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Review article

# Formaldehyde in China: Production, consumption, exposure levels, and health effects

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ABSTRACT

Formaldehyde, an economically important chemical, is classified as a human carcinogen that causes nasopharyngeal cancer and probably leukemia. As China is the largest producer and consumer of formaldehyde in the world, the Chinese population is potentially at increased risk for cancer and other associated health effects. In this paper we review formaldehyde production, consumption, exposure, and health effects in China. We collected and analyzed over 200 Chinese and English documents from scientific journals, selected newspapers, government publications, and websites pertaining to formaldehyde and its subsequent health effects.

Over the last 20 years, China's formaldehyde industry has experienced unprecedented growth, and now produces and consumes one-third of the world's formaldehyde. More than 65% of the Chinese formaldehyde output is used to produce resins mainly found in wood products — the major source of indoor pollution in China. Although the Chinese government has issued a series of standards to regulate formaldehyde exposure, concentrations in homes, office buildings, workshops, public places, and food often exceed the national standards. In addition, there have been numerous reports of formaldehyde-induced health problems, including poisoning and cancer. The lack of quality epidemiological studies and basic data on exposed populations emphasizes the need for more extensive studies on formaldehyde and its related health effects in China.

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*Abbreviations:* ALS, Amyotrophic lateral sclerosis; ALT, Alanine-amino transferase; BDO, 1,4-butanediol; CA, Chromosome aberrations; CI, Confidence interval; EU, European Union; FDR, Fecundability density ratios; GAQSIQ, General Administration of Quality Supervision, Inspection, and Quarantine, PR China; GDP, Gross domestic product; Hb, Hemoglobin; IARC, International Agency for Research on Cancer; kt, Kiloton; MAC, Maximum allowable concentration; MDI, Diphenylmethane diisocyanate; MF, Melamine-formaldehyde; MN, Micronuclei; MOH, Ministry of Health, P.R. China; OEL, Occupational exposure limit; ppm, Parts per million; PF, Phenol-formaldehyde; Plt, Platelet; RBC, Red blood cell; RMB, Renminbi, Chinese currency; RR, Relative risk; SCE, Sister-chromatid exchange; STEL, Short-term exposure limit; TWA, Time-weighted average; UF, Urea-formaldehyde; USD, US dollars, American currency; VOC, Volatile organic compound; WBC, White blood cell; WHO, World Health Organization.

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## 1. Introduction

Formaldehyde ($CH_2O$) is an important chemical for the global economy, widely used in construction, wood processing, furniture, textiles, carpeting, and in the chemical industry. It has been classified as a human carcinogen that causes nasopharyngeal cancer and probably leukemia (IARC, 2006).

As the most populous developing country in the world, China has experienced rapid economic growth and a simultaneous rise in demand for formaldehyde over the past 20 years. In 2004, China surpassed the United States as the largest formaldehyde producer and consumer in the world (Li and Wang, 2006). Coinciding with this growth, formaldehyde pollution has also increased considerably in China, particularly in indoor and outdoor air, occupational settings, and contaminated food.

Although formaldehyde is a natural metabolic product of the human body, high-dose exposure increases the risk of acute poisoning, while prolonged exposure can lead to chronic toxicity and even cancer (IARC, 2006). Recently, many cases of poisoning, allergy, asthma, pulmonary damage, cancer and death were reported as a result of formaldehyde exposure from contaminated foods, drinking water, and polluted indoor air. As the Chinese formaldehyde industry grows to meet the demands of economic expansion and as formaldehyde pollution increasingly impacts millions of people, the adverse health effects are of escalating concern in Chinese society and require further investigation. Since formaldehyde is widely used throughout the world, such an investigation would also be of international relevance. Here we review formaldehyde production, consumption, exposure, and health effects in China, and demonstrate a need for better regulation of formaldehyde exposure in this rapidly developing nation and in other countries similarly experiencing a “risk transition” (Corvalan et al., 1999).

We conducted extensive Internet searches on English and Chinese bibliographic databases that included: PubMed (2008); Web of Science Direct (2008); China National Knowledge Infrastructure (2008), which contains 7426 Chinese-language journals from 1915 to the present; Chinese standards dating back to 1957; 515 Chinese newspapers from 2000 to the present; and other official websites. This review cites a few newspaper reports that we believe to be reasonably reliable, for informative and descriptive data, when primary sources of information are not publicly available. Additionally, numerical data on China and many other nations were collected from 200 formaldehyde-related documents and compiled into figures and tables with the purpose of creating a comprehensive resource for future studies. Although no systematic screening procedures were employed, we excluded some literature of questionable accuracy.

## 2. Economic overview of formaldehyde

### 2.1. Production capacity and output

The Chinese formaldehyde industry began in 1956 with an initial annual production capacity of only 3 kilotons (kt). After three decades of slow growth, the manufacturing of formaldehyde and formaldehyde containing products accelerated in the 1990s (Fig. 1A), overtaking the United States as the highest producer in the world in 2004 (Li and Wang, 2006).

China's actual formaldehyde output has closely mirrored its production capacity (Fig. 1A), and reached a staggering 12,000 kt in 2007, about 4000 times the amount five decades earlier. Based on the average 2007 price of ¥1817 Chinese *yuan* renminbi (RMB) per ton (Zhu, 2008), the total formaldehyde produced in 2007 was valued at ¥20 billion, or about $3 billion US dollars (USD). In 2006, China produced 34% of the total global output (Fig. 1B), 2.4 times that of the US and 4 times that of Germany (Jin and Li, 2007; Zhou, 2008).

Presently, most Chinese provinces have formaldehyde production facilities. Fig. 1C shows the number of production facilities located within each province, totaling 354 for Mainland China. Rapidly developing coastal provinces represent 42% of the formaldehyde factories and about 60% of the national capacity and output (Zhou, 2008).

### 2.2. Consumption and distribution

China also leads the world in formaldehyde consumption, utilizing 11,990 kt in 2007 (Zhu, 2008). Because formaldehyde easily polymerizes at high concentrations and after long storage periods, it is often used commercially as a 37% aqueous solution (formalin) and sold locally, with less than 0.1% traded internationally (Zhou, 2008).

Formaldehyde is a raw material used in many different industries. Fig. 2A shows the relative proportions of formaldehyde consumption by category in China. More than 65% of the total formaldehyde is used to synthesize resins including urea-formaldehyde (UF), phenol-formaldehyde (PF), and melamine-formaldehyde (MF), which are often found in construction materials that contribute directly to indoor formaldehyde pollution. While these resins also make up the majority of worldwide formaldehyde consumption (Fig. 2B), less formaldehyde goes to polyacetal and diphenylmethane diisocyanate (MDI) production in China than in other parts of the world.

The rapid growth of China's formaldehyde industry, unparalleled by any other country in the world, has resulted in unprecedented pollution problems.

## 3. Formaldehyde exposure and regulation

Prior to 1990, occupational exposures in the chemical and timber industries, and in anatomy and pathology laboratories were the primary sources of formaldehyde exposure in China. Recently however, exposure from newly remodeled homes, offices, public settings, food, fabrics, carpets, and even from ambient air in major cities has dramatically increased. Formaldehyde levels between 0.1 and 0.5 parts per million (ppm, about 0.12–0.6 $mg/m^3$) are detectable by human senses, between 0.5 and 1.0 ppm (0.6–1.2 $mg/m^3$) can cause eye irritation, and above 1.0 ppm (1.23 $mg/m^3$) can irritate the nose and throat (NICNAS, 2006). Exposure levels in China often exceed

