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Original Article

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Exposures to Fumigants and Residual Chemicals in Workers Handling Cargo from Shipping Containers and Export Logs in New Zealand

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Abstract

Objectives: Previous studies have reported high concentrations of airborne fumigants and other chemicals inside unopened shipping containers, but it is unclear whether this is reflective of worker exposures.

Methods: We collected personal 8-h air samples using a whole-air sampling method. Samples were analysed for 1,2-dibromoethane, chloropicrin, ethylene oxide, hydrogen cyanide, hydrogen phosphide, methyl bromide, 1,2-dichloroethane, C2-alkylbenzenes, acetaldehyde, ammonia, benzene, formaldehyde, methanol, styrene, and toluene. Additive Mixture Values (AMVs) were calculated using the New Zealand Workplace Exposure standard (WES) and American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) of the 8-h, time-weighted average exposure limit. Linear regression was conducted to assess associations with work characteristics.

Results: We included 133 workers handling shipping containers, 15 retail workers unpacking container goods, 40 workers loading fumigated and non-fumigated export logs, and 5 fumigators. A total of 193 personal 8-h air measurements were collected. Exposures were generally low, with >50% below the limit of detection for most chemicals, and none exceeding the NZ WES, although formaldehyde exceeded the TLV in 26.2% of all measurements. The AMV-TLV threshold of 1 was exceeded in 29.0% of the measurements. Levels and detection frequencies of most chemicals varied little between occupational groups, although exposure to methyl bromide was highest in the fumigators (median 43 ppb) without exceeding the TLV of 1000 ppb. Duration spent inside the container was associated with significantly higher levels of ethylene oxide, C2-alkylbenzenes, and acetaldehyde, but levels were well below the TLV/WES. Exposure levels did not differ between workers handling fumigated and non-fumigated containers.

Conclusions: Personal exposures of workers handling container cargo in New Zealand were mainly below current exposure standards, with formaldehyde the main contributor to overall exposure. However, as it is not clear whether working conditions of participants included in this study were representative of this industry as a whole, and not all relevant exposures were measured, we cannot exclude the possibility that high exposures may occur in some workers.

Keywords: chemicals; exposure determinants; fumigation/fumigant; occupational exposure; personal air sampling; shipping container/sea container; ventilation

Introduction

Globally, goods transported in containers have risen from 100 million metric tonnes in 1980 to 1.7 billion metric tonnes in 2015 (Statista, 2018). In New Zealand, over 500 000 containers were imported from the third quarter of 2018 to the end of the second quarter in 2019, representing more than 15 million tonnes of container goods (New Zealand Ministry of Transport, 2018). A proportion of these containers require fumigation either for biosecurity reasons or to prevent damage to the cargo.

Several case reports of acute poisoning in workers handling shipping cargo have been reported (Spijkerboer *et al.*, 2008; Breeman, 2009; Preisser *et al.*, 2011, 2012; Kloth *et al.*, 2014; Roberts *et al.*, 2014; Baur *et al.*, 2015; European Agency for Safety and Health at Work, 2018), with exposure to fumigants or chemicals off-gassed from products or packaging materials the most likely causes (Preisser *et al.*, 2011, 2012; Baur *et al.*, 2015). Symptoms varied from skin irritation, respiratory distress, to seizures and persistent neurological deficits (Spijkerboer *et al.*, 2008; Preisser *et al.*, 2011, 2012; Kloth *et al.*, 2014; Baur *et al.*, 2015). Subsequent studies, reviewed by the European Agency for Safety and Health at Work (2018), found elevated concentrations of fumigants and other chemicals in the air of unopened shipping containers (Knol-de Vos, 2002; de Groot, 2007; Baur *et al.*, 2010; Budnik *et al.*, 2010; Fahrenholtz *et al.*, 2010; Tortarolo, 2011; New Zealand Customs Service, 2012; Svedberg and Johanson, 2017), with the latest study showing that levels exceeding Swedish occupational exposure limits occurred in 13% of all tested containers, with exceedance rates varying from 0 to 33% dependent on the port where samples were taken (Svedberg and Johanson, 2017). Several studies have also reported elevated levels of fumigant and other residual chemicals in packaging and container goods (Knol-de Vos *et al.*, 2005; Budnik *et al.*, 2017), suggesting that retail staff and consumers may also be at risk (Knol-de Vos *et al.*, 2005; Baur *et al.*, 2010; Preisser *et al.*, 2011, 2012).

One small study that measured airborne personal exposures of fumigants and other off-gassed chemicals in 12 container workers over a 2–3 h period showed that all exposures were below the relevant workplace exposure limits (Safe Work Australia, 2011). This is consistent with an experimental study using tracer gas showing exposures in workers, averaged over the time of unloading, of only 1–7% of the initial tracer gas concentrations in the container (Svedberg and Johanson, 2013). The lower personal exposures were attributed to the rapid decline in concentration following the opening of containers and subsequent ventilation (Svedberg and Johanson, 2013; Braconnier and Keller, 2015). Nonetheless, both experimental studies showed that high exposure may still occur as demonstrated by peak exposures of up to 70% of the original tracer gas concentrations (Svedberg and Johanson, 2013).

Thus, despite health concerns for workers involved in unloading shipping containers and/or handling container goods, little is known about work exposures to fumigants and chemicals off-gassed from products or packaging material. This study assessed, for the first time on a large scale, full-shift (8-h) exposures to fumigants and other off-gassed chemicals in workers handling cargo from shipping containers, including a small number of retail workers. In addition, we measured the same chemicals in a small group of fumigators and a group of port workers who were loading export logs, some of which had previously been fumigated with methyl bromide, a toxic chemical that is associated with both acute poisoning (Spijkerboer *et al.*, 2008; Preisser *et al.*, 2012; Kloth *et al.*, 2014; Baur *et al.*, 2015) and chronic health effects (Spijkerboer *et al.*, 2008; Budnik *et al.*, 2012; Preisser *et al.*, 2012).

