual. Res.* 8: 178–187.

Chien, C.L., Tsai, C.J., Ku K.W. and Li, S.N. (2007). Ventilation Control of Air Pollutant during Preventive Maintenance of a Metal Etcher in Semiconductor Industry. *Aerosol Air Qual. Res.* 7: 469–488.

Chinery, R.L. and Gleason, A.K. (1993). A Compartmental Model for the Prediction of Breath Concentration and Absorbed Dose of Chloroform after Exposure while Showering. *Risk Anal.* 13: 51–63.

Choosong, T., Chomanee, J., Tekasakul, P., Tekasakul, S., Otani1, Y., Hata, M. and Furuuchi1, M. (2010). Workplace Environment and Personal Exposure of PM and PAHs to Workers in Natural Rubber Sheet Factories Contaminated by Wood Burning Smoke. *Aerosol Air Qual. Res.* 10: 8–21.

Devai, I. and DeLaune, R.D. (1999). Emission of Reduced Malodorous Sulfur Gases from Wastewater Treatment Plants. *Water Sci. Technol.* 71: 203–208.

DOH (2008). Compilation of Exposure Factors, Department of Health, Executive Yuan, Taiwan, URL:

http://www.doh.gov.tw/.

Dong, C.D., Huang, K.L., Chen, C.W., Lee, C.W., Lin, H.Y. and Chen, C.F. (2002). Estimation of Air Pollutants Emission from Ships in the Kaohsiung Harbor Area. *Aerosol Air Qual. Res.* 2: 31–40.

Durmusoglua, E., Taspinarb, F. and Karademira, A. (2010). Health Risk Assessment of BTEX Emissions in the Landfill Environment. *J. Hazard. Mater.* 176: 870–877.

Environmental Protection Bureau, Kaohsiung City Government (2009). Investigation and Evaluation of VOCs Total Emissions from the Storm and Sewerage Systems in Kaohsiung City Area, Environmental Protection Bureau, Kaohsiung City Government Report (in Chinese), Taiwan.

Gostelow, P., Parsons, S.A. and Sturtz, R.M. (2001). Odor Measurements for Sewage Treatment Works. *Water Res*. 35: 579–597.

Guo, H., Lee S.C., Chan L.Y. and Li W.M. (2004). Risk Assessment of Exposure to Volatile Organic Compounds in Different Indoor Environments. *Environ. Res.* 94: 57–66.

Haas, B.S. and Herrmann, R. (1996). Transport of Chlorinated Hydrocarbons between Sewage and Sewer Atmosphere. *Water Sci. Technol.* 34: 557–564.

Haas, B.S. and Herrmann, R. (1998). Tracing Volatile Organic Compounds in Sewers. *Water Sci. Technol.* 37: 295–301.

Hinwood, A.L., Rodriguez, C., Runnion, T., Farrar, D., Murray, F., Horton, A., Glass, D., Sheppeard, V., Edwards, J.W., Denison, L., Whitworth, T., Eiser, C., Bulsara, M., Gillett, R.W., Powell, J., Lawson, S., Weeks, I. and Galbally, I. (2007). Risk Factors for Increased BTEX Exposure in Four Australian Cities. *Chemosphere* 66: 533–541.

Huisman, J. L., Weber, N. and Gujer, W. (2004). Reaeration in Sewers. *Water Res*. 38: 1089–1100.

Kuo, H.W., Chiang, T.F., Lo, I.I., Lai, J.S., Chan, C.C. and Wang, J.D. (1998). Estimate of Cancer Risk from Chloroform Exposure during Shower in Taiwan. *Sci. Total Environ*. 218: 1–7.

Lee, C.W., Mohr, S.N. and Weisel, C.P. (2001). Toxickinetics of Human Exposure to Methyl Tertiary-Butyl Ether (MTBE) Following Short-term Controlled Exposures. *J. Exposure Anal. Environ. Epidemiol.* 11: 67–78.

Lee, S.C., Guo H., Li W.M. and Chan L.Y. (2002). Inter-comparison of Air Pollutant Concentrations in Different Indoor Environment in Hong Kong. *Atmos. Environ*. 36: 1929–1940.