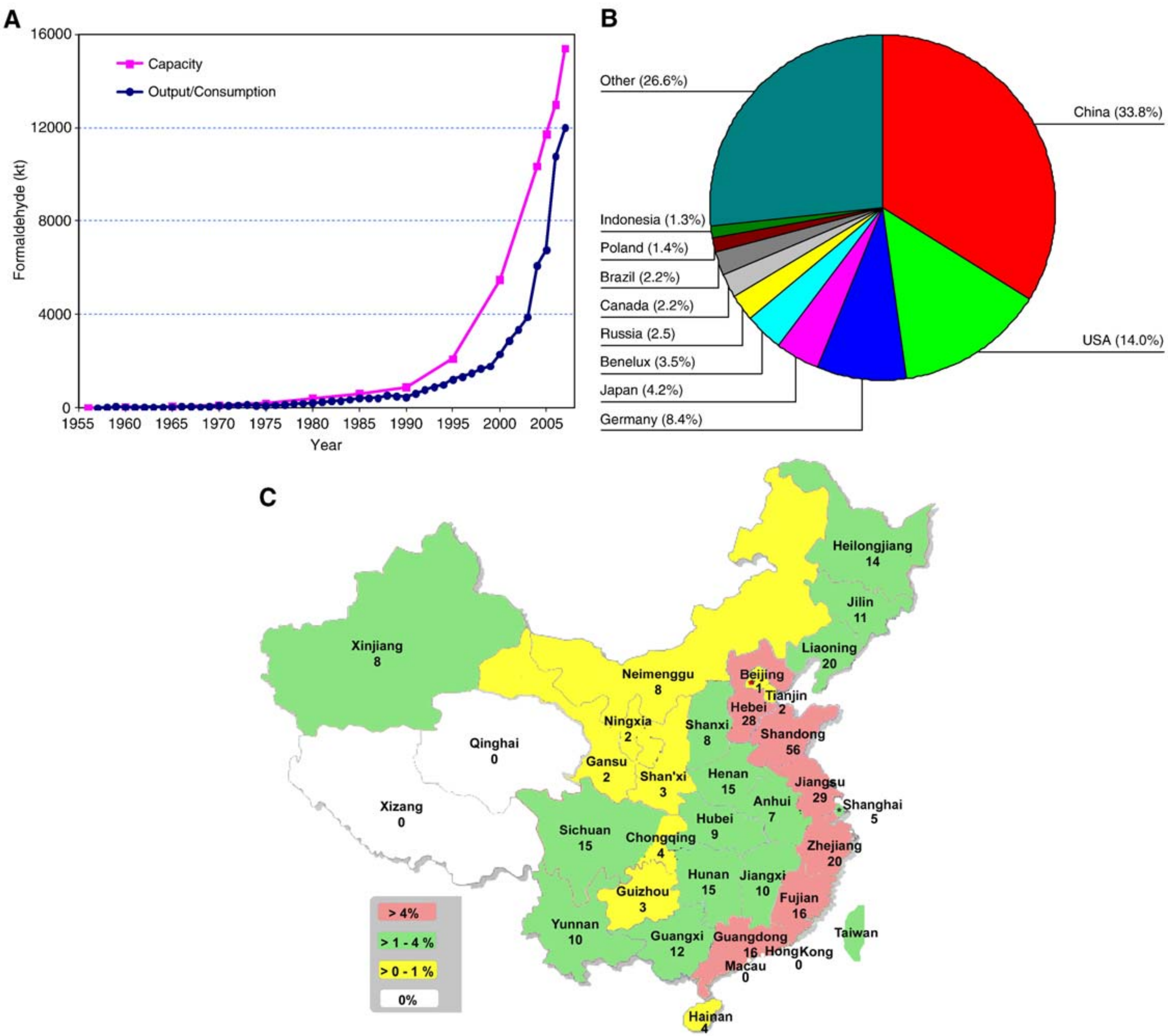


**Fig. 1.** Production capacity, output and consumption of formaldehyde in China and the makeup of formaldehyde output worldwide. A: Levels formaldehyde production capacity, output and consumption in China, from 1956–2007. In 2007, the production capacity was 15,393 kt, while output and consumption were 12,000 kt and 11,990 kt, respectively. B: Countries contributing to formaldehyde's output worldwide. The total global output for formaldehyde was 31,940 kt in 2006. China alone contributed nearly 34%. Benelux includes Belgium, Netherlands and Luxembourg. C: Each color represents that province's percent contribution to the national formaldehyde output. Directly below, the number of formaldehyde factories for each province is listed for the year 2006. From Li and Wang (2006), Jin and Li (2007), Zhu (2008) and Zhou (2008).

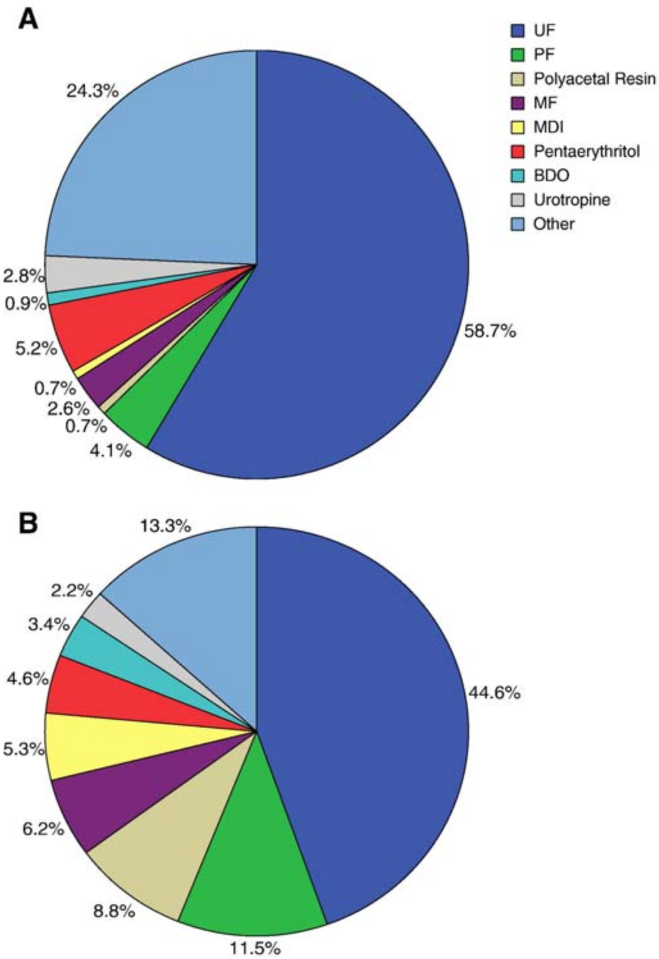


**Fig. 2.** Distribution of formaldehyde consumption in China and worldwide. A: Distribution (%) of China's formaldehyde consumption by type (total of 6100 kt of formaldehyde in 2004) B**:** Distribution (%) of the global average of formaldehyde consumption by type (total of 31,912 kt of formaldehyde in 2006). From Li and Wang (2006), Jin and Li (2007). Abbreviations: BDO: 1, 4-butanediol; MDI: Diphenylmethane diisocyanate; MF: Melamine formaldehyde resin; PF: Phenol-formaldehyde resin; UF: Urea-formaldehyde resin.

these values. To reduce pollution levels, the Chinese government has issued and updated a series of national standards regulating formaldehyde levels in the air, building and decorating materials, textiles, water and food, the most current of which are summarized in Table 1.

### 3.1. Outdoor exposure

Outdoor formaldehyde concentrations for several Chinese cities are detailed in Table 2. China's large cities have formaldehyde levels similar to cities in other developing countries such as Egypt, Mexico, and Brazil, but significantly higher than those of large cities in developed countries like Japan, Sweden and Canada (Zhang et al., 2009). Typical of most countries in the world, outdoor air standards are unregulated in China. Although research exclusively targeting China's outdoor rural formaldehyde levels has been limited, several indoor studies have measured rural outdoor concentration ranges of 10 to 20 μg/m$^3$ (Liu et al., 1993; Xu et al., 2008).

### 3.2. Indoor residential exposure

Modern home furnishings and fuel burning are the most significant sources of indoor formaldehyde pollution globally (Zhang and Smith, 1999). Both sources are important contributors to high indoor levels of formaldehyde in China because of poorly ventilated and inefficient stoves used in the countryside and the tremendous rise in home remodeling rates in the cities. Newly built residences and recently remodeled apartments release high levels of indoor formaldehyde, and with the continued expansion of these sectors, which comprised 3.5% (¥650 billion RMB or $70 billion USD) of the annual GDP (gross domestic product) in 2005 (Song, 2006), indoor residential exposure to formaldehyde is also expected to increase.

A residential indoor formaldehyde maximum allowable concentration (MAC) was established at 0.08 mg/m$^3$ by the Chinese Ministry of Health (MOH, 1995). In 2002, this value was officially readjusted to the World Health Organization's (WHO) recommended limit of 0.1 mg/m$^3$ or about 0.08 ppm (WHO-ROE, 2000), and the standard's scope was expanded to cover office buildings (GAQSIQ et al., 2002). Many other countries, such as Japan and the United Kingdom, have also adopted 0.1 mg/m$^3$ as the non-occupational formaldehyde indoor limit. Canada, Germany and Singapore have a slightly higher indoor limit of 0.1 ppm (about 0.123 mg/m$^3$). No national indoor limit currently exists in the United States (Zhang et al., 2009) (Fig. 3).

Even with these standards in place, formaldehyde exposure in China remains high. During the period 2002–2004, more than 69.4% of all newly built or remodeled houses had indoor formaldehyde levels exceeding the national standard (Table 3). Several studies measuring indoor formaldehyde levels in recently remodeled residences found that all sampled homes, with the exception of those in Hong Kong, had either maximum or average concentrations exceeding the national standard of 0.1 mg/m$^3$ (Table 4). In contrast, many international cities have average indoor formaldehyde concentrations well below 0.1 mg/m$^3$ (Zhang et al., 2009).

It has been reported that indoor formaldehyde concentrations typically decrease with time, usually falling below 0.1 mg/m$^3$ about 6 months after remodeling (Chi et al., 2007; Lin et al., 2005a; Zhang et al., 2007a). However, data in Table 4 shows that levels can remain high even up to 1 year after remodeling. In newly remodeled bedrooms in 11 cities of Jiangxi province, average formaldehyde levels measured 0.25 mg/m$^3$. In one instance, after 2 years of remodeling, formaldehyde levels still remained at 0.138 mg/m$^3$ (Zhang et al., 2007b). Seasonal fluctuations in formaldehyde levels also occur, with summer levels on average higher than winter levels in all regions, except Shizuishan (Yao et al., 2005).

Furnishings and textiles containing excessive formaldehyde levels also contribute to indoor air pollution, even in older and unremodeled homes. In 2003, the General Administration of Quality Supervision, Inspection, and Quarantine, PR China (GAQSIQ) tested bedding fabrics found in homes of 16 different cities (Wang, 2003). For many products, formaldehyde levels exceeded their respective standards, with one product having a level more than 4 times the accepted limit of 75 mg/kg (Table 1). In 2007, the Nanjing Gulou District Court in Jiangsu Province fined a furniture company ¥20,000 RMB for manufacturing wooden closets that released formaldehyde levels exceeding the standard of 1.5 mg/L (Table 1), which induced allergic symptoms in consumers (Liu and Li, 2007).

### 3.3. Indoor office exposure

The sources of formaldehyde pollution in offices are similar to those in households. Table 5 shows that with the exception of new office buildings in Pingdingshan, all other office air samples from 9 different studies had average or maximum indoor formaldehyde concentrations higher than both the Chinese indoor standard (Table 1) and the WHO indoor formaldehyde limit of 0.1 mg/m$^3$ (GAQSIQ et al., 2002; WHO-ROE, 2000).