Methods

Study design

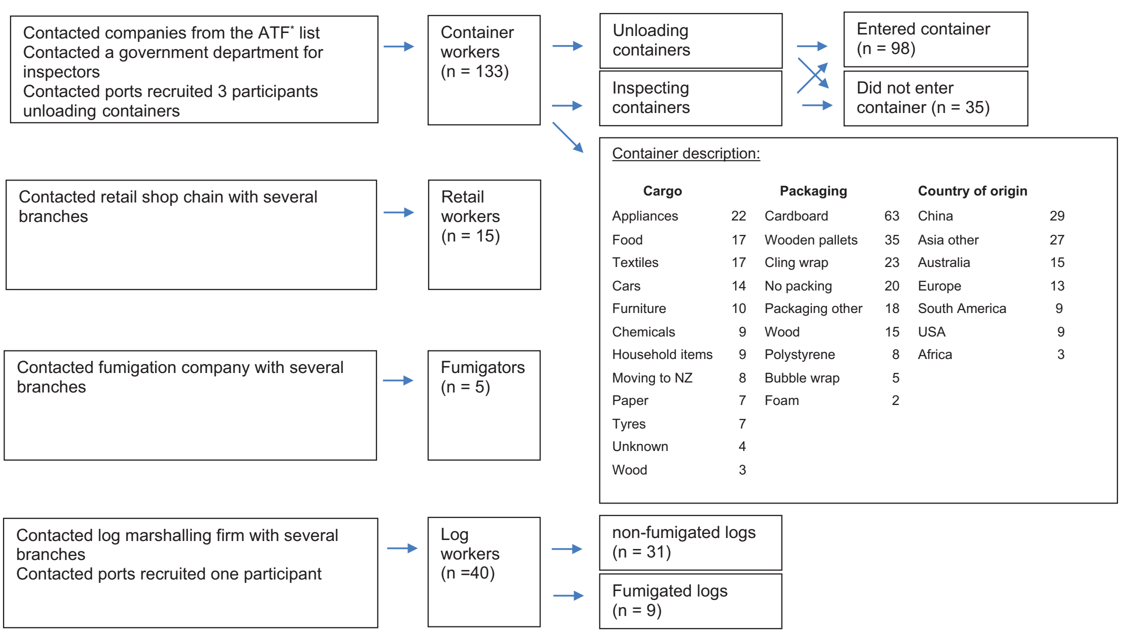
This study is an exposure survey nested in a larger cross-sectional health study of workers handling cargo from shipping containers and export logs and was aimed to assess personal exposures to fumigants and other residual chemicals. The health survey involved 493 participants from 100 companies selected from a list of Accredited Transitional Facilities (ATF) published by the New Zealand Ministry of Primary Industries. These are companies accredited to open and inspect (for biosecurity reasons) overseas containers. The average age of the participants was 39 years (range: 17–79 years), 79% were male, and average employment duration at the current workplace was 6.7 years (median: 4 years). We randomly invited 31 companies to participate in the exposure survey all of whom accepted, with air sampling provided at no cost often being the primary reason for participation.

The exposure survey involved 8-h personal airborne exposure measurements in workers handling shipping containers, retail workers handling cargo, export log workers involved in loading logs onto ships, and fumigators. Measurements were conducted year-round and across a range of working conditions e.g. different seasons and meteorological conditions, company size, night and day shifts, and throughput of cargo. All workers who entered shipping containers recorded the time spent unloading each container, the nature of the cargo and packaging, and the country of origin of the container. Before entry, all containers were passively ventilated (open door), except for two containers that had fan-ventilation, and one container that had an extraction unit. Ventilation times for passive ventilation were not routinely recorded, but observations by fieldworkers suggest it varied greatly from a few minutes to 30 min for non-fumigated containers and up to 24 h for fumigated containers.

Written consent was obtained from all participants and ethics approval was granted by the Multi-region Ethics Committee of the New Zealand Ministry of Health (MEC/12/02/010).

Participant recruitment

The 31 companies that participated in the air sampling had a workforce size and total throughput of cargo reflective of this industry in New Zealand, but no formal test was done to assess whether this sample was representative of the industry as a whole. The companies comprised distribution centres (*n* = 3), third party logistics providers (*n* = 13) or companies unloading their own imported containers (*n* =9). We also recruited a government department involved in inspecting overseas containers (*n* = 1), a company specializing in export log operations (*n* = 1), port companies (*n* = 2), a fumigation company (*n* = 1), and a retail store company (*n* = 1; Fig. 1). The companies, situated at nine locations throughout New Zealand, ranged in size from owner-operated to large distribution centres, with the number of participants mostly reflecting the size of the company (1–2 participants, 13 companies; 3–6 participants, 11 companies; and 7–39 participants, 7 companies). In these 31 companies, management identified potential



*ATF Accredited Transitional Facilities are companies, which are certified by the NZ Ministry for Primary Industries to biosecurity, inspect import containers

Figure 1. Flowchart of participant recruitment and grouping.

participants based on availability and workplace requirements resulting in 193 workers participating in the study (Fig. 1), with four participants declining to participate.

