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# Benzene, toluene and xylenes in newly renovated homes and associated health risk in Guangzhou, China

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ABSTRACT

Decoration and refurbishment in homes is associated with rapid urbanization in China. Its popularity has led to indoor elevated levels of benzene, toluene, and xylenes (BTX), posing adverse health effects to occupants. In this study, concentration levels of BTX and associated health risk were investigated in homes with new renovations in urban and suburban areas in Guangzhou, China. All air samples were collected with passive samplers for 24 h exposure in winter 2012. The average concentrations of benzene, toluene, *m*/*p*-xylene and *o*-xylene were 18.5 μg/m$^3$, 173.2 μg/m$^3$, 58.1 μg/m$^3$ and 40.8 μg/m$^3$ respectively, similar to or higher than those reported in previous studies for new homes or recently renovated homes, but generally greater than those measured in old homes. Higher BTX concentrations were observed in urban homes than in suburban homes. The mean incremental lifetime cancer risk induced by inhalation exposure to benzene in newly renovated homes in Guangzhou was $6.8 \times 10^{-6}$, higher than the acceptable risk level of $1.0 \times 10^{-6}$ and those estimated for old homes. Taking into consideration the variation in exposure concentration, potency factor and exposure factors, the incremental risk decreased to $4.7 \times 10^{-6}$. Monte Carlo simulation provides a clearer picture of cancer risk with a range of $1.0 \times 10^{-6}$ $-1.2 \times 10^{-5}$ for the selected population. Results of sensitivity analysis show that the accuracy of risk assessment could be enhanced by specifying the dose–response characterization and increasing the sample size. This study provides representative statistics regarding the BTX exposures and benzene cancer risk in newly renovated homes.



## 1. Introduction

Public concern regarding indoor airborne volatile organic compounds (VOCs) continues to grow worldwide due to their widely distributed indoor emission sources, their adverse human health effects and the fact that modern people spend around 90% of their lifetime in indoor [1]. Among these VOCs, benzene, toluene and xylenes (BTX) have been recognized as principal indoor air pollutants and were ranked the most frequently detected compounds in indoor [2,3]. Their concentrations were generally higher in indoor air than in outdoor air [4,5]. In addition, epidemiologic and case studies provide clear evidence of a causal association between exposure to indoor BTX and adverse health effects such as irritation of the eyes, skin, mucous membranes and respiratory tract [6–9]. There is also suggestive evidence that they can be associated with the etiology of chronic asthma and cancer [6,10]. And benzene has been reported as the predominant risk entity in indoor air compared with formaldehyde, naphthalene [11,12].

Exposure in homes represents a significant proportion of the total population exposure to BTX [11,13]. Indoor elevated BTX levels can result from widely-presented indoor sources such as building materials, decoration and renovation materials, adhesives, solvents, cooking and Environmental Tobacco Smoking (ETS) [7,14–16] and outdoor air pollution [17]. Loh et al. [11] ranked the cancer risks of organic air pollutants in different microenvironments in the USA, concluding that the exposures occurred at home accounted for over 40% of the total exposures and the associated risks accounted for over 50% of the total.

In association with its economic boom of the last three decades, China has experienced rapid and massive urbanization with large growth in urban populations and both absolute and per capita housing area. For example, the permanent population in Guangzhou grew from 9.97 million to 12.75 million from 2006 to 2011 and the per capita housing area in Guangzhou increased from 3.97 m$^2$ to 21.89 m$^2$ from 1980 to 2011 [18]. Accompanying these trends, decoration and refurbishment in residential

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buildings has become popular in China [5,6,19]. However, the newly renovated homes are often detected with elevated levels of BTX [16,20–22] and even show significant associations with the occurrence of sick building syndrome for inhabitants [23]. Brown [16] found that decoration materials or new furniture in new or renovated dwellings led to much higher indoor VOC concentrations, which could persist above "baseline" levels for several weeks. Other studies have shown that BTX levels in new or renovated dwellings remained elevated for 2 or 3 years [20,21]. In China, Liu et al. [22] compared the VOC levels in homes with renovation age less than 5 years and renovation age more than 5 years, finding that the former had nearly 2 times higher benzene levels than the latter. In terms of other developing countries, such as India [24], Thailand [25], Argentina [26], Egypt [27], available BTX measurements were mainly relevant to outdoor and occupational environments and there are few studies relevant to indoor residential VOC measurement; much less is known about VOC levels in newly renovated homes.