### 3.4. Indoor public place exposure

To regulate the indoor air quality of hotels, entertainment places, shopping malls, and other public facilities, the MOH established an

**Table 1**
Current national standards regulating formaldehyde in China.

| Applied scope of standard | Current standard | | References |
|---|---|---|---|
| | Name | Level[a] | |
| Air | | | |
| Public place[b] | MAC | 0.12 mg/m$^3$ | MOH (1996) |
| Workplace | MAC | 0.5 mg/m$^3$ | MOH (2007) |
| Indoor | Average in 1 h | 0.1 mg/m$^3$ | GAQSIQ et al. (2002) |
| Civil building engineering I[c] | Free formaldehyde | 0.08 mg/m$^3$ | MOC (2001) |
| Civil building engineering II[d] | Free formaldehyde | 0.12 mg/m$^3$ | MOC (2001) |
| Building materials | | | |
| Wood-based panels and decorated wood-based panels | CRFF (environmental test cabin) | 0.12 mg/m$^3$ (E1) | MOC (2001) |
| | CFF (dry material perforation) | 9 mg/100 g (E1) | MOC (2001) |
| Adhesive timber structure | CRFF | 0.12 mg/m$^3$ | MOC (2001) |
| Drapery | CRFF | 0.12 mg/m$^3$ | MOC (2001) |
| Parquet type A | RCF | 9 mg/100 g | GAQSIQ (2000) |
| Parquet type B | RCF | 9–40 mg/100 g | GAQSIQ (2000) |
| Decorating materials | | | GAQSIQ (2001a) |
| Density fiberboard[e] | RCF (perforated extraction) | 9 mg/100 g (E1); 30 mg/100 g (E2) | |
| Veneer[f] | RCF (desiccator) | 1.5 mg/L (E1); 5.0 mg/L (E2) | |
| Surface decorated wood-based panels[g] | RCF (climate cabinet) | 0.12 mg/m$^3$ (E2) | |
| | RCF (desiccator) | 1.5 mg/L (E2) | |
| Interior architectural coatings | Free formaldehyde | 0.1 g/kg | |
| Solvent base cementing compound | Free formaldehyde | 0.5 g/kg | |
| Water base cementing compound | Free formaldehyde | 1 g/kg | |
| Wooden furniture | RCF | 1.5 mg/L | |
| Wallpaper | Content of formaldehyde | 120 mg/kg | |
| Carpet[h] | RCF | 0.05 mg/m$^2$h | |
| Textiles | | | GAQSIQ (2001b) |
| Infant product | Content of formaldehyde | 20 mg/kg | |
| Dermal contact product | Content of formaldehyde | 75 mg/kg | |
| Non-dermal contact product | Content of formaldehyde | 300 mg/kg | |
| Indoor decorating product | Content of formaldehyde | 300 mg/kg | |
| Water | | | |
| Drinking water | Content of formaldehyde | 0.9 mg/L | MOH (2006) |
| Food | | | |
| Fermented alcoholic beverages | Content of formaldehyde | 2 mg/L | MOH (2005) |
| Diagnose of occupational disease | | | |
| Acute formaldehyde poisoning | Suggested[i] | >>0.5 mg/m$^3$ | MOH (2002b) |

Abbreviations: MAC, maximum allowable concentration (for air in workplace); CRFF, content of released free formaldehyde (for wood); CFF, content of free formaldehyde (for wood); RCF, released content of formaldehyde (for wood); MOH, Ministry of Health, PR China; MOC, Ministry of Construction, PR China; GAQSIQ, General Administration of Quality Supervision, Inspection and Quarantine, PR China.

[a] E1: available for use indoor; E2: available for use indoor only after surface treatment.
[b] Includes 9 standards listed for: hotels, entertainment places, barbershops and beauty shops, gymnasiums, libraries, museums and exhibition centers, malls and book stores, hospital waiting rooms, public transportation waiting rooms, and restaurants.
[c] Includes residences, office buildings, hospital wards, senior citizen facilities, kindergarten and elementary classrooms.
[d] Includes hotels, entertainment places, book stores, libraries, exhibition halls, gyms, malls, public transit and hospital waiting rooms, restaurants, and barbershops.
[e] Includes medium density fiberboard, high density fiberboard, flakeboard, and oriented shaving board.
[f] Includes veneer, decorating faced plywood, and hipboard.
[g] Includes floor laminate covering, hard wood floors, bamboo flooring, surfaces decorated wood-based panels with paper impregnated thermosetting resins.
[h] Includes carpet, carpet lining and carpet cementing compounds.
[i] MOH (2002b) suggested that a patient could be diagnosed with acute poisoning if exposed to formaldehyde at a "higher concentration" in a "short time."

indoor formaldehyde MAC of 0.12 mg/m$^3$ in 1996 (Table 1). However, the formaldehyde concentrations of most public places in China were found to exceed this level (Table 6).

### 3.5. Occupational exposure

Historically, occupational exposure has been the dominant source of formaldehyde exposure in China. In 1979, the MOH established a MAC of 3 mg/m$^3$ (MOH, 1979) as the only Occupational Exposure Limit (OEL) for formaldehyde. In 2002, that value was significantly reduced to 0.5 mg/m$^3$ (MOH, 2002a), and remains the occupational standard today (MOH, 2007). Other countries employ time-weighted averages (TWA) and/or short-term exposure limits (STEL) rather than MACs (Zhang et al., 2009). For example, the USA's OEL (also known as Permissible Exposure Limit) is 0.75 ppm (0.92 mg/m$^3$, 8-h TWA) with a STEL of 2 ppm (2.46 mg/m$^3$) (OSHA, 1992), while the United Kingdom is 2 ppm for both TWA and STEL (HSE, 2007).

Despite the low formaldehyde OEL in China compared with other countries, formaldehyde exposure levels generally have been high across many different Chinese industries (Table 7). The wood processing industry has the highest average industrial formaldehyde concentration, caused in part by unventilated workshops and a lack of employee safety precautions. Prior to 2002, average occupational formaldehyde levels exceeded 0.5 mg/m$^3$, and in one case reached 46.14 mg/m$^3$ (Gao et al., 1988). However, with the implementation of new standards after 2002, concentrations found in most factories, including those in the wood processing industry, met the 2002 OEL of 0.5 mg/m$^3$.

Exposure levels in anatomy and pathology laboratories are still extremely high, often exceeding the 0.5 mg/m$^3$ limit (Table 8), due primarily to the evaporation of formalin used for the preservation of tissues and specimens. One study found that even when anatomy laboratories were not in use, minimum formaldehyde concentrations were still above 0.25 mg/m$^3$, with a few extreme instances measuring between 13.01 and 20.94 mg/m$^3$ (Zhang et al., 2007d). In Shanghai, the average formaldehyde concentration in 11 hospital pathology laboratories was 1.60 mg/m$^3$, with one case measuring as high as 5.84 mg/m$^3$ (Fan et al., 2006).

**Table 2**
Outdoor formaldehyde concentrations in selected Chinese cities.

| City | Sample number | Formaldehyde (μg/m$^3$) | | Sampling time | References |
|---|---|---|---|---|---|
| | | Mean ± SD | Range | | |
| Beijing | 9 | 25.4 ± 12.4 | | 2004 summer | Wang et al. (2007a) |
| | 86 | 4.2 ± 2.8 | 1.1–2.1 | 2004–2005 winter | Pang and Mu (2006) |
| | 9 | 4.7 ± 3.1 | | 2004–2005 winter | Wang et al. (2007a) |
| | 110 | 19.5 ± 8.9 | 2.6–52.9 | 2005 summer | Pang and Mu (2006) |
| | 140 | 19.51 ± 5.57 | 5.69–101 | 2005 summer | Xu et al. (2006) |
| | | 35.96 | | 2006 summer | Duan et al. (2008) |
| Guangzhou | 25 | 12.37 ± 7.33 | 6.43–29.00 | 2002 summer | Feng et al. (2004) |
| | 20 | | 6.7–13.4 | 2004 | Lü et al. (2006) |
| | 9 | 15.0 ± 4.0 | | 2004 summer | Wang et al. (2007a) |
| | 9 | 10.5 ± 3.2 | | 2004–2005 winter | Wang et al., (2007a) |
| Hong Kong | 4 | | 8.3–16.7 | 2001 summer | Ho et al. (2006) |
| | 120 | 6.1 | | 2001 summer | Guo et al. (2004) |
| | 5 | | 4.7–8.8 | 2001–2002 winter | Ho et al. (2006) |
| | 120 | 5.2 | | 2001 winter | Guo et al. (2004) |
| Qingdao | 6 | 3.64 | 0.46–4.81 | 1997–1998 winter | Tan et al. (2002) |
| | 4 | 9.95 | 8.84–10.30 | 1998 summer | Tan et al. (2002) |
| Shanghai | 9 | 16.3 ± 1.5 | | 2004 summer | Wang et al. (2007a) |
| | 9 | 9.2 ± 2.2 | | 2004–2005 winter | Wang et al. (2007a) |
| Taiyuan | 11 | 30 | 20–50 | 2001 | Zheng and Liu (2002) |
| | 9 | 5.8 ± 0.6 | 5.0–7.0 | 2004 | Zhao et al. (2008) |
| Xi'an | 9 | 9.9 ± 2.9 | | 2004 summer | Wang et al. (2007a) |
| | 9 | 6.5 ± 2.2 | | 2004–2005 winter | Wang et al. (2007a) |
| **Total** | **732** | **11.7**[a] | | **1997–2006** | |

[a] Formula: the average outdoor formaldehyde concentration in Chinese cities = $\sum$ (sample number × mean concentration)/total sample number, excluding samples without mean concentrations. The calculated average is 11.7 μg/m$^3$ for the period of 1997–2006.