Air sampling

We collected full-shift (8-h) airborne personal measurements in the period 2013–2016, using a whole-air method (Restek Corporation, Bellefonte, PA, USA) (Keer *et al.*, 2016). Briefly, teflon tubing running from the participant's breathing zone was connected to a 400cc stainless steel and Siltek treated sampling canister (Restek Corporation, Bellefonte, PA, USA) negatively pressurized to near full vacuum (−30 mmHg). A flow controller (Restek Corporation, Bellefonte, PA, USA) was used to maintain a flow rate of 0.9 ml min^{-1} and sampling was stopped when air pressure in the canisters reached between −5 and −3 mmHg. All workers wore the sampling equipment continuously throughout their work-shift, except for fumigators who removed the sampling equipment when wearing respiratory protective equipment (no other workers wore respirators).

Workers entering a container spent on average 3.8 h (standard deviation 2.4; range 0.02–8 h) on these duties. The cargo, packaging, the origin of the container, and the way the containers were packed varied widely (Fig. 1).

We sampled 15 shipping container handlers twice on different days. Because the cargo and the countries of origin of the containers unloaded were different, we treated these 'repeat' measurements as independent observations. In addition, and to allow comparisons to be made between handling fumigated and non-fumigated logs, eight log workers were sampled twice, with the first measurement taken when non-fumigated logs were handled and the second when handling fumigated logs. Working conditions were very similar on both days with sampling done on two consecutive days with similar meteorological conditions and work tasks.

Laboratory analyses

Air samples were analysed by Syft Technologies, Christchurch, New Zealand using Selected Ion Flow Tube Mass Spectrometry (Syft-Technology, 2005; Milligan *et al.*, 2007; Smith and Spanel, 2015) for several common fumigants and harmful chemicals frequently found in shipping containers. The fumigants included: 1,2-dibromoethane [CAS No. 106-93-4], chloropicrin [76-06-2], ethylene oxide [75-21-8], hydrogen cyanide [74-90-8], hydrogen phosphide [7803-51-2], and methyl bromide [74-83-9]. Other hazardous chemicals included: 1,2-dichloroethane [107-06-2], C2-alkylbenzenes [108-38-3, 95-47-6, 106-42-3, 100-41-4], acetaldehyde [75-07-0], ammonia [7664-41-7], benzene [71-43-2], formaldehyde [50-00-0], styrene [100-42-5], and toluene [108-88-3]. Blank canisters were analysed with each series of measurements. Formaldehyde concentrations of 10 measurements were excluded because of high readings of the blanks.

For each chemical the limits of detection (LoD), the 8-h, time-weighted average exposure limit based on the New Zealand Workplace Exposure standards (WESs) and the Threshold Limit Values (TLVs) set by the American Conference of Governmental Industrial Hygienists (ACGIH) are provided in Table 1. Exposures were expressed in parts per billion (ppb). In addition to reporting levels for each chemical separately, we also calculated the combined exposure expressed as the 'sum-value' i.e. the concentrations of all chemicals added up, and the Additive Mixture Value (AMV), i.e. an estimate of the combined toxic effect of chemicals. To calculate the AMV as defined by the ACIGH (ACGIH, 2019), each chemical was given a toxicity score by dividing the measured level by the appropriate TLV and WES followed by summation of the toxicity scores of all chemicals measured in the sample, thus providing an AMV-TLV and an AMV-WES for each sample. An AMV exceeding 1 was considered to be above the exposure limit for that mixture.

Statistical analyses

Statistical analyses were conducted using Stata version 13.1 (StataCorp LP, College Station, TX, USA). Measurements below the LoD were assigned a value of half the LoD. Medians, 75 percentiles, and maximum levels were used to summarize exposure data for the four different occupational groups (container handlers, retail workers, export log workers, and fumigators) and for subgroups of container handlers.

We used linear regression to assess differences in exposure between occupational groups using container handlers as the reference group. Analyses were left-censored (using the Tobit function in Stata) for individual chemicals due to the large number of samples with concentrations below the LoD (Helsel, 2010; Ogden, 2010); for sum-value and AMVs there was no need to left-censor the analyses. Within the group of container handlers we compared personal exposure levels of participants entering containers with those not entering containers (n = 35) but who were working at the same premises. This allowed us to assess whether entering containers was associated with higher exposures due to the presence of residual fumigants and/or off-gassed

Table 1. Descriptive statistics for personal 8-h exposure of participants by occupational group.