Therefore, close inspection of previous studies reveals that the health risk associated with exposure to BTX for homes with new renovations in China or other countries have been rarely evaluated. The objectives of this study were to characterize BTX exposure in homes with new renovations in urban and suburban areas in Guangzhou, China; to identify possible sources for indoor BTX; to estimate and compare the daily inhalation exposures and cancer risks with those estimated for other cities in China and abroad. In addition, we assessed the uncertainty of risk assessment.

## 2. Methods

### 2.1. Sampling site and study design

The field study was carried out in urban and suburban districts of Guangzhou, the capital city of Guangdong Province, which has been one of the most rapidly developing regions in China over the last three decades. Guangzhou has a permanent population of 12.75 million distributed over a 7434.4 $km^2$, and belongs to the Pearl River Delta in the south of China.

In this study, 30 urban and 13 suburban homes/apartments distributed in urban and suburban areas in Guangzhou were selected for exposure assessment based on (a) recent renovations and (b) locations with relatively high population density. All were voluntarily selected and checked for recent renovation with the help of a local company (Amway) in Guangzhou and all are located in business or residential district. Diffusive samplers (THPDS, Tsinghua Passive Diffusive Sampler) developed in our previous study [28] were used for indoor BTX investigation. Within addition to field sampling, a questionnaire was given to participants to collect information on apartment characteristics and potential sources of the selected analytes during the sampling period. Of the measured apartments, over 60 percent were constructed after 2000 and all have been renovated (decorated and/or refurnished) within the past two years. To evaluate the contribution of ETS to BTX concentrations, ETS during sampling was recorded and 15 smoking homes were identified. Table 1 gives main details about the investigated dwellings. More specific information regarding the renovation of the investigated houses is provided in Table S1.

**Table 1**
Characteristics of measured dwellings in Guangzhou.

| | | Number | Percentage |
|---|---|---|---|
| *Location* | Urban | 30 | 70% |
| | Suburban | 13 | 30% |
| *Building age* | Before 1980 | 0 | 0% |
| | 1980–1990 | 7 | 16% |
| | 1991–2000 | 10 | 23% |
| | 2001–2010 | 20 | 47% |
| | After 2010 | 6 | 14% |
| *Renovation* | Within 2 years | 43 | 100% |
| *Smoking* | No | 28 | 65% |
| | Yes | 15 | 35% |
| *Bedroom* | | 34 | 79% |
| *Living room* | | 9 | 21% |

### 2.2. Sampling method and analysis

Air samples in the investigated residences were collected with passive sampling method for 24 h in December 2012. Diffusive samplers (THPDS) were mailed by the Building Environment Testing Center, Tsinghua University, to householders of these apartments with instruction materials. As the bedroom and living room are the most frequently occupied areas at home, the samplers were placed in the bedroom (preferred) or living room at a height of approximately 1.5 m from the floor and away both from local sources of VOCs and the ventilation system. After sampling, the samplers were stored in sealed aluminum bags before being sent back to the center via mail.

BTX samples on passive samplers were analyzed by an automated thermal desorber (Series 2 ULTRA, Markes International Ltd) interfaced with a gas chromatograph (Agilent GC-6850) and a mass spectrometer (Agilent MS-5975C). The desorber was operated in a two-stage mode; the cold trap was filled with Tenax TA 60/80 mesh. An analytical column with a structure of 30 m × 0.25 mm × 0.25 μm (Agilent 19091S-433E) was used for chromatographic separation. Table 2 presents the details of analytical parameters.

Quality control implemented in analysis of the target compounds included measuring desorption efficiency using field blanks and measuring method detection limits (MDLs) and storage life. Accuracy of this method has been confirmed by comparison with a commonly-used active sampling method during the field test [28]. Although only one sample was taken at each selected home, the repeatability of six parallel samples had been evaluated in our previous study [28] and results showed that the average repeatability was typically below than 10%. Besides, the linearity of ATD-GC/MS in response for the target organics was evaluated before each analysis series, and the linear regression of the spiked masses and the peak areas showed that $R^2$ exceeded 0.998 [28]. More details can be found in the reference [28]. BTX levels that were below the MDLs or were not detected were replaced with half of the MDLs in the statistical analyses.