### 3.6. Food exposure

Formaldehyde is a natural metabolite in many living things, and is thus present in many foods such as shiitake mushrooms, which have a high base content of formaldehyde ranging from 40 to 380 mg/kg (Yang et al., 2007). Many fresh marine products such as mackerel, squid, pomfret, hairtail, sea cucumber, red shrimp, yellow croaker, scallop and octopus naturally have an average formaldehyde base content of 2.177 ± 1.414 mg/kg (Wang et al., 2007a). However, the illegal practice of using synthetic formaldehyde (Rongalite®) as a food preservative is common in Chinese markets, resulting in levels that exceed the national standards and negatively affect human health. Seven independent studies in Fuzhou, Dalian, Guangzhou, Shangqiu, Yantai and Shanghai discovered that marine products illegally treated with formaldehyde preservatives had a formaldehyde content exceeding 300 mg/kg, with extreme cases reaching 4250 mg/kg (Cai

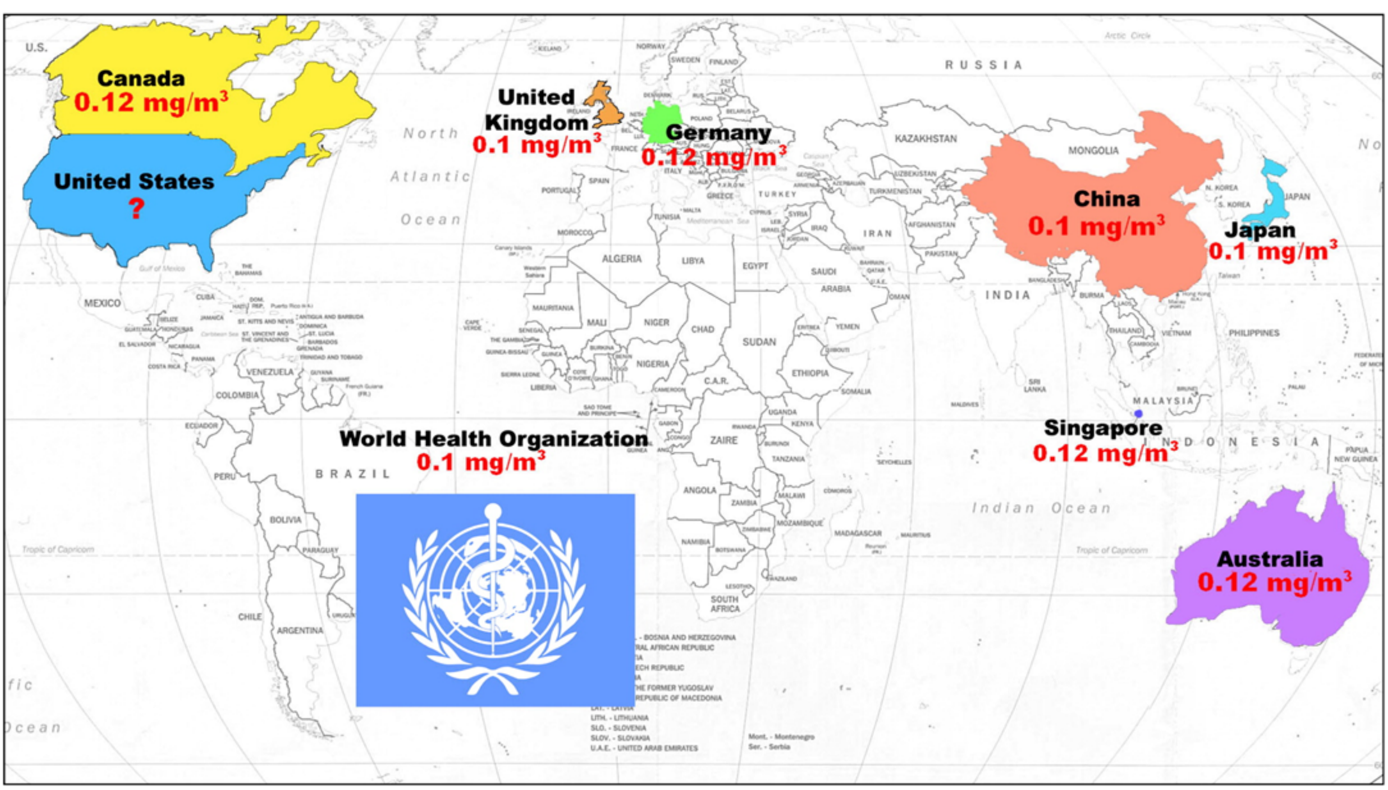


**Fig. 3.** Current formaldehyde indoor exposure limits for various countries. Several countries have adopted the WHO indoor formaldehyde exposure limit, with values listed here in mg/m$^3$. Countries with original limits in parts per million (ppm) were converted to mg/m$^3$ by a factor of 1.23.

**Table 3**
Percentage of new or newly remodeled homes with formaldehyde levels above the indoor residential standard in China.

| City | Number of households | Percentage above standard (%) | Sampling time | Reference |
|---|---|---|---|---|
| Urumqi | 200 | 82.5 | 2002–2004 | Han et al. (2007) |
| Beijing | 1400 | 60 | 2004 | Song (2006) |
| Qingdao | 85 | 70 | 2004 | Song (2006) |
| Nanjing | 365 | 80 | 2004 | Song (2006) |
| Shenzhen | 400 | 90 | 2004 | Song (2006) |
| Yinchuan | 174 | 60 | 2004 | Song (2006) |
| Jiangxi[a] | 167 | 80 | 2004–2005 | Zhang et al. (2007b) |
| **Total** | **2791** | **70**[b] | **2002–2005** | |

[a] Includes 11 cities: Nanchang, Fuzhou, Ganzhou, Jian, Jingdezhen, Jiujiang, Pingxiang, Shangrao, Xinyu, Yichun, Yingtan.
[b] Formula: the average percentage of homes with levels above the indoor residential standard in Chinese cities = $\sum$ (number of households × percentage above standard)/ total number of households. The average is 70% for the period of 2002–2005.

et al., 2000; Li et al., 2006; Lin et al., 2005b; Nie, 2005; Wang et al., 2007b; Xu et al., 2004; Zhang et al., 2006b).

Sixty different fresh fruits exhibited formaldehyde content below 2.74 mg/kg in a 2007 study, but with refrigeration, this value increased 2.3–3.8 times (Ma et al., 2007). The vermicelli noodle was also assessed for formaldehyde in two different studies, and the ranges found were 0.011–2.859 mg/kg and 1.0–3.38 mg/kg, respectively (Hu et al., 2003; Li et al., 2003).

Between 2003 and 2005, Chinese consumers were alarmed by media alerts of toxic formaldehyde found in beer (Zhang et al., 2005). However, a national investigation showed that all marketed beers, both domestic and imported, contained formaldehyde concentrations ranging between 0.1 and 0.9 mg/kg (GAQSIQ, 2005), which are well below the national standard of 2 mg/L (MOH, 2005).

### 3.7. Estimated personal exposure

To help conceptualize the daily formaldehyde level to which a typical Chinese urban dweller is exposed, an estimated personal daily exposure was calculated based on the average levels (see table footnotes) listed in the corresponding tables. Assuming that exposure to formaldehyde is 0.0117 mg/m$^3$ outdoors for 4-h (Table 2), 0.238 mg/m$^3$ in a remodeled home for 12-h (Table 4), and 0.256 mg/m$^3$ in a new office building for 8-h (Table 5), hypothetically, a typical person could be exposed to an average concentration (similar to TWA, 24-h) of 0.21 mg/m$^3$ per hour each workday, not including the occasional exposure from food. During the weekend, assuming he or she was exposed to formaldehyde in public places (4-h, 0.144 mg/m$^3$, Table 6), outdoors (6-h) and in the home (14-h), a person could encounter 0.17 mg/m$^3$ on average per hour per weekend day. Thus, a person living in a Chinese city could be continually exposed to formaldehyde

**Table 4**
Indoor formaldehyde concentrations in recently remodeled homes in urban and rural China.

| Area | Sample number | Formaldehyde (μg/m$^3$) | | Time since remodeling | Sampling time | References |
|---|---|---|---|---|---|---|
| | | Mean ± SD | Range | | | |
| Urban | | | | | | |
| Beijing | 1207 | 180 ± 170 | | <1 year | 2002–2004 | Xu et al. (2007a) |
| | 530 | 210 ± 152 | 25–1382 | <6 months | 2003 winter | Yao et al. (2005) |
| | 389 | 278 ± 211 | 25–1879 | <6 months | 2003 summer | Yao et al. (2005) |
| | 54 | 150 | 15–420 | 4 months | 2004 | Zhang et al. (2007a) |
| | 54 | 30 | 5–40 | 6 months | 2004 | Zhang et al. (2007a) |
| Shanghai | 166 | 100 ± 60 | | <1 year | 2002–2004 | Xu et al. (2007a) |
| | 182 | 205 ± 135 | 25–869 | <6 months | 2003 winter | Yao et al. (2005) |
| Tianjin | 154 | 130 ± 80 | | <1 year | 2002–2004 | Xu et al. (2007a) |
| | 159 | 125 ± 79 | | 6–12 months | 2003 summer | Liu et al. (2005) |
| | 164 | 267 ± 170 | 25–1100 | <6 months | 2003 winter | Yao et al. (2005) |
| Chongqing | 198 | 142 ± 84 | 25–461 | <6 months | 2003 winter | Yao et al. (2005) |
| | 202 | 397 ± 172 | 121–1182 | <6 months | 2003 summer | Yao et al. (2005) |
| Hongkong | 6 | | 11–22 | 6 months | 1999 summer | Lee et al. (2002) |
| Maoming | 48 | | 33–901 | 5.5 months | 2003 | Lin et al. (2005a) |
| Nanjing | 427 | 200 ± 170 | | <1 year | 2002–2004 | Xu et al. (2007a) |
| Jiangxi[a] | 455 | 250[b] | 6–1070 | N/A | 2004–2005 | Zhang et al. (2007b) |
| Changchun | 56 | 320 ± 290 | 80–590 | 3 months | 2006 | Ren and Liu (2007) |
| | 201 | 412 ± 208 | 25–1243 | <6 months | 2003 winter | Yao et al. (2005) |
| Shizuishan | 212 | 610 ± 311 | 104–1712 | <6 months | 2003 winter | Yao et al. (2005) |
| | 196 | 251 ± 139 | 29–1167 | <6 months | 2003 summer | Yao et al. (2005) |
| Urumuqi | 198 | 409[b] | 0–5590 | <3 years | 2002–2004 | Han et al. (2007) |
| Dalian | 30 | 130 | 0–500 | N/A | 2002 winter | Zhao et al. (2004) |
| Shenyang | 20 | 390 | 150–820 | <1 month | 2006 | Yang (2007b) |
| Shiyan | 150 | 270 | 60–1290 | <1 year | 2006 | Lin (2007) |
| Wuhan | 319 | 239[b] | 11–1021 | 1–4 months | 2005 | Chi et al. (2007) |
| | 128 | 88[b] | 10–381 | 4–6 months | 2005 | Chi et al. (2007) |
| **Subtotal** | **5905** | **238**[c] | | | **1999–2006** | |
| Rural | | | | | | |
| Shunyi | 711 | 34[b] | 28–38 | No remodeling | 1993 winter | Liu et al. (1993) |
| | 479 | 34[b] | 23–43 | No remodeling | 1993 summer | Liu et al. (1993) |
| Changzhou | | | 133–300 | <6 months | 2005 | Zhang et al. (2008) |
| Hefei | 30 | 40 | | No remodeling | 2006 | Xu et al. (2008) |
| | 30 (Kitchen) | 60 | | No remodeling | 2006 | Xu et al. (2008) |
| Fuyang | 30 | 20 | | No remodeling | 2006 | Xu et al. (2008) |
| | 30 (Kitchen) | 50 | | No remodeling | 2006 | Xu et al. (2008) |
| Pingdingshan | 38 | | 48–344 | <3 years | 2006 | Zhou et al. (2007) |
| **Subtotal** | **1348** | **35**[c] | | | **1993–2006** | |