Chemical (ppb[b])	WES[c]	TLV[d]	LoD	Container handlers (*n* = 133)[a]			Retail workers (*n* = 15)			Export log workers (*n* = 40)			Fumigators (*n* = 5)		
				<LoD (%)	Median (p75)	Max	<LoD (%)	Median (p75)	Max	<LoD (%)	Median (p75)	Max	<LoD (%)	Median (p75)	Max
Fumigants															
1,2-Dibromoethane	500	—	5	71.4	<LoD (<LoD)	61.2	86.7	<LoD (<LoD)	6.7	55.0	<LoD (7.0)	11.5	80.0	<LoD (<LoD)	8.6
Chloropicrin	100	100	5	88.7	<LoD (<LoD)	27.8	100.0	<LoD (<LoD)	<LoD	100.0	<LoD (<LoD)	2.5	60.0	<LoD (9.6)	13.9
Ethylene oxide	1000	1000	10	88.7	<LoD (<LoD)	130.1	66.7	<LoD (16.5)	33.7	60.0	<LoD (19.8)	54.8	100.0	<LoD (<LoD)	5.0
Hydrogen cyanide	10 000[e]	4700[e]	3	78.9	<LoD (<LoD)	36.7	93.3	<LoD (<LoD)	19.4	75.0	<LoD (2.5)	47.2	80.0	<LoD (<LoD)	6.6
Hydrogen phosphide	300	50	3	75.9	<LoD (<LoD)	39.1	80.0	<LoD (<LoD)	12.0	50.0	2.3 (6.8)	29.6	60.0	<LoD (5.0)	10.6
Methyl bromide	5000	1000	5	66.2	<LoD (7.2)	66.2	100.0	<LoD (<LoD)	<LoD	62.5	<LoD (7.0)	133.9	0	43.3 (108.7)	156.9
Non-fumigants															
1,2-Dichloroethane	5000	10 000	5	79.7	<LoD (<LoD)	43.3	100.0	<LoD (<LoD)	<LoD	75.0	<LoD (3.8)	14.9	60.0	<LoD (26.7)	40.0
C2-alkylbenzenes	50 000	20 000	5	51.9	<LoD (9.8)	219.6	100.0	<LoD (<LoD)	<LoD	97.5	<LoD (<LoD)	5.6	60.0	<LoD (8.1)	12.1
Acetaldehyde	20 000	25 000[e]	25	61.7	<LoD (41.7)	526.4	80.0	<LoD (<LoD)	62.8	45.0	29.6 (51.9)	459.6	40.0	48.6 (193.1)	251.2
Ammonia	25 000	25 000	15	83.5	<LoD (<LoD)	183.8	93.3	<LoD (<LoD)	18.0	50.0	18.0 (65.0)	193.2	100.0	<LoD (<LoD)	<LoD
Benzene	1000	500	5	88.0	<LoD (<LoD)	25.7	86.7	<LoD (<LoD)	6.6	97.5	<LoD (<LoD)	8.4	60.0	<LoD (9.7)	13.4
Formaldehyde	500	100	25	44.7	31.4 (123.8)	389.0	13.3	58.0 (97.2)	304.3	37.5	45.9 (96.2)	164.6	20.0	38.4 (40.1)	254.1
Styrene	20 000	20 000	2	92.5	<LoD (<LoD)	6.7	100.0	<LoD (<LoD)	<LoD	100.0	<LoD (<LoD)	1.0	60.0	<LoD (4.7)	5.4
Toluene	50 000	20 000	3	29.3	6 (14.8)	926.6	40.0	3.8 (5.4)	19.4	32.5	4.2 (9.4)	102.2	0	4.2 (3.6–8.9)	10.1
Other				**AMV >1 (%)**			**AMV >1 (%)**			**AMV >1 (%)**			**AMV >1 (%)**		
Sum-value	n/a	n/a	n/a	n/a	148.1 (83.6–291.5)	1011.1	n/a	117.5 (89.5–152.3)	451.8	n/a	190.6 (114.9–280.5)	704.7	n/a	387.8 (103.1–486.7)	496.5
AMV[f] (WES)	1	1	n/a	0	0.1 (0.1–0.3)	0.8	0	0.2 (0.1–0.2)	0.7	0	0.2 (0.1–0.3)	0.4	0	0.2 (0.1–0.3)	0.6
AMV[g] (TLV)	1	1	n/a	29.3	0.4 (0.2–1.3)	3.9	26.7	0.7 (0.5–1.0)	3.1	30.0	0.7 (0.3–1.1)	1.7	20.0	0.6 (0.5–0.9)	2.6

n/a, not applicable.
[a]*n* (formaldehyde) = 123.
[b]ppb: parts per billion.
[c]8-h WES set by WorkSafe NZ (2018).
[d]8-h WES (TLV) set by American Conference of Governmental Industrial Hygienists (2019).
[e]These chemicals do not have a time-weighted average limit but only a ceiling limit which was used instead.
[f]AMV using the WES.
[g]AMV using the TLV and excluding 1,2-dibromoethane because the ACIGH has not set a TLV for 1,2-dibromoethane.

chemicals from cargo or packaging in these containers. Within this group of workers, we also assessed associations with the fumigation status of the cargo (11 measurements were excluded due to unknown fumigation status) and duration of unloading containers (4 measurements were excluded due to unknown duration). As exposure values were ln-transformed prior to regression analyses, regression coefficients represent relative differences, or exposure ratios (ERs), with an ER of e.g. 2 indicating that the exposure for a particular occupational group is twice as high compared with the reference group. When modelling the number of hours spent unloading containers, the ER represents an increase or decrease in exposure associated with 1 additional hour of unloading containers (i.e. an ER of 1.3 indicates that an hour of unloading is associated with a 30% higher exposure, with and ER of 0.7 indicating a 30% reduction in exposure for each hour worked).

Analyses to assess associations with cargo type, packaging materials, and country of origin were not conducted due to participants often unloading multiple containers with different cargo and from different countries on the same day (samples were collected during an 8-h shift rather than it being targeted towards work related to a specific container).

In log workers we compared (using left-censored linear regression) exposures measured on days that fumigated logs were loaded (n = 10) with those of days that non-fumigated logs were loaded (n = 9).

Spearman correlation analyses were conducted to estimate the contribution of each chemical and sum-value to the AMV-TLV and AMV-WES.

Results

A total of 193 personal air samples were collected from 133 workers handling shipping containers, 15 retail workers unpacking container goods, 40 workers loading fumigated and non-fumigated export logs, and 5 fumigators. Of those handling shipping containers, 98 entered one or more containers whilst 35 did not enter any container on the day that measurements were taken (they did dispatch and office work; Fig. 1). Of the 98 participants who entered containers, 31 stated they had unloaded at least one fumigated container on the day that exposures were measured (Fig. 1). Of the 40 measurements in log workers, 9 involved sampling workers who were loading fumigated logs. Four of five fumigators applied fumigation at the time of sample collection (Fig. 1). All retail workers and workers who did not enter a container stated that they did not know whether the goods they handled were fumigated or not.