**Table 2**
Details of analytical parameters.

| | Parameter | Value |
|---|---|---|
| ATD | Desorption temperature | 300 °C |
| | Desorption time | 30 min |
| | Temperature of the focusing trap | −10 to 300 °C |
| | Trap package | Tenax TA |
| | Split flow | 54.8 ml/min |
| GC | Carrier gas | Helium |
| | Column flow | 1.0 ml/min |
| | Column temperature program | 3 min at 40 °C<br>5 °C/min–55 °C<br>10 °C/min–100 °C<br>20 °C/min–280 °C |
| Auxiliary parameter | Total split ratio | 1:30 (1/31 of analytes reaches column and detector) |

### 2.3. Data analysis

Correlation analysis, non-parametric test and principal component analysis (PCA) were performed using the SPSS software package (version 16.0, SPSS Inc., USA). The Mann–Whitney–Wilcoxon test was used to test for a significant difference between two independent samples. Statistical significance was acknowledged for $p$-value of $<0.05$.

The average chronic daily intake ($CDI$ in μg/kg/day) associated with inhalation exposure to an individual compound in homes was calculated with the methodology proposed by U.S. EPA [29]:

$$CDI_i = \frac{0.5 \times C_i \times IR \times ED \times EF}{BW \times ATL} \quad (1)$$

where $C$ is the measured exposure concentration for chemical $i$ (μg/m$^3$); $IR$, the adult inhalation rate (m$^3$/h); $ED$, the exposure duration in the homes (h/d); $EF$, the exposure frequency (years); $BW$, an adult body weight (kg); $ATL$, the average time of life (70 years) and the coefficient of 0.5 represents the absorption factor for inhalation exposure to BTX [29]. For Chinese adults, a mean body weight of 60 kg, a mean inhalation rate of 0.69 m$^3$/h [30] and a mean residence time of 16.3 h [31] were used to obtain the chronic daily dose.

A recent study conducted by Liu et al., indicated that the VOC levels in renovated homes were significantly higher than those in old homes and this situation remained at least 5 years [22]. Thus, we used 5 years as the effective exposure duration to estimate the incremental lifetime cancer risk due to the residential renovation.

Benzene is a human carcinogen. The lifetime cancer risk ($LCR$) posed by benzene was estimated as a simple multiple of the $CDI$ and a potency factor proposed by U.S. EPA [29]:

$$LCR = CDI \times PF \quad (2)$$

where $PF$ is the potency factor for benzene, (μg/kg/day)$^{-1}$, which is derived from the inhalation unit risk. It should be noted that U.S. EPA [29] provides two $PF$ values for benzene, i.e. $1.5 \times 10^{-5}$ and $5.5 \times 10^{-5}$ (μg/kg/day)$^{-1}$. The higher $PF$ for benzene was used in this study to obtain the upper-bound estimate of cancer risk from inhalation exposure.

## 3. Results and discussion

### 3.1. Concentration levels

A statistical summary of residential indoor BTX concentrations is presented in Table 3. The arithmetic average levels of benzene, toluene, $m/p$-xylene and $o$-xylene were 18.5 μg/m$^3$, 173.2 μg/m$^3$, 58.1 μg/m$^3$ and 40.8 μg/m$^3$ respectively, and were higher than their corresponding geometric means. Considerable ranges in indoor levels were observed, with large standard deviations. Clear differences between the arithmetic mean, geometric mean and median concentrations of BTX, indicate that BTX concentration distributions were highly skewed. Toluene was the most abundant compound, accounting for about 60% of the total compounds, followed by $m/p$-xylene, $o$-xylene and benzene.

**Table 3**
Descriptive statistics of BTX concentrations (μg/m$^3$) in 43 Guangzhou homes.

| | Arithmetic mean (AM) | Geometric mean (GM) | Median | Maximum | Standard deviation |
|---|---|---|---|---|---|
| Benzene (72.1%) | 18.5 | 14.0 | 18.8 | 43.7 | 11.6 |
| Toluene (90.7%) | 173.2 | 95.8 | 181.0 | 431.0 | 129.5 |
| $m/p$-Xylene (86.0%) | 58.1 | 33.3 | 46.0 | 347.7 | 62.8 |
| $o$-Xylene (74.4%) | 40.8 | 25.2 | 33.9 | 54.7 | 39.7 |

Data in the bracket represents the percentage above the MDLs.