[a] Includes 11 cities: Nanchang, Fuzhou, Ganzhou, Jian, Jingdezhen, Jiujiang, Pingxiang, Shangrao, Xinyu, Yichun, Yingtan.
[b] Combined average calculated from subsets of means with corresponding sample sizes given in the original paper.
[c] Formula: the average formaldehyde concentration in remodeled homes in urban/rural area of Chinese cities = $\sum$ (sample number × mean concentration) / total sample number, excluding samples without mean concentrations. The calculated urban average is 238 μg/m$^3$ between 1999–2006. The rural average is 35 μg/m$^3$ in the period of 1993–2006.

**Table 5**
Indoor formaldehyde concentrations in Chinese offices.

| City | Sample number | Formaldehyde (μg/m$^3$) | | Sampling time | References |
|---|---|---|---|---|---|
| | | Mean ± SD | Range | | |
| Hongkong | 40 | 83 ± 62 | 22–273 | 1996 | Mui et al. (2008) |
| Nanjing | 7 | 220 ± 170 | 80–500 | 2002 | Wang et al. (2003) |
| Hefei | 117 | 210 ± 88 | 17–490 | 2002–2003 | Wang et al. (2004) |
| Urumuqi | 44 | 270–500 | 0–1510 | 2002–2004 | Han et al. (2007) |
| Nanjing | 10 | 533 | 176–1359 | 2002–2004 | Huang et al. (2007a) |
| Haerbin | 6 | 1320–2250 | | 2003–2004 | Xiao et al. (2006) |
| Jiangxi[a] | 62 | 324 | 15–3390 | 2004–2005 | Zhang et al. (2007b) |
| Pingdingshan | 14 | 58 ± 19[b] | 28–90 | 2005 | Jiang (2006) |
| Zhuhai | 51 | 130 ± 130 | | 2005 | Zhao et al. (2007) |
| **Total** | **351** | **256**[c] | | **1996–2005** | |

[a] Includes 11 cities: Nanchang, Fuzhou, Ganzhou, Jian, Jingdezhen, Jiujiang, Pingxiang, Shangrao, Xinyu, Yichun, Yingtan.
[b] Mean and SD calculated from the actual data given in the original paper.
[c] Formula: the average indoor formaldehyde concentrations of offices in China = $\sum$ (sample number × mean concentration) / total sample number. The calculated average is 256 μg/m$^3$ for the period of 1996–2005.

at a level higher than the WHO recommended indoor limit of 0.1 mg/m$^3$ (WHO-ROE, 2000). Similarly, a person working in an industrial or professional workplace (Tables 7 & 8) can also be exposed occupationally to average formaldehyde levels at 0.58 or 0.61 mg/m$^3$ per hour per day, respectively, which exceed the 2007 MOH standard of 0.5 mg/m$^3$ (Table 1).

## 4. Health effects of formaldehyde

The cumulative effects of ambient, residential, occupational, and food exposure to formaldehyde have resulted in adverse human health effects. There have been many documented cases of formaldehyde exposure from polluted air, water and contaminated food in the past two decades. Many of these have resulted in negative health outcomes, and public concern regarding the health effects of formaldehyde exposure continues to grow today, both in China and worldwide.

### *4.1. Acute toxicity and immunotoxicity*

Formaldehyde is known to induce acute poisoning, cause irritation, as well as other immunotoxic effects.

**Table 6**
Indoor formaldehyde concentrations of public places in selected Chinese cities.

| Place name | City | Sample number | Formaldehyde (μg/m$^3$) | | Sampling time | References |
|---|---|---|---|---|---|---|
| | | | Mean ± SD | Range | | |
| Hotel guest room | Luoyang | 41 | 200 ± 40 | | 2002–2004 | Zhao (2005) |
| | Haikou | 42 | 290 ± 20 | | 2002 | Lü (2004) |
| | Shenzhen | 10 | 158 ± 39 | | N/A | Lin (2003) |
| | Guangzhou | 105 | 66 ± 28 | 40–140 | 2001 | Wang (2004) |
| | Guangzhou | 56 | 60 ± 30 | 30–150 | 2001 | Jiang (2002) |
| | Jiangxi[a] | 46 | 149 | 10–670 | 2004–2005 | Zhang et al. (2007b) |
| Karaoke TV | Luoyang | 58 | 350 ± 20 | | 2002–2004 | Zhao (2005) |
| | Haikou | 30 | 350 ± 30 | | 2002 | Lü (2004) |
| | Shenzhen | 10 | 182 ± 46 | | N/A | Lin (2003) |
| | Guangzhou | 29 | 70 ± 20 | 30–110 | 2001 | Jiang (2002) |
| Ball room | Guangzhou | 36 | 50 ± 10 | 40–90 | 2001 | Jiang (2002) |
| | Guangzhou | 28 | 30 ± 22 | 26–63 | 2002 summer | Feng et al. (2004) |
| Massage room | Luoyang | 32 | 310 ± 30 | | 2002–2004 | Zhao (2005) |
| | Haikou | 21 | 380 ± 40 | | 2002 | Lü (2004) |
| Mall | Hongkong | 9 | | 15–60 | 1999 summer | Li et al. (2001) |
| | Luoyang | 30 | 180 ± 30 | | 2002–2004 | Zhao (2005) |
| | Haikou | 20 | 270 ± 30 | | 2002 | Lü (2004) |
| | Shenzhen | 10 | 125 ± 27 | | N/A | Lin (2003) |
| | Guangzhou | 137 | 74 ± 36 | 40–200 | 2000 | Wang (2004) |
| Furniture market | Beijing | 134 | | 69–380 | N/A winter | Lü et al. (2001) |
| | Beijing | 216 | | 260–1180 | N/A summer | Lü et al. (2001) |
| | Anyang | 30 | | ?–449 | N/A | Wang and Han (2003) |
| Library (Journal room) | Qiqihaer | 20 | 44 | 30–56 | 2005 | Wu et al. (2006) |
| (Stack room) | Qiqihaer | 20 | 48 | 38–103 | 2005 | Wu et al. (2006) |
| (Reading room) | Qiqihaer | 20 | 19 | 9–33 | 2005 | Wu et al. (2006) |
| Dining Hall | Guangzhou | 87 | 55 ± 34 | 40–160 | 2000 | Wang (2004) |
| Train (soft berth) | Lanzhou | | 115 ± 21 | 74–160 | N/A | Zuo (2003) |
| (Soft berth) | Beijing | 27 | 74 ± 42 | | 2005 | Lu (2007) |
| (Hard berth) | Lanzhou | | 55 ± 8 | 25–86 | N/A | Zuo (2003) |
| (Hard seat) | Lanzhou | | 34 ± 14 | 12–61 | N/A | Zuo (2003) |
| Automobile[b] | Jinzhou | 20 | 330–570 | | N/A | Qu et al. (2007) |
| **Total** | | **1324** | **144**[c] | | **1996–2005** | |

[a] Includes 11 cities: Nanchang, Fuzhou, Ganzhou, Jian, Jingdezhen, Jiujiang, Pingxiang, Shangrao, Xinyu, Yichun, Yingtan.
[b] Includes indoor levels of newly manufactured cars, vans, buses, trucks and other multi-functional vehicles.
[c] Formula: the average indoor formaldehyde concentration of public places in selected Chinese cities = $\sum$ (sample number × mean concentration) / total sample number (excluding samples without mean). The calculated average is 144 μg/m$^3$ for the period of 1996–2005.