Lee, S.C., Guo, H. Lam, S.M.J. and Lau, S.L.A. (2004). Multipathway Risk Assessment on Disinfection By-products of Drinking Water in Hong Kong. *Environ. Res*. 94: 47–56.

Lin, C.W. (2001). Hazardous Air Pollutant Source Emissions for a Chemical Manufacturing Facility in Taiwan. *Water Air Soil Pollut.* 128: 321–337.

Lyons, R.A., Wright, D., Fielder, A., McCabe, M., Gunneberg, A., Nash, P., Routledge, P. and Rees, H. (2002). Investigation of an Acute Chemical Exposure Incident to Fluorinated Hydrocarbons. *Occup. Environ. Med*. 57: 577–581.

Matthijs, E., Debaere, G., Itrich, N., Masscheleyn, P., Rottiers, A., Stalmans, M. and Federle, T. (1995). The Fate of Detergent Surfactants in Sewer Systems. *Water Sci. Technol.* 31: 321–328.

Matos, J.S. and Aires, C.M. (1995). Mathematical Modeling of Sulphide and Hydrogen Sulphide Gas Build-up in the Costa Do Estoril Sewerage System. *Water Sci. Technol.* 31: 255–261.

Morello-Frosch, R.A., Woodruff, T.J., Axelrad, D.A. and Caldwell, J.C. (2000). Air Toxics and Health Risks in California: the Public Health Implications of Outdoor Concentrations. *Risk Anal*. 20: 273–291.

Muezzinoglu, A. (2003). A Study of Volatile Organic Sulfur Emissions Causing Urban Odors. *Chemosphere* 51: 245–252.

Ohuraa, T., Amagaia, T. and Fusaya, M. (2006). Regional Assessment of Ambient Volatile Organic Compounds in an Industrial Harbor Area, Shizuoka, Japan. *Atmos. Environ*. 40: 238–248.

Padosch S.A., Dettmeyer, R.B., Kroner, L.U., Preuss, J. and Madea, B. (2005). An Unusual Occupational Accident: Fall into a Sewage Plant Tank with Lethal Outcome. *Forensic Sci. Int.* 149: 39–45.

Paxeus, N., Robinson, P. and Balmer, P. (1992). Study of Organic Pollutants in Municipal Wastewater in Goteborg, Sweden. *Water Sci. Technol.* 25: 249–256.

Paxeus, N. (1996). Vehicle Washing as a Source of Organic Pollutants in Municipal Wastewater. *Water Sci. Technol.* 33: 1–8.

Tam, B.N. and Neumann, C.M. (2004). A Human Health Assessment of Hazardous Air Pollutants in Portland, OR. *J. Environ. Manage.* 73: 131–145.

USEPA (1998). Integrated Risk Information System-Benzene. URL: http://www.epa.gov/iris/subst.o276.htm.

Veldkamp, R.G. and Wiggers, J.B.M. (1997). A Statistical Approach to Pollutant Emissions from Combined Sewer Systems. *Water Sci. Technol.* 36: 95–110.

Vorkamp, K., Hass, B.S. and Herrman, R. (1998). Development of Passive Samplers for the Detection of Chlorinated Hydrocarbons in Sewers. *Water Sci. Technol.* 37: 311–318.

Wallace, L.A. (1991). Comparison of Risks from Outdoor and Indoor Exposure to Toxic Chemicals. *Environ. Health Perspect.* 95:7–13.

Wang, H.K., Huang, C.H., Chen, K.S. and Peng, Y.P. (2010). Seasonal Variation and Source Apportionment of Atmospheric Carbonyl Compounds in Urban Kaohsiung, Taiwan. *Aerosol Air Qual. Res.* 10: 559–570.

Watt, M.M., Watt, S.J. and Seaton, A. (1997). Episode of Toxic Gas Exposure in Sewer Worker. *Occup. Environ. Med*. 54: 277–280.

Zuo, Z., Wang, J., Lin, C.H. and Pui, D.Y.H. (2010). VOC Outgassing from Baked and Unbaked Ventilation Filters. *Aerosol Air Qual. Res.* 10: 265–271.

Received for review, September 18, 2010
Accepted, January 19, 2011