In several developed countries, indoor benzene, toluene and xylenes levels have been found to be consistent with outdoor concentrations, which originated outdoors as vehicle emissions and industrial combustion [5,32,33]. However, indoor BTX concentrations obtained in this study, were noticeably higher than ambient BTX concentrations in Guangzhou. Tang et al. [34] reported outdoor BTX levels of 8.8 μg/m$^3$, 37.7 μg/m$^3$, 12.9 μg/m$^3$ and 4.9 μg/m$^3$ for benzene, toluene, $m/p$-xylene and $o$-xylene respectively, and much lower ambient BTX concentrations reported by Zhang et al. [25]. This suggests that indoor elevated levels of BTX in the recently renovated residences were principally contributed by indoor sources.

Currently, there are no reference concentrations of BTX for 24 h or chronic exposure indoors but only the guideline values for short-term (1 h) exposure to indoor BTX in China. The short-term limits in China for indoor BTX concentrations are 110 μg/m$^3$ for benzene, 200 μg/m$^3$ for toluene and 200 μg/m$^3$ for xylenes [35]. In this study, the 24 h BTX average concentrations measured in Guangzhou homes were lower than the short-term limits; however, 17 and 4 out of 43 homes had toluene and xylenes concentrations above the limits. Although the Chinese 1 h limits seem to be adequately protective for acute effects, prolonged exposure to concentrations under these limits could imply carcinogenic risks 2–3 orders of magnitude higher than the commonly acceptable risk of $10^{-6}$ for long-term exposure [12].

Table 4 presents the residential BTX concentrations in cities in China and abroad. For new homes or recently renovated homes, the mean concentration of benzene (18.5 μg/m$^3$) observed in Guangzhou is similar to concentrations observed in Beijing [22,36]. The mean toluene level in Guangzhou falls in the range of 250 to 6.9 μg/m$^3$ reported by Brown [16] for a new dwelling within 35 weeks after construction in Melbourne, but is higher than that in Beijing [22]. However, noticeably greater levels of xylenes were observed in this study than in other studies [16,21,22]. For old homes or homes without recent renovations, the average concentration of benzene measured in this study is generally greater than in other cities, except for the indoor benzene levels reported for Asan (Korea), Seoul (Korea) and Kolkata (India). These higher levels were either contributed to outdoor ambient air pollution [26] or associated with indoor fuel combustion [37]. Of the toluene and xylenes mean concentrations listed in Table 4, the values reported here are the highest, although concentrations of toluene up to 522.5 μg/m$^3$ were detected in an urban family house in Clermont-Ferrand, France [10] and a higher single value of 552.6 μg/m$^3$ for toluene was reported by Liu et al. [22] for a Beijing's home. In brief, the levels of BTX in this study were similar to or higher than those reported before for new homes or recently renovated homes, and generally higher than those found in old homes with a few exceptions. It is thus clear that indoor BTX pollution in newly renovated homes in China is a serious problem.

Although elevated BTX levels in the residences of Guangzhou cannot yet be fully explained, we can nonetheless note that along with rapid urbanization, decoration or renovation materials containing BTX are commonly used in Chinese residences for renovation [5,22,38]. Meanwhile, the use of BTX in solvents and adhesives has decreased in developed countries since the 1970s when their adverse health effects were confirmed [14]. A possible factor may be the different guideline limits on indoor BTX levels set by different countries or regions. For example, the value implemented for benzene in Flanders (Belgium) is 2 μg/m$^3$, whereas the guideline limit in China is 110 μg/m$^3$. A stricter regulation may make manufacturers reduce the amount of BTX contained in consumer products.