**Table 7**
Occupational exposure concentrations of formaldehyde in Chinese factories.

| Workshop | City | Sample number | Formaldehyde ($mg/m^3$) | | Sampling time | References |
|---|---|---|---|---|---|---|
| | | | Mean ± SD | Range | | |
| Chemical industry | | | | | | |
| Vinylon production | Shanghai | | 2.51 | 0.95–5.72 | 1990 | Jin and Zhu (1992) |
| Hexamine workshop | Qingzhen | | 0.787 | | 1990 | Dai and Bao (1999) |
| Polyacetal workshop | Qingzhen | | 1.023 | | 1990 | Dai and Bao (1999) |
| Formaldehyde oxidation | Changchun | 196 | 1.2 | 0.01–2.10 | 1988–1997 | Zhang et al. (1999) |
| Formaldehyde storage | Changchun | 206 | 1.3 | 0.02–1.80 | 1988–1997 | Zhang et al. (1999) |
| Formaldehyde workshop | Jinsha | 22 | 0.985 | | 1994 | Cheng et al. (1995) |
| Formaldehyde workshop | Shanghai | | | 0–2.88 | 1995 | Huan et al. (2001) |
| Formaldehyde workshop | Shanghai | | | 0–3.66 | 1995 | Huan et al. (2001) |
| Formaldehyde workshop | Shanghai | 12 | 2.53 ± 2.17 | 0.24–8.03 | 1996 | Wang et al. (1997) |
| Formaldehyde production | Muyang | 48 | 1.07 | 0.5–3.5 | 2001 | Li and Chen (2002) |
| Formaldehyde workshop | Hengyang | 21 | 0.029 | 0.022–0.044 | 2006 | Yang (2007a) |
| Wood Industry | | | | | | |
| Cork compression | Yuncheng | 28 | 3.01[a] | 0.33–46.14 | 1985 | Gao et al. (1988) |
| Wood processing | Hefei | 104 | 3.07 ± 5.83 | 0.7–19.2 | 1995 | Feng et al. (1996) |
| Wood processing | Fuzhou | 72 | 0.92 ± 0.4 | | 1990–1998 | Pan et al. (2000) |
| Wood processing | Fuzhou | 90 | 0.87 ± 0.5 | | 1990–1998 | Pan et al. (2000) |
| Blocking | Shanghai | 40 | 1.13 ± 0.59 | 0.35–2.60 | 2002 | Fan et al. (2004) |
| Blocking | Kunshan | | 0.18 | | 2005 | Shi et al. (2006) |
| Density fiberboard | Liaocheng | 60 | 0.42 | 0.11–0.86 | 2003 | Geng et al. (2004) |
| Density fiberboard | | | 0.41 | 0.14–3.20 | 2005 | Jiang et al. (2006) |
| Textile and shoe industry | | | | | | |
| Resin collar | Changzhou | 18 | | 0.22–0.62 | 1989 summer | Tao et al. (1990) |
| Resin collar | Changzhou | 9 | | 1.39–5.59 | 1989 winter | Tao et al. (1990) |
| Paint/production | Fuzhou | 56 | 1.92 ± 0.8 | 0.4–4.3 | 2000 | Pan et al. (2001) |
| Insulation and map industry | | | | | | |
| Insulating material | Changzhou | 8 | | 0.15–0.39 | 1989 summer | Tao et al. (1990) |
| Insulating material | Changzhou | 8 | | 0.64–0.93 | 1989 winter | Tao et al. (1990) |
| Map printing | Yuncheng | 28 | 0.64[a] | 0.04–1.79 | 1985 | Gao et al. (1988) |
| Food industry | | | | | | |
| Germination hood | Qingyuan | | | 0.6–23.0 | 2000 | Wu and Wu (2001) |
| Germination room | Qingyuan | | | 0.05–0.36 | 2000 | Wu and Wu (2001) |
| Germination room | Wuhan | 24 | | 0.44–6.84 | 2005 | Xu et al. (2007b) |
| **Total** | | **1050** | **1.37**[b] | | **1985–2006** | |

[a] Combined average calculated from subsets of means with corresponding sample sizes given in the original paper.
[b] Formula: the average industrial occupational exposure to formaldehyde = $\sum$ (sample number × mean exposure) / total sample number (excluding samples without mean). The calculated average is 1.37 $mg/m^3$ for the period of 1985–2006.

**Table 8**
Formaldehyde levels of anatomy and pathology laboratories in Chinese medical colleges and hospitals.

| Location | City | Sample number | Formaldehyde ($mg/m^3$) | | Sampling time | References |
|---|---|---|---|---|---|---|
| | | | Mean ± SD | Range | | |
| Medical college | | | | | | |
| Anatomy labs | Lanzhou | 2 | 4.134 | | 1998 | Li et al. (1999) |
| | Dalian | 12 | 1.074 ± 0.454 | | 1999 | Ye et al. (2000) |
| | Wuhan | 3 | 8.349 ± 2.644[a] | 5.869–11.131 | 2002 | Peng et al. (2003) |
| | Luzhou | 2 | | 12.95–20.94 | 2002 | Zhang et al. (2007d) |
| | Urumuqi | 9 | 0.326 ± 0.508 | 0.037–3.98 | 2006 | Lu et al. (2007) |
| Teacher offices | Lanzhou | 2 | 0.386 | | 1998 | Li et al. (1999) |
| | Dalian | 12 | 0.200 ± 0.088 | | 1999 | Ye et al. (2000) |
| | Urumuqi | 9 | 0.040 ± 0.020 | | 2006 | Lu et al. (2007) |
| Corridors | Dalian | 14 | 0.315 ± 0.117 | | 1999 | Ye et al. (2000) |
| | Urumuqi | 9 | 0.056 ± 0.040 | | 2006 | Lu et al. (2007) |
| Specimen workshops | Lanzhou | 2 | 1.100 | | 1998 | Li et al. (1999) |
| Anatomy classrooms | Lanzhou | 4 | 2.514 | | 1998 | Li et al. (1999) |
| Specimen rooms | Lanzhou | 2 | 12.783 | | 1998 | Li et al. (1999) |
| Hospital | | | | | | |
| Pathology rooms | Shanghai | 85 | 1.60 ± 1.10 | 0.18–5.84 | 2003 | Fan et al. (2006) |
| | Chaoyang, Beijing | 2 | | 0.086–0.088 | 2005 | Li and Li (2007) |
| | Xuanwu, Beijing | 2 | | 0.610–0.630 | 2005 | Li and Li (2007) |
| | Xicheng, Beijing | 2 | | 1.300–1.500 | 2005 | Li and Li (2007) |
| | Chongwen, Beijing | 2 | | 1.900–2.000 | 2005 | Li and Li (2007) |
| | Bengpu | 40 | | 0.184–0.931[b] | 2003 | Cheng et al. (2004) |
| Hemodialysis labs | Taiwan | 27 | 0.184[c] | 0.06–3.44 | | Kuo et al. (1997) |
| **Total** | | **215** | **1.46**[d] | | **1998–2006** | |

[a] After opening the cadaver container for 20 minutes without turning on the circulation system.
[b] Includes diagnostic rooms, stock rooms, and offices.
[c] Combined average calculated from subsets of means with corresponding sample sizes given in the original paper.
[d] Formula: the average formaldehyde concentration in anatomical laboratories and pathological rooms = $\sum$ (sample number × mean concentration ) / total sample number (excluding samples without mean). The calculated average is 1.46 $mg/m^3$ for the period of 1998–2006.

#### 4.1.1. Acute poisoning

In 1998, 17 employees of a pharmaceutical company who continuously inhaled formaldehyde vapors showed symptoms of irritated eyes, tearing, sneezing, coughing, chest congestion, fever, heartburn, lethargy, and loss of appetite. As a result of the poisoning, some even experienced vomiting, abdominal pain, and nodal tachycardia (Hao et al., 1998). In 2000, a 32-year-old male experienced abdominal pain, bloody stool, hematemesis, and a high serum alanine-amino transferase (ALT) level of 105 µg/L after imbibing 300 mL of formaldehyde-contaminated water (Liu and Song, 2001). Another 26-year-old male died of extreme abdominal pain, cyanosis, and gastric mucosal degeneration just two hours after drinking a cup of water containing concentrated formaldehyde (Hao, 2004). Sixty students at a middle school discovered they were poisoned 30 min after consuming formaldehyde preserved Pacific saury fish. They all reported symptoms of nausea, while 83% experienced vomiting, and 50% experienced dizziness (Li and Song, 2006; Zhang et al., 2006a). Thirty-eight middle school employees also reported similar symptoms after eating formaldehyde preserved fish, with the onset of these symptoms occurring 0.5–2 h after consumption (Li and Song, 2006; Zhang et al., 2006b). Because formaldehyde is illegally used as a food preservative, formaldehyde-induced food poisoning remains a huge problem in China.

#### 4.1.2. Irritation

Acute mucus membrane irritation is the most common side effect of formaldehyde poisoning, often leading to dry skin, dermatitis, tearing eyes, sneezing, and coughing. Serious formaldehyde exposure often results in eye conjunctivitis, nasal and pharyngeal diseases, and can even increase the likelihood of dangerous conditions such as laryngospasm and pulmonary edema. One man, whose face was directly exposed to a large amount of formalin, suffered from facial swelling and cornea degeneration (Li, 1997), while similarly exposed employees of a wood processing factory experienced pharyngeal congestion, chronic rhinitis, and decreased olfactory functioning (Wang et al., 1999). Another study confirmed these results when 66 chemical industrial workers who were occupationally exposed to formaldehyde reported increased occurrences of congestion in the cornea, nasal membrane, and pharynx (Zhang et al., 1999).

#### 4.1.3. Dermal allergies

Formaldehyde exposure is also known to directly cause dermal allergies (Cronin, 1991). Four out of 10 operators of chemical melting devices in a PF factory experienced dermatitis after occupational contact with formaldehyde (Su and Zheng, 1995). In another instance on a mushroom farm, two-thirds of the employees, who were exposed to formaldehyde levels ranging from 0.60–23 mg/m$^3$, developed dermatitis on their arms and forearms, with symptoms that included red spots, swelling, irritation, pain, and burning sensation (Wu and Wu, 2001).

#### 4.1.4. Allergic asthma

It has been shown that the likelihood for the development of allergic asthma increases proportionately with indoor formaldehyde concentration, especially when levels exceed 0.12 mg/m$^3$ (Yue et al., 2004). In 1996, 60 mushroom farmers experienced coughing and asthma after occupational exposure to gaseous formaldehyde (Xiang, 1996).

#### 4.1.5. Comparison with international cases

Cases of formaldehyde-induced acute poisoning are not unique to China. A 2006 French study found that inhalation of formaldehyde at 0.1 mg/m$^3$, the WHO's recommended maximum value for indoor environments in a 30 min period, resulted in heightened sensitivity to other allergens in asthmatic patients (Casset et al., 2006). Furthermore, a Finish study reported that formaldehyde was the more likely agent causing sensory irritation than the mixture of common volatile organic compounds (VOCs) occurring in Finnish buildings sampled between 2001 and 2006 (Salonen et al., 2009). An Australian study also found that indoor formaldehyde levels exceeding 0.06 mg/m$^3$ significantly increased children's chances of developing asthma (Rumchev et al., 2002).