Overall, detection frequencies of individual chemicals were below 50%, except for formaldehyde (Table 1). Maximum exposure levels were below 30% of the corresponding WES/TLV, except for formaldehyde (Table 1). The New Zealand WES was never exceeded for any of the chemicals and the WES-based AMV never exceeded '1'. The ACGIH TLV was only exceeded for formaldehyde, which occurred in 26.2% of measurements (container handlers, 29%; retail workers, 20%; export log workers, 20%; and fumigators, 20%). The TLV-based AMV exceeded '1' in 29% of all measurements (container handlers, 29%; retail workers, 27%; export log workers, 30%; and fumigators, 20%), which was largely due to formaldehyde, i.e. of the 56 measurements exceeding the AMV-TLV, 48 also exceeded the TLV for formaldehyde, with the remaining six measurements very close to the TLV (data not shown). This is also evident from the high correlation between AMVs and the toxicity score for formaldehyde (WES r = 0.93, P < 0.001; TLV r = 0.96, P < 0.001; n = 183). For fumigators, methyl bromide was detected in all measurements, but levels were still well below the WES and the TLV (Table 1).

Regression comparing different occupational groups with container handlers showed significantly higher exposures to methyl bromide, 1,2-dichloroethane, and styrene in fumigators (Table 2). Log workers had significantly greater exposures of ethylene oxide and ammonia whilst exposure to C2-alkylbenzenes was lower. Retail workers had significantly lower exposures of toluene. Although the highest detection rate and median value for formaldehyde were observed in retail workers (Table 1), exposure levels were not significantly different from other occupational groups (Table 2).

Among container handlers, the AMV-TLV was more often exceeded in those who entered containers (36.7%) compared with those who did not (8.6%; Table 3), with AMV-TLV levels 70% higher (Table 4). Entering a container, was also associated with higher exposure to formaldehyde, ethylene oxide, and acetaldehyde whilst exposures to 1,2-dibromoethane, chloropicrin, methyl bromide, 1,2-dichloroethane, benzene, and styrene were reduced (Table 4). When comparing workers handling fumigated versus non-fumigated containers we found that fewer measurements exceeded the AMV-TLV threshold level of 1 in those who handled fumigated containers (Table 3). Similarly, in those handling fumigated containers the AMV-TLV and AMV-WES levels were 40 and 10% lower, respectively; a significantly reduced exposure (Table 4) to C2-alkylbenzenes was also found (Table 4).

Table 2. ERs of personal 8-h exposures for retail workers, log workers, and fumigators, compared with container handlers (n = 133)[a].

Chemical (ppb[b])	Retail workers (n = 15)	Log workers (n = 40)	Fumigators (n = 5)
	ER (95% CI)	ER (95% CI)	ER (95% CI)
Fumigants			
1,2-Dibromoethane	0.5 (0.2–1.1)	1.2 (0.8–1.9)	0.7 (0.2–2.6)
Chloropicrin	-	-	3.7 (0.7–21.2)
Ethylene oxide	1.1 (0.9–1.4)	1.2* (1.0–1.4)	0.9 (0.6–1.3)
Hydrogen cyanide	0.9 (0.6–1.2)	0.9 (0.8–1.2)	0.9 (0.5–1.5)
Hydrogen phosphide	0.9 (0.6–1.2)	1.2 (1.0–1.5)	1.1 (0.6–1.8)
Methyl bromide	-	1.1 (0.6–1.9)	16.2*** (5.0–52.7)
Non-fumigants			
1,2-Dichloroethane	-	1.1 (0.6–1.9)	3.3* (1.0–11.2)
C2-alkylbenzenes	-	0.10*** (0–0.3)	0.7 (0.2–2.7)
Acetaldehyde	0.4 (0.1–1.1)	1.4 (0.8–2.5)	2.7 (0.7–10.1)
Ammonia	0.2 (0–2.0)	5.8*** (2.3–15.1)	-
Benzene	0.9 (0.4–2.4)	0.4 (0.2–1.1)	2.8 (0.8–9.1)
Formaldehyde	1.5 (0.8–3.0)	1.0 (0.6–1.7)	1.2 (0.4–3.7)
Styrene	-	-	4.4* (1.0–19.2)
Toluene	0.5* (0.3–0.9)	0.7 (0.5–1.1)	0.6 (0.2–1.7)
Other			
Sum-value	0.7 (0.5–1.1)	1.1 (0.8–1.4)	1.4 (0.8–2.7)
AMV[c] (WES)	1.0 (0.9–1.1)	1.0 (0.9–1.0)	1.0 (0.9–1.2)
AMV[d] (TLV)	1.0 (0.6–1.5)	0.9 (0.7–1.2)	1.1 (0.5–2.4)

- insufficient data.
[a]n (formaldehyde) = 123.
[b]ppb: parts per billion.
[c]AMV using the WES.
[d]AMV using the TLV and excluding 1,2-dibromoethane because the ACIGH has not set a TLV for 1,2-dibromoethane.
*P < 0.05.
***P < 0.001.

Regression showed that for 1 additional hour of unloading a container, exposures to ethylene oxide, C2-alkylbenzenes, and acetaldehyde increased by 10, 30, and 20%, respectively (Table 4). No significant associations were found for other chemicals, sum-value, or AMVs. Further analyses controlling for whether a container was fumigated did not significantly affect the ERs (data not shown).