**Table 4**
Comparison with other studies reporting BTX measurement in dwellings of different countries.

| Studies | Locations | Sampling methods | Remarks | Concentrations (μg/m$^3$) | | | |
|---|---|---|---|---|---|---|---|
| | | | | Benzene | Toluene | *m*/*p*-Xylene | *o*-Xylene |
| Current | Guangzhou, China | Passive sampling for 24 h, December 2012 | 43 homes | 18.5[a]/11.6[b] | 173.2[a]/129.5[b] | 58.1[a]/62.8[b] | 40.8[a]/39.7[b] |
| *Homes with new renovations* | | | | | | | |
| Huang et al. [36] | Beijing, China | Active sampling for 45 min, July 2008–September 2012 | 379 homes newly remodeled within 1 year | 17[a]/16[b] | – | – | – |
| Liu et al. [22] | Beijing, China | Active sampling for 30 min, November–December 2009 | 152 homes recently renovated within 5 years | 16.3[a]/14.7[b] | 45.2[a]/24.7[b] | 12.3[a]/5.3[b] | |
| Brown [16] | Melbourne, Australia | Active sampling for 30–50 min | A new dwelling (living room) | ~30–2.2[a] (2–246 days) | 250–6.9[a] (2–246 days) | 30–2.8[a] (2–246 days) | – |
| Shin and Jo [21] | Daegu, Korea | Active sampling for 3 h | 25 new houses | – | 94–27[a] (1–24 weeks) | 20–2.8[a] (1–24 weeks) | 8.7–2.3[a] (1–24 weeks) |
| *Homes without new renovations* | | | | | | | |
| Lee and Li [45] | Hong Kong, China | Canister sampling for 8 h | Living rooms of 6 homes | 4.7[a]/0.5[b] | 52.1[a]/8.4[b] | 3.9[a]/1.2[b] | 4.5[a]/0.4[b] |
| Guo et al. [46] | Hong Kong, China | Passive sampling for 24 h, November 2002 | Living rooms of 100 homes | – | 15.3[a]/45.4[b] | – | 3.0[a]/2.3[b] |
| Zhou et al. [43] | Tianjin, China | Passive sampling for 5 days, May 2008 | Living rooms of 12 homes | 6.1[a]/7.6[b] | 7.5[a]/4.2[b] | 1.6[a]/1.6[b] | 0.5[a]/0.6[b] |
| Liu et al. [22] | Beijing, China | Active sampling for 30 min, November–December 2009 | 255 homes with renovations > 5 years | 9.7[a]/5.7[b] | 26.4[a]/13.2[b] | 11.5[a]/3.4[b] | |
| Ohura et al. [5] | Hangzhou, China | Active sampling for 30 min, August in 2006, January in 2007 | Bedrooms of 14 homes | 8.5[GM] | 26.7[GM] | 11.9[GM] | 4.6[GM] |
| | Shizuoka, Japan | Passive sampling for 24 h, August–September in 2006, January–March in 2007 | Bedrooms of 57 homes | 1.0[GM] | 7.2[GM] | 2.0[GM] | 0.8[GM] |
| Kim et al. [4] | Birmingham, England | Active sampling for 2 h | 12 homes | 13.9[a]/13.8[b] | 38.4[a]/21.7[b] | 7.2[a] | 1.9[a]/1.3[b] |
| Son et al. [26] | Asan, Korea<br>Seoul, Korea | Passive sampling for 24 h, August 2001 | Living rooms of 30 homes | 20.3[a]/12.6[b]<br>43.7[a]/80.1[b] | 17.3[a]/13.1[b]<br>170.6[a]/183.3[b] | 10.4[a]/7.5[b]<br>27.5[a]/65.0[b] | 9.3[a]/6.7[b]<br>33.4[a]/72.2[b] |
| Raw et al. [42] | England | Passive sampling for 4 weeks | Bedrooms of 796 homes | 3.0[GM] | 15.1[GM] | 3.8[GM] | – |
| Zhu et al. [3] | Ottawa, Canada | Active sampling for 100 min, November 2002–March 2003 | Living rooms of 75 homes | 2.9[a] | 11.5[a] | 7.5[a] | 5.1[a] |
| Majumdar et al. [37] | Kolkata, India | Active sampling for 3–4 h, March–June 2005 | Living rooms of 45 homes | 42.0[a]/33.2[b] | 69.3[a]/41.4[b] | 52.1[a]/31.1[b] | 21.6[a]/10.6[b] |

Note: [a]arithmetic mean, [b]standard deviation, [GM]geometric mean.

In addition, active and passive sampling are both used for indoor IAQ measurements (Table 4). Active sampling is more suitable for short-term exposure, while passive sampling is more suited in assessing long-term time-weighted averages of 24 h or even several weeks for air pollutants.

### 3.2. Comparison of urban and suburban levels

Fig. 1 shows BTX concentration relationships between urban and suburban homes in Guangzhou. Results of Mann–Whitney–Wilcoxon test reveal that the concentrations of toluene and *m*/*p*-xylene were significantly different between urban and suburban dwellings with *p*-values lower than 0.05, while benzene and *o*-xylene concentrations in homes from these two districts showed no significant difference as the *p*-values of 0.11 and 0.41 indicate. However, 1.5–2.2 times greater BTX concentrations were observed in urban houses than in suburban houses. The variation might be attributed to the likely higher socio-economic status (e.g. incomes) of the urban dwellers [18], which in turn affects indoor consumer product use and the strength of indoor sources. Similar results have been reported in other countries. Up to two times higher BTX concentrations in urban than rural dwellings were observed by Hulin and Caillaud [10] in France. Also, Son et al. [26] compared the BTX levels in two Korean cities, Asan (a medium city) and Seoul (a large, metropolitan city), finding that BTX levels in Seoul were significantly higher than those in Asan.