### 4.2. Chronic toxicity

Long-term exposure to elevated levels of formaldehyde in the occupational setting has resulted in upper and lower airway irritation; eye irritation; and degenerative, inflammatory and hyperplastic changes of the nasal mucosa in humans (Edling et al., 1988; Ritchie and Lehnen, 1987; Wilhelmsson and Holmstrom, 1992). In China the health effects from chronic formaldehyde exposure are more common than those from acute toxicity. Symptoms can include coughing, wheezing, expectoration, pharyngeal congestion, chronic pharyngitis, chronic rhinitis, loss of olfactory functioning, eye irritation, lacrimation, and cornea disorder, etc. There are also reports of irritated skin, heartburn, tremor, body sores, chest pain, lethargy, abdominal pain, and loss of appetite (Dai and Bao, 1999; Fan et al., 2006, 2004; Geng et al., 2004; Li et al., 1999; Li and Chen, 2002; Shi et al., 2006; Wu and Wu, 2001; Xu et al., 2007a; Zhang et al., 1999).

#### 4.2.1. Neurotoxicity

Chronic exposure to formaldehyde can result in symptoms of neurasthenia, which include headaches, dizziness, sleep disorders, and memory loss. Many reports indicate that chronic exposure to formaldehyde increases the chances of headache and dizziness by 30–60% (Feng et al., 1996; Gao et al., 1988; Liu and Guo, 2004; Lu et al., 2007; Tang and Zhang, 2003; Tao et al., 1990; Wang et al., 1999; Yu et al., 2000; Yuan and Dong, 2007).

Recently, the association between exposure to chemicals including formaldehyde and amyotrophic lateral sclerosis (ALS) mortality was assessed in a prospective cohort study investigating 1 million participants in the American Cancer Society's Cancer Prevention Study II (Weisskopf et al., 2009). A non-significant increase in relative risk (RR) of 1.34 with 95% confidence interval (CI) 0.93–1.92 in ALS mortality was found among individuals who reported exposure to formaldehyde. Excluding those with a missing duration of formaldehyde exposure, the RR was 2.47 (95% CI 1.58–3.86), and there was a strongly significant dose–response relation with increasing years of exposure ($P_{\mathrm{trend}} = 0.0004$). Previously, it was shown that apart from age and gender, cigarette smoking is perhaps the most consistent non-genetic risk factor for ALS (Armon, 2003). Formaldehyde is a by-product of cigarette smoke, which may account for up to 10–25% of indoor air formaldehyde exposure (ATSDR, 1999).

#### 4.2.2. Pulmonary function damage

There have been six reports of formaldehyde-induced pulmonary disorders in chronically exposed workers in China, all of which found abnormal pulmonary function and obstruction in the small airways of the patients. In one of the studies, factory workers chronically exposed to formaldehyde concentrations of $3.07 \pm 5.83$ mg/m$^3$ experienced a decrease in pulmonary ventilation, relative to a control group (Wang et al., 2000). Chronic exposure to lower concentrations of 1.3 mg/m$^3$ significantly decreased maximum midexpiratory flow and forced vital capacity values (Zhang et al., 1999). Similarly, other studies showed amplified pulmonary damage with increased exposure over time (Fan et al., 2006; Feng et al., 1996; Li and Chen, 2002; Wang et al., 1999), along with more abnormalities in the small airways and higher resistance to pulmonary ventilation (Hong et al., 2007).

### 4.3. Hematotoxicity

Hematotoxicity is defined as toxicity caused by chemical exposure to the blood and hematopoietic system, often resulting in decreased blood cell counts. In one recent case report, a previously healthy woman was diagnosed with pancytopenia (a type of anemia), which showed lower than normal white blood cell (WBC), red blood cell (RBC), platelet (Plt) and hemoglobin (Hb) counts, after just 3 months of moving into a newly remodeled apartment (Huang et al., 2007b). Her blood counts were $3.3\times10^9$/L WBC, $2.13\times10^{12}$/L RBC, $8.5\times10^9$/L Plt, and 60 g/L Hb, while the normal ranges defined in China are $(4.0–10.0)\times10^9$/L, $(3.5–5.5)\times10^{12}$/L, $(100–300)\times10^9$/L, and (100–160) g/L, respectively. The formaldehyde level measured in the apartment was 4 times the indoor national standard of 0.1 mg/m$^3$, while other measured chemicals such as benzene and toluene did not exceed national indoor limits (Huang et al., 2007b). Two other lymphocyte subset studies from the same group found that formaldehyde increased B cells but decreased total T cells (CD3) and T-helper cells (CD8) in the blood of exposed workers, while T-suppressor (CD4) cells remained unchanged (Yan et al., 1994; Ye et al., 2005).

Eight studies have been conducted in China concerning hematological parameters in formaldehyde-exposed humans and published mainly in Chinese journals. The results of these studies are summarized in Table 9. The majority of the studies show that long-term exposure can decrease the number of WBC and possibly lower platelet and hemoglobin counts (Cheng et al., 2004; Kuo et al., 1997; Qian et al., 1988; Tang and Zhang, 2003; Tong et al., 2007; Yang, 2007a). In a detailed study of occupationally-exposed nurses, personal and area exposure data, as well as complete blood cell counts, were collected. These data, however, were reported as a correlation matrix for complete blood count, formaldehyde concentration and work duration. The study concluded that the correlation between the decrease in WBCs and increase in formaldehyde concentration is the best indicator of exposure among the other outcomes (Kuo et al., 1997). One study of only 10 exposed subjects showed a non-significant decrease in WBC counts compared to the 10 controls (Xu et al., 2007b), likely due to the small sample size. Another study reported no significant differences in WBC and Hb in individuals occupationally exposed to formaldehyde (Feng et al., 1996).

### 4.4. Reproductive toxicity

Formaldehyde's teratogenicity and its effects on human reproduction are still a matter of scientific controversy. Very limited research has been conducted that specifically targets formaldehyde's effects on human reproduction in China. To the best of our knowledge, there have been no studies on formaldehyde's effects on male reproduction, however, three general health studies included findings on menstrual disorders and heavy menstrual flow (menorrhagia) in women occupationally exposed to formaldehyde. In a food additive factory, more than 70% of the female employees exposed to formaldehyde through inhalation (0.82–5.96 mg/m$^3$) reported abnormal menstrual cycles, while only 17% reported this in the control group (Xu et al., 2007b). Abnormal menstrual cycles were also reported in anatomy teachers who were occupationally exposed to formaldehyde levels exceeding the MAC of 0.5 mg/m$^3$, in some cases reaching 3.98 mg/m$^3$ (Lu et al., 2007), while others reported painful menstruation (dysmenorrhea) and increased menstrual flow that had not occurred prior to working in the current setting (Li et al., 1999). In one case report, a 25-year old woman who worked in a veneer factory during her first trimester gave birth to a deformed baby, and occupational exposure to formaldehyde was suspected (Zhang, 2003).

Pregnancy outcomes and formaldehyde exposure have been more rigorously studied outside of China. Several early international studies showed no difference in reproductive health between formaldehyde exposed and unexposed populations (Hemminki et al., 1985; Hemminki et al., 1982; Lindbohm et al., 1991; Stucker et al., 1990). A meta-analysis of adverse pregnancy outcomes found that most epidemiological studies examining spontaneous abortion showed some evidence of increased risk (RR 1.4, 95% CI 0.9–2.1), although this could be reduced by adjusting for reporting and publication bias (Collins et al., 2001). In a retrospective case-control study, a significant association between spontaneous abortion and formalin exposure (odds-ratio 3.5, 95% CI 1.1–11.2) was found in Finnish women who worked in pathology or histology laboratories for more than 3 days per week (Taskinen et al., 1994). Another study of female wood workers found significantly lower fecundability density ratios (FDR, a ratio of average incidence densities of pregnancies) in women highly exposed to formaldehyde (FDR 0.64, 95% CI 0.43–0.92, $P=0.02$), even after adjustments for smoking and alcohol consumption (Taskinen et al., 1999). An earlier study in the former Soviet Union reported higher infertility among exposed workers but a definition of infertility was not provided and confounding effects were not examined (Shumilina, 1975). In the same study, it was also found that formaldehyde exposure increased cases of menstrual disorder and dysmenorrhea (Shumilina, 1975), similar to the Chinese studies described above (Li et al., 1999; Lu et al., 2007; Xu et al., 2007b).

**Table 9**
Summary of formaldehyde-induced hematotoxicity (decreased blood cell counts) reported in Chinese studies.

| Study | Site | [Formaldehyde] (mg/m$^3$) | Subject[a] | | Blood cell count | | | Notes |
|---|---|---|---|---|---|---|---|---|
| | | | Group | N | WBC ($\times10^9$/L) | Plt ($\times10^9$/L) | Hb (g/L) | |
| Tong, 2007 | Jiangsu | N/A | Exposed | 65 | 5.42 ± 2.04*** | 172.48 ± 87.57*** | 125.66 ± 21.83 | WBC & Plt counts decreased with increasing work years |
| | | | Control | 70 | 6.61 ± 1.66 | 243.10 ± 84.08 | 128.59 ± 13.11 | |
| Yang, 2007[b] | Hunan | 0.022–0.044 | Exposed | 239 | 33/239 (14%)** | 26/239 (11%)** | 77/239 (32%)** | All counts also decreased with increasing work years. |
| | | | Control | 200 | 8/200 (4%) | 2/200 (1%) | 43/200 (21.5%) | |
| Cheng, 2004[b] | Anhui | 0.24–0.93 | Exposed | 72 | 10/72 (14%)* | N/A | N/A | |
| | | | Control | 150 | 8/150 (5%) | | | |
| Tang, 2003 | Henan | N/A | Exposed | 110 | 4.91 ± 1.17 | N/A | N/A | WBC count decreased with increasing work years. |
| | | | Control | 120 | 5.92 ± 1.51 | | | |
| Kuo, 1997 | Taiwan | 0.184[c] | Exposed | 50 | NR | NR | NR | Reported significant correlation of decreased WBC count with increased [FA] |
| | | | Control | 71 | | | | |
| Qian, 1988 | Shanxi | ~3 (Estimated) | Exposed | 55 | 5.39*** | N/A | N/A | Reported increase in IgM, IgA, and Eosinophils counts. |
| | | | Control | 41 | 6.22 | | | |
| Xu, 2007b | Hubei | 0.44–6.84 | Exposed | 10 | 5.74 ± 1.35 | 122.46 ± 32.87 | 119.77 ± 11 | WBC counts decreased, but NS. |
| | | | Control | 10 | 6.48 ± 2.15 | 118.84 ± 22.52 | 120 ± 10 | |
| Feng, 1996 | Anhui | 0.7–19.2 | Exposed | 104 | NS | N/A | NS | Original data not provided. |
| | | | Control | 68 | | | | |

Abbreviations: WBC, white blood cell; Plt, platelet; Hb, hemoglobin; N/A, not available; NR, not reported; NS, not significant; [FA], formaldehyde concentration.
*P* values: $*p<0.05$, $**p<0.01$, $***p<0.001$.
[a] Most exposed subjects are industrial workers, with the exception of pathologists in the Cheng et al. (2004) study, and nurses in Kuo et al. (1997).
[b] Numbers of subjects with decreased blood cell counts are given. Percentage (%) is calculated from subjects with abnormal counts among total subjects.
[c] Combined average calculated from subsets of area sampling means with corresponding sample sizes given in the original paper. Source: Table 5, Kuo et al. (1997).