Log workers loading fumigated logs, compared with those loading non-fumigated logs, were exposed to significantly higher methyl bromide [median 14.6 versus 3.9 ppb; ER 4.1, confidence interval (CI) 1.6–10.9; n = 19] and formaldehyde (median 98.9 versus 61.4 ppb; ER 1.9, CI 1.1–3.0; n = 19) levels compared with workers loading non-fumigated logs, while ammonia levels were lower (median 7.5 versus 49.79 ppb; ER 0.3, CI 0.1–0.9; data not shown in tables). However, all methyl bromide exposures (maximum 133.9 ppb, Table1) were well below the WES (5000 ppb) and the TLV (1000 ppb). The median AMV-WES and AMV-TLV were both significantly higher in log workers loading fumigated logs (AMV-WES 0.27 versus 0.17; ER 1.1, CI 1.0–1.2; and AMV-TLV 1.1 versus 0.69; ER 1.5, CI 1.0–2.1; n = 19; data not shown in tables) and AMV-TLV values exceeded '1' in three (30%) measurements from log workers loading non-fumigated logs versus eight (88.9%) in those loading fumigated logs (data nor shown). All exceedances were attributable to levels above (or very close) to the TLV for formaldehyde (AMV-WES limits were never exceeded).

Discussion

This study showed that personal 8-h exposures of fumigants and other chemicals in New Zealand workers handling cargo from shipping containers or loading

Table 3. Descriptive statistics of personal 8-h exposures for container handlers (n = 133), by whether they entered containers or not, and for those entering containers by whether they were fumigated or not.

Chemical (ppb[f])	WES[g]	TLV[h]	LoD	Container handlers (n = 133)				Container handlers entering containers with known fumigation status (n = 87)[e]			
				Participants entering containers (n = 98)[a]		Participants not entering container (n = 35)[b]		Handled fumigated container (n = 31)[c]		Did not handle fumigated container (n = 56)[d]	
				<LoD (%)	Median (p75)	<LoD (%)	Median (p75)	<LoD (%)	Median (p75)	<LoD (%)	Median (p75)
Fumigants											
1,2-Dibromoethane	500	—	5	77.6	<LoD (<LoD)	54.3	<LoD (14.9)	77.4	<LoD (<LoD)	73.2	<LoD (<LoD)
Chloropicrin	100	100	5	95.9	<LoD (<LoD)	68.6	<LoD (7.5)	93.5	<LoD (<LoD)	96.4	<LoD (<LoD)
Ethylene oxide	1000	1000	10	84.7	<LoD (<LoD)	100.0	<LoD (<LoD)	87.1	<LoD (<LoD)	85.7	<LoD (<LoD)
Hydrogen cyanide	10 000[i]	4700[i]	3	78.6	<LoD (<LoD)	80.0	<LoD (<LoD)	83.9	<LoD (<LoD)	71.4	<LoD (5.4)
Hydrogen phosphide	300	50	3	77.6	<LoD (<LoD)	71.4	<LoD (5.8)	83.9	<LoD (<LoD)	73.2	<LoD (4.4)
Methyl bromide	5000	1000	5	73.5	<LoD (5.2)	45.7	5.9 (10.8)	64.5	<LoD (9.2)	78.6	<LoD (<LoD)
Non-fumigants											
1,2-Dichloroethane	5000	10 000	5	83.7	<LoD (<LoD)	68.6	<LoD (6.9)	90.3	<LoD (<LoD)	76.8	<LoD (<LoD)
C2-alkylbenzenes	50 000	20 000	5	52.0	<LoD (9.8)	51.4	<LoD (13.6)	74.2	<LoD (6.4)	46.4	5.5 (10.2)
Acetaldehyde	20 000	25 000[i]	25	57.1	<LoD (50.7)	74.3	<LoD (31.7)	64.5	<LoD (32.2)	55.4	<LoD (55.1)
Ammonia	25 000	25 000	15	85.7	<LoD (<LoD)	77.1	<LoD (<LoD)	87.1	<LoD (<LoD)	82.1	<LoD (<LoD)
Benzene	1000	500	5	91.8	<LoD (<LoD)	77.1	<LoD (<LoD)	90.3	<LoD (<LoD)	91.1	<LoD (<LoD)
Formaldehyde	500	100	25	41.7	38.3 (144.6)	55.6	<LoD (32.3)	50.0	21.1 (65.1)	36.4	38.4 (196.2)
Styrene	20 000	20 000	2	95.9	<LoD (<LoD)	82.9	<LoD (<LoD)	96.8	<LoD (<LoD)	96.4	<LoD (<LoD)
Toluene	50 000	20 000	3	32.7	5.6 (13.7)	20.0	6.6 (19.5)	48.4	3.2 (8.0)	28.6	5.4 (12.1)
Other				**AMV >1 (%)**		**AMV >1 (%)**		**AMV >1 (%)**		**AMV >1 (%)**	
Sum-value	n/a	n/a	n/a	n/a	183.5 (83.6–308.7)	n/a	125.8 (82.9–248.6)	n/a	134.9 (75.3–266.6)	n/a	189.6 (79.6–337.9)
AMV[j] (WES)	1	1	n/a	0	0.2 (0.1–0.4)	0	0.1 (0.1–0.2)	0	0.1 (0.1–0.2)	0	0.2 (0.1–0.5)
AMV[k] (TLV)	1	1	n/a	36.7	0.5 (0.2–1.6)	8.6	0.2 (0.3–0.6)	19.4	0.4 (0.2–0.8)	48.2	0.5 (0.2–2.2)

n/a, not applicable.
[a]n (formaldehyde) = 96.
[b]n (formaldehyde) = 27.
[c]n (formaldehyde) = 30.
[d]n (formaldehyde) = 55.
[e]n (formaldehyde) = 85.
[f]ppb: parts per billion.
[g]8-h WES set by WorkSafe NZ (2018).
[h]8-h WES (TLV) set by American Conference of Governmental Industrial Hygienists (2019).
[i]These chemicals do not have a time-weighted average limit but only a ceiling limit which was used instead.
[j]AMV using the WES.
[k]AMV using the TLV and excluding 1,2-dibromoethane because the ACIGH has not set a TLV for 1,2-dibromoethane.