### 3.3. Source identification

It is known that benzene, toluene and xylenes are associated with ETS. Herein, BTX concentrations in 15 smoking and 28 non-smoking homes are presented in Fig. 2, with significance obtained from the Mann–Whitney–Wilcoxon test. Interestingly, smoking homes were found to have non-significantly higher mean concentrations of BTX than non-smoking homes. This indicates that additional, dominant but non-ETS sources of BTX exist in domestic environments.

Correlation analysis was performed to further identify possible emission sources of indoor BTX. Relationships among residential indoor BTX levels in Guangzhou are given in Table 5. The ratio of BTX averages was 1.0/9.5/3.2/2.0 (benzene/toluene/*m*/*p*-xylene/*o*-xylene). The targeted aromatic compounds were significantly correlated, with correlation coefficients ($R$) ranging from 0.48 to 0.90 and *p*-values equal to or less than 0.001. The good inter-correlation of the compounds indicates common sources for indoor BTX.

However, correlation analysis alone is not sufficient to demonstrate that indoor BTX has the same sources. Therefore, the

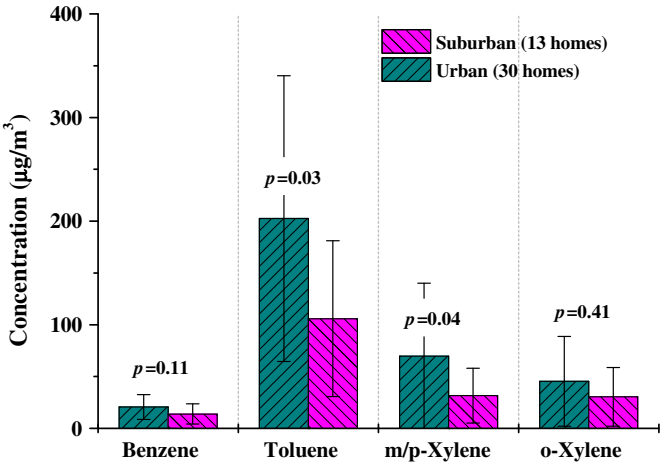


**Fig. 1.** Comparison of BTX concentrations between 30 urban and 13 suburban homes (*p*-value: Mann–Whitney–Wilcoxon test).

principal component analysis receptor model technique [5,39,40] was used. Only one factor (eigenvalues > 1.0) was extracted by PCA analysis and it accounted for 76% of the total variance. This further argues that only one main source exists for indoor BTX. Because BTX concentrations outdoors were significantly lower than indoors (see Section 3.1), we conclude that recent renovation, which includes new decoration material, new furniture and the use of solvents and adhesives, is the most important domestic source of BTX in this study, and is a greater source than residential smoking.

### 3.4. Assessment of exposure and cancer risk

The average estimates of chronic daily inhalation exposure to benzene, toluene, *m*/*p*-xylene and *o*-xylene, calculated using Eq. (1), were 0.1 μg/kg/day, 1.2 μg/kg/day, 0.4 μg/kg/day and 0.3 μg/kg/day, respectively. The *CDI*s are less than the Reference Dose for Chronic Oral Exposure, which is an estimate (with uncertainty spanning perhaps an order of magnitude) of a daily exposure to the human population (including sensitive subgroups) that is likely to be without an appreciable risk of deleterious effects during a lifetime [29]. The incremental lifetime cancer risk associated with exposure to benzene in the newly renovated homes of Guangzhou was 6.8 per million, higher than the acceptable risk level of 1 per million [12,41]. And the risk in urban and suburban areas of Guangzhou were $7.5 \times 10^{-6}$ and $5.1 \times 10^{-6}$ respectively, with no significant difference ($p > 0.05$) for participants.