### 4.5. Genotoxicity

It has been shown that formaldehyde exposure induces DNA and chromosomal damage in human peripheral blood cells (Zhang et al., 2009). In China, workers exposed to formaldehyde showed an increase in DNA damage in peripheral lymphocytes measured by single cell gel electrophoresis (Comet assay) (Jiang, 2006; Tong et al., 2006; Yu et al., 2005). Another study reported elevated occurrences of chromosome aberrations (CA) such as chromatid breakage, chromosomal fragmentation, dicentric chromosome, and aneuploidy in peripheral lymphocytes of workers chronically exposed on average to 2.51 mg/m$^3$ of formaldehyde for 10.5 years (Jin and Zhu, 1992). Several studies have shown that short-term (8 weeks) exposure to high levels of formaldehyde (0.508–0.985 mg/m$^3$) increased micronuclei (MN) frequency in nasal epithelial cells (Cheng et al., 1995), while long-term (>1 year) exposure increased MN frequency in lymphocytes (Wang et al., 1997; Ye et al., 2005; Yu et al., 2005). Three separate Chinese studies have concluded that the rate of sister chromatid exchanges (SCE) did not increase in the peripheral lymphocytes of formaldehyde-exposed individuals (Jin and Zhu, 1992; Li et al., 1988; Ye et al., 2005). More recently, in a 2008 Portuguese case-control study, SCE and MN frequencies in peripheral lymphocytes were significantly higher in formaldehyde-exposed subjects than the control group (Costa et al., 2008). An earlier study in former Czechoslovakia reported increased levels of CA in the peripheral blood lymphocytes of children exposed to formaldehyde in prefabricated schools (Neri et al., 2006).

### 4.6. Carcinogenesis

Formaldehyde has been tested for carcinogenicity by inhalation, oral administration, topical application, and subcutaneous injections in rodents. It has been proposed that, based on the weight of evidence from *in vivo* studies, the likely mode of action for formaldehyde-induced nasal tumors in animals is relevant to humans at least qualitatively (McGregor et al., 2006). Based on comprehensive research and large-scale human studies conducted internationally, the International Agency for Research on Cancer (IARC) recently classified formaldehyde as a human carcinogen that causes nasopharyngeal cancer (IARC, 2006). Popularly known as the "Cantonese Cancer", nasopharyngeal malignancy kills as many as 13,000 Chinese people each year — more than 10 times the nasopharyngeal fatalities in the rest of the world (Jia, 2008). Although viral infection has been suspected to be the cause, formaldehyde exposure from Guangdong's industries and possibly from seafood consumption cannot be excluded. Despite this, China has conducted only limited research on formaldehyde's carcinogenic effects.

To date, there have only been 4 small retrospective cohort studies on the carcinogenicity of formaldehyde in China, all of which lack clear epidemiological design and are more than 10 years old (Cui et al., 1997; Dai and Bao, 1999; Jiang et al., 1990; Wang et al., 1989). The cancer mortality rate increased in all of the studies, while the incidences of gastric cancer and brain tumor increased in 3 and 2 of the 4 studies, respectively. More recently, two cases were reported of thyroid cancer in female textile workers in Shanghai but formaldehyde exposure data was not reported, though formaldehyde was suspected, and co-exposure to benzene may have occurred (Wong et al., 2006).

Additionally, one case of malignant lymphoma (Jiang et al., 1990) and one case of leukemia (Cui et al., 1997) were reported. In a 2006 court case, a local judge in Fujian Province awarded compensation for the first case of formaldehyde induced childhood leukemia in China. After being exposed to a formaldehyde concentration of 0.39 mg/m$^3$ for 8 months in a newly decorated home, a 4-year-old girl suffered from fatal leukemia, and the decorating company was required to provide compensation (Dai, 2006). Some studies have suggested that the increase in childhood leukemia cases is associated with the increase in indoor air formaldehyde pollution from newly remodeled homes (Du et al., 2008; Zhang et al., 2007a,b,c,d), although other explanations such as 'population mixing' caused by relocation cannot be excluded (Greaves, 1997).

The IARC concluded that there was "strong but not sufficient evidence for a causal association between leukemia and occupational exposure to formaldehyde" (IARC, 2006). The evidence was considered insufficient because a mechanism or mode of action for formaldehyde induced leukemia could not be identified in humans. It has been argued that compared to known leukemogens, there is a lack of biological plausibility for a causal relationship for formaldehyde and leukemia (Golden et al., 2006). However, the most recent follow-up study of the largest National Cancer Institute cohort study that provided the "strong" evidence for the IARC 2006 report (Hauptmann et al., 2003) demonstrated statistically significant increased risks for all lymphohematopoietic malignancies (RR 1.37; 95% CI 1.03–1.81, $P_{\text{trend}} = .02$) and Hodgkin lymphoma (RR 3.96; 95% CI 1.31–12.02, $P_{\text{trend}} = .01$) (Beane Freeman et al., 2009). Statistically nonsignificant increases were observed for multiple myeloma (RR=2.04, 95% CI 1.01-4.12, $P_{\text{trend}} > 0.50$), all leukemia (RR = 1.42, 95% CI 0.92-2.18, $P_{\text{trend}} = 0.12$), and myeloid leukemia (RR=1.78, 95% CI 0.87-3.64 $P_{\text{trend}} = 0.13$). Our recent meta-analysis of studies to date supports the association with myeloid leukemia (Zhang et al., 2009).

### 4.7. Formaldehyde regulation and public health

Occupational and environmental exposure to formaldehyde is a public health concern that needs to be addressed globally. In particular, the health effects of chronic exposure are less well characterized than those of acute exposure, especially in vulnerable populations such as children, the elderly, and those with asthma.

The Council of the European Union (EU) has placed formaldehyde, along with other biocidal products, under review with a goal of removing them from the European market (EU, 2007). In the EU, Annex VI of the Cosmetics Directive 76/768/EC requires that many finished products must be labeled with the warning 'Contains Formaldehyde' where the concentration of formaldehyde in the finished product exceeds 0.05%. The maximum authorized concentration of free formaldehyde and paraformaldehyde is 0.2% in cosmetic products, except for oral hygiene products where the maximum concentration of free formaldehyde is 0.1% (EU, 2002 and 2008). Canada has already adopted measures to limit formaldehyde exposure by completely banning the use of urea-formaldehyde (UF) foam insulation, an insulation material that releases excess formaldehyde after installation (CMHC, 2009).

After Hurricane Katrina struck the Gulf Coast of the United States in 2005, hurricane victims were temporarily housed in government-provided trailers that exposed victims to dangerous levels of formaldehyde (CDC, 2008). As a result, trailer residents suffered from sinus infections, respiratory problems, and burning sensation in the eyes among many other symptoms (Eaton, 2008).

Similarly, after the 2008 Sichuan earthquake, many survivors were housed in mobile homes constructed with medium-density fiberboard that emitted, in some cases, 5 times the maximum level of formaldehyde allowed by Chinese standards (EpochTimes, 2009). In early April 2009, more than 100 miscarriages were recorded in the community, which could be potentially attributed to formaldehyde, though other confounders have not yet been considered (Pearson, 2009).

## 5. Conclusions

Based on over 200 Chinese and English articles pertaining to formaldehyde, this review aims to provide a comprehensive analysis of the market, exposure, regulation, and effects on human health of formaldehyde in China. The rapid growth of formaldehyde-related industries in China in the past two decades has resulted in China's current status as the world's largest producer and consumer of formaldehyde. This has been paralleled by increases in formaldehyde pollution and associated health problems. Although the Chinese government has implemented a series of standards to regulate formaldehyde, the lack of enforcement has resulted in only limited success in controlling exposures. Consequently, a large number of Chinese individuals continually encounter multiple sources of formaldehyde exposure every day. These include: environmental, occupational, residential and contaminated food.

Given the magnitude of formaldehyde exposure in China, both in terms of the number of people exposed and the levels of formaldehyde exposure, the potential health consequences of formaldehyde are of serious concern. The number of case reports on a wide range of formaldehyde-induced health effects, including poisoning and cancer, has multiplied dramatically in recent years. Even so, the quantity and the quality of studies on formaldehyde's health effects in China remain limited; to date, there have been few, if any, well designed systematic studies on formaldehyde-exposed populations. Consequently, China urgently needs to conduct epidemiological studies on formaldehyde's health effects, as well as extensive investigations on the characteristics of formaldehyde-exposed populations. In the meantime, molecular epidemiological studies, through biomarker discovery, could elucidate the carcinogenic potential of formaldehyde in the Chinese population and lead to important interventions to protect human health, not just in China, but also in the world population at risk.

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