Table 4. ERs of personal 8-h exposures for container handlers entering containers, handling fumigated containers, and by duration spent unloading containers.

Chemical (ppb[d])	All container handlers (n = 133)	Container handlers entering containers (n = 98)	
	Participants entering containers (n = 98) versus not entering (n = 35)[a]	Handled fumigated container (n = 31) versus not fumigated (n = 56)[b]	Duration of unloading containers (h) (n = 94)[c]
	ER (95% CI)	ER (95% CI)	ER (95% CI)
Fumigants			
1,2-Dibromoethane	0.4** (0.2–0.7)	0.7 (0.4–1.4)	0.9 (0.8–1.0)
Chloropicrin	0.2*** (0.1–0.5)	1.6 (0.3–8.1)	0.6 (0.3–1.1)
Ethylene oxide	1.2* (1.0–1.4)	1.0 (0.8–1.2)	1.1*** (1.1–1.1)
Hydrogen cyanide	1.0 (0.8–1.3)	0.9 (0.6–1.1)	1.0 (0.9–1)
Hydrogen phosphide	0.8 (0.6–1.0)	0.9 (0.7–1.1)	1.0 (1.0–1.1)
Methyl bromide	0.5* (0.3–0.9)	2.0 (0.9–4.5)	0.9 (0.7–1)
Non-fumigants			
1,2-Dichloroethane	0.5* (0.3–0.9)	0.6 (0.3–1.3)	1.0 (0.8–1.1)
C2-alkylbenzenes	1.1 (0.6–1.9)	0.4** (0.2–0.8)	1.3*** (1.1–1.4)
Acetaldehyde	2.2* (1.1–4.5)	0.6 (0.3–1.4)	1.2** (1.1–1.4)
Ammonia	0.4 (0.1–1.6)	0.8 (0.2–4.3)	0.8 (0.6–1.2)
Benzene	0.5* (0.2–0.9)	1.1 (0.5–2.3)	1.0 (0.9–1.2)
Formaldehyde	2.5** (1.3–4.8)	0.5 (0.3–1.1)	1.0 (0.9–1.2)
Styrene	0.4* (0.2–0.9)	1.0 (0.2–4.4)	0.9 (0.7–1.2)
Toluene	0.9 (0.6–1.4)	1.1 (0.7–1.8)	1.0 (0.9–1.1)
Other			
Sum-value	1.3 (1.0–1.7)	0.8 (0.6–1.2)	1.1 (1.0–1.1)
AMV[e] (WES)	1.1 (1.0–1.2)	0.9* (0.8–1.0)	1.0 (1.0–1.0)
AMV[f] (TLV)	1.7** (1.2–2.4)	0.6* (0.4–1.0)	1.0 (1.0–1.1)

[a]n (formaldehyde) = 123.
[b]n (formaldehyde) = 85.
[c]n (formaldehyde) = 92.
[d]ppb: parts per billion.
[e]AMV using the WES.
[f]AMV using the TLV and excluding 1,2-dibromoethane because the ACIGH has not set a TLV for 1,2-dibromoethane.
*P < 0.05.
**P < 0.01.
***P < 0.001.

logs were below current national and international exposure standards. The exception was formaldehyde, for which 26.2% of all measurements exceeded the ACGIH TLV, and exposure levels for formaldehyde were significantly higher in container handlers entering containers compared with those who did not. We also found a significant association between duration of unloading containers and exposures to ethylene oxide, acetaldehyde, and C2-alkylbenzenes exposures, but all measurements were below the WES/TLV. Exposure levels differed between container handlers handling fumigated and non-fumigated containers with lower exposures to ethylene oxide and both AMVs in those unloading fumigated containers.

Our findings are consistent with a previous, but much smaller study, which showed low exposures to fumigants and other chemicals in workers (n = 10) unloading containers (Safe Work Australia, 2011). In addition, an experimental study using tracer gas measured low personal exposures in workers unloading containers (Svedberg and Johanson, 2013). This is in contrast with the considerable higher detection rates and concentrations reported for air measurements taken from unopened containers (Knol-de Vos, 2002; de Groot, 2007;

Baur *et al.*, 2010; Budnik *et al.*, 2010; Fahrenholtz *et al.*, 2010; Tortarolo, 2011; New Zealand Customs Service, 2012; Svedberg and Johanson, 2017; European Agency for Safety and Health at Work, 2018), which had led to the assumption that workers are likely to be highly exposed, potentially contributing to the adverse health effects reported for workers in this industry (Spijkerboer *et al.*, 2008; Preisser *et al.*, 2011, 2012; Kloth *et al.*, 2014; Roberts *et al.*, 2014; Baur *et al.*, 2015).

The considerably (and somewhat unexpected) lower exposures measured in our study may be due to a rapid decline in chemical concentrations inside the container following the opening of container doors, as shown in previous studies (Svedberg and Johanson, 2013; Braconnier and Keller, 2015). In our study, most containers were not entered until at least a few minutes after opening the doors. Fumigated containers are required to have longer ventilation periods (up to 24 h) and this may explain why we observed some lower exposures for workers entering containers that had been fumigated compared with those not fumigated (Table 4). Containers were also generally positioned outside, thus further increasing natural ventilation. Moreover, in this study most containers were transported by trucks from the port to the distribution network and/or final destination, which may increase air exchange rates in the container (Bethke *et al.*, 2013; Svedberg and Johanson, 2017), thus reducing the concentration of chemicals inside the containers. Furthermore, participants carried out only part of their work inside the containers.