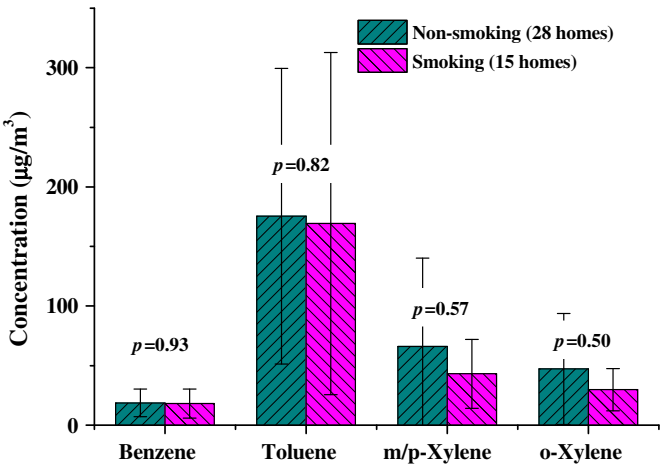


**Fig. 2.** Comparison of BTX concentrations between 28 non-smoking and 15 smoking homes (*p*-value: Mann–Whitney–Wilcoxon test).

**Table 5**
Correlation matrix for indoor BTX in Guangzhou homes.

| Correlation | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Benzene | 1 | – | 0.90 | 0.60 | 0.48 |
| Toluene | 2 | $p < 0.001$ | – | 0.66 | 0.56 |
| *m*/*p*-Xylene | 3 | $p < 0.001$ | $p < 0.001$ | – | 0.86 |
| *o*-Xylene | 4 | 0.001 | $p < 0.001$ | $p < 0.001$ | – |

Note: Upper triangle area contains the correlation coefficient, while lower triangle area contains the *p*-value.

Fig. 3 presents BTX findings in previous studies for comparison. The incremental *LCR* posed by benzene in Guangzhou is consistent with those in Beijing for recently renovated homes. However, much lower incremental risks, only one-sixth to one-third of that in Guangzhou, were obtained for old homes in Tianjin, England, and Ottawa [3,42,43]. Nonetheless, homes with additional and strong indoor sources, such as indoor fuel combustion, may have a much greater cancer risk associated with benzene ($1.5 \times 10^{-5}$) [37]. Moreover, in comparison with the total lifetime cancer risk estimated based on personal exposure to a set of VOCs in Tianjin [43] and South Baltimore [44], the incremental lifetime cancer risk posed by 5-year exposure to benzene in the recently renovated homes of Guangzhou shows a significant portion.

The comparison highlights great health risk level of newly renovated homes in China. In addition, occupants in newly renovated dwellings are actually exposed to a mixture of air toxics which could pose much higher health risk than benzene alone.

### 3.5. Uncertainty and sensitivity analysis

High uncertainty accompanies risk assessment especially when only a single point value is used to estimate the risk for a population. Therefore, given the probability distributions of relevant parameters in Eqs. (1) and (2), Monte Carlo simulation was implemented using Crystal Ball software to simulate the distribution of risk for the selected population. In order to obtain a true picture of the distribution of risk, 5000 iterations were run and a histogram of risk was produced. As presented in Fig. 4, the range of

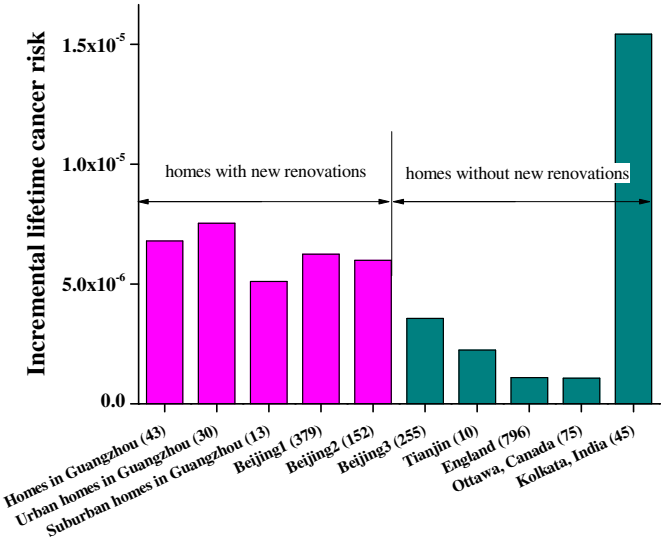


**Fig. 3.** Incremental lifetime cancer risk posed by benzene in homes of different countries.

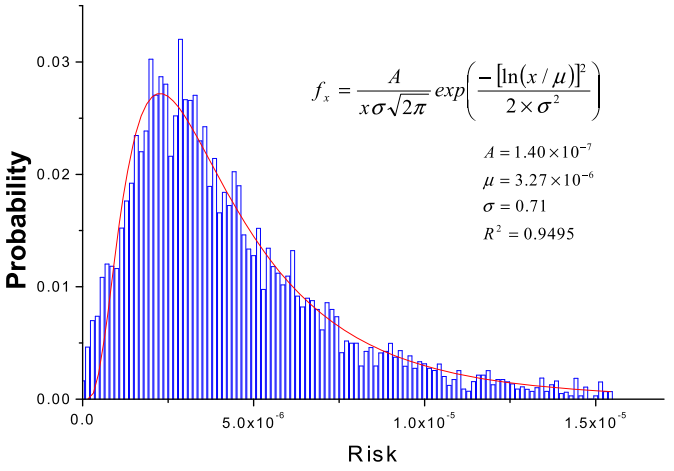


**Fig. 4.** Estimates of incremental lifetime cancer risk from benzene by Monte Carlo simulation (5000 iterations).

the incremental risk was predicted to be $1.0 \times 10^{-6}$ (5th percentile) and $1.2 \times 10^{-5}$ (95th percentile) with mean and median values of $4.7 \times 10^{-6}$ and $3.6 \times 10^{-6}$ respectively. Lognormal distribution gives the best fitting model for the frequency distribution of the benzene incremental cancer risk estimates. It should be noted that with the variation in the inhalation rate, exposure duration, body weight and potency factor taken into account, the mean incremental risk decreased to $4.7 \times 10^{-5}$, which suggests that the risk would be overestimated when the variability is not included. Nonetheless, the risk is still greater than the $1.0 \times 10^{-6}$ benchmark, indicating that the selected population is suffering noteworthy benzene cancer risk.

Results of sensitivity analysis show that *PF* and benzene concentration distribution contributed approximately 90% of the total variance of risk. The uncertainties related to potency factor affect the risk assessment, because it is derived from the cancer unit risk which in turn is obtained by linear extrapolation from the high-dose animal or human studies to the low doses of environmental exposure using either a maximum likelihood estimate or the upper 95% confidence limit on the dose response function [11,29]. There are also uncertainties in low-dose exposure scenarios and, moreover, a clear understanding of mechanisms has not yet been achieved. In addition, the limited field samples result in uncertainties in the benzene concentration distribution. It is expected that more samples taken in different seasons could give a better description of the distributions of BTX concentrations in the new/renovated residences, and further improve the accuracy of the risk estimates. Finally, desorption of analytes from passive samplers and the limitations inherent in the instrument analysis are also sources of uncertainty for risk assessment.

## 4. Conclusions

In this study, we measured the 24 h average concentrations of benzene, toluene, and xylenes (BTX) in 43 homes in Guangzhou, China. Toluene was the most abundant BTX compound, followed in order by *m*/*p*-xylene, *o*-xylene and benzene. BTX levels in this study were similar to or higher than those reported before in Beijing for new homes or recently renovated homes, but generally higher than those observed in old homes with only a few exceptions. BTX concentrations in urban homes were generally higher than those in suburban homes, although significant differences were confirmed only for toluene and *m*/*p*-xylene concentrations. Correlations and factor analysis suggested that new renovations including new decoration material, use of solvents and new furniture were the dominant domestic source of BTX rather than Environmental Tobacco Smoking in the investigated houses.

The means of chronic daily inhalation exposure and incremental lifetime cancer risk due to benzene were 0.1 μg/kg/day and $6.8 \times 10^{-6}$ in Guangzhou, which is similar to those reported in Beijing for new or recently renovated homes, but were generally higher than those for old homes. Monte Carlo simulation provides a clearer picture of benzene risk with a range of $1.0 \times 10^{-6}$–$1.2 \times 10^{-5}$ for the selected homes (population). And taking into consideration the variation in exposure concentration, potency factor and exposure factors (inhalation rate, body weight, exposure duration), the incremental risk decreased to $4.7 \times 10^{-6}$. Though the variability was high, the cancer risk was still greater than the acceptable risk level of $1.0 \times 10^{-6}$. And results of sensitivity analysis show that future research could enhance the accuracy of risk assessment by specifying the dose–response characterization and increasing the sample size.

While more efforts are needed to assess the cancer risks induced by exposure to the mixture of air contaminants, the present study demonstrates an urgent need for measures to reduce the pollution resulting from residential renovations.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.buildenv.2013.10.013.

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