An alternative explanation for why exposures were low may be bias due to participants being selected by management (see methods) who may have favoured workers who were less likely to have high exposure, thus potentially resulting in an underestimation of exposure. However, based on job descriptions and field observations, the group of participants appeared representative of the general workforce in these areas, but this was not formally tested. In addition, as workers and management were aware measurements were being taken, longer venting times may have been applied, potentially underestimating exposure but again this was not supported by field observations. Other reasons why exposures may have been lower than expected based on previous studies measuring container air, could be due to: changes in fumigant-use in recent times (our study was conducted several years after most previous studies); different patterns in cargo and transport times compared with previous studies which were mainly conducted in Europe; and changes to work practices.

In this study, formaldehyde, which is both a carcinogen (Worksafe New Zealand, 2018; ACGIH, 2019) and sensitizer, was the main contributor to overall exposure to volatiles in all occupational groups. It exceeded the ACGIH TLV in 26.2% of all measurements and was the main predictor of higher AMV levels, with the AMV-TLV exceeding '1' in 29% of all measurements. Thus, detection rates and exposure levels of formaldehyde were high compared with most other chemicals, which is consistent with the findings of a small study involving personal exposures (Safe Work Australia, 2011) and several studies measuring container air (Knol-de Vos, 2002; Baur *et al.*, 2010; Tortarolo, 2011; New Zealand Customs Service, 2012; Svedberg and Johanson, 2017). Formaldehyde is ubiquitously found in the environment as a result of combustion processes and is used in a wide range of manufacturing processes, such as the textile industry, car manufacturing and plywood and carpet manufacturing (where it is part of the adhesives used). Higher exposures in container handlers may therefore be due to its wide use and subsequent off-gassing from cargo, packaging, and wooden container floors (Svedberg and Johanson, 2017). Formaldehyde also has a slower decay rate compared with many other volatile organic components (Holos *et al.*, 2019) potentially resulting in longer exposure durations. Retail workers had the highest detection rate and median exposure for formaldehyde, potentially due to its release when opening packaging or from continuous off-gassing from products (Knol-de Vos *et al.*, 2005; Kloth *et al.*, 2014; Baur *et al.*, 2015; Budnik *et al.*, 2017). In addition, many workers from all occupational groups were likely exposed to formaldehyde from exhaust fumes of trucks and heavy machinery operating in close vicinity. To put these exposures into context, levels were generally higher than exposures among the general population in five Swedish cities (mean 15.8 ppb) (Hagenbjork-Gustafsson *et al.*, 2014), but median values for formaldehyde were similar or only slightly above levels typically observed in the home environment (Salthammer *et al.*, 2010).

Levels and detection frequencies of most chemicals varied little between occupational groups, although methyl bromide exposure was clearly higher for fumigators compared with other groups. However, the fumigant levels measured in fumigators were low compared with the exposure standards possibly due to workers wearing respirators during fumigation, which was taken into account by workers removing personal sampling equipment when using respirators.

As expected, workers handling fumigated logs were exposed to higher levels of methyl bromide compared with workers handling non-fumigated logs, although levels were still well below the exposure standards. Exposures to formaldehyde were also higher on days that workers handled fumigated containers; the reasons for this are not clear as working conditions were very similar for fumigated and non-fumigated containers.

We found positive associations with duration spent unloading containers for some chemicals, but not for others. It is possible that the overall time spent unloading containers is too crude a proxy for exposure, particularly as many workers unloaded multiple containers during a single work-shift, with each containing different cargo and therefore contributing to different types and level of exposures. In addition, short-term peak exposures may contribute most to the average exposure as has been shown for other exposures in other occupational settings (Meijster *et al.*, 2008), which if true, could be another, or additional, explanation why duration was not always associated with exposure.

A strength of this study was that exposures were measured for a full 8-h shift, enabling comparisons with the corresponding exposure standards. However, as a consequence, information on peak exposures was not available despite this potentially posing a greater health risk to workers (Svedberg and Johanson, 2013). Also, and this is an important limitation, as it is not clear whether working conditions of participants included in this study were representative of this industry as a whole, and that all relevant exposures were measured, we cannot exclude the possibility that high exposures may occur in at least some workers. Other limitations include the high number of non-detectable measurements and the relatively small number of workers measured, particularly when considering the large number of possible exposure determinants, such as cargo, packaging, and container ventilation time. In addition, as participants frequently unloaded several containers with different cargo and packaging, and from countries of different origin as part of the same 8-h shift, we were not able to measure the impact of these parameters or other determinants of exposure such as concentrations of chemicals inside the containers prior to opening them, meteorological factors, or ventilation times. Furthermore, and as noted above, while this study included a wide range of chemicals, it did not measure all possible pollutants in container air (e.g. terpenes were not included), and the AMVs presented may therefore be underestimates. Also, the choice of assigning a fixed concentration (i.e. LoD/2) to samples that were not detectable might have affected the calculated AMVs. However, using a concentration that is equivalent to the LoD for samples <LoD did not appreciably change the results (i.e. the AMV of only two samples increased to a level >1 and only when using TLVs; no difference was found for WES-based AMVs), indicating this is not a significant issue.

In conclusion, this study has shown low exposures to fumigants and residual chemicals (with the exception for formaldehyde) in a sample of New Zealand workers handling cargo and export logs, likely due to the container ventilation periods observed before entry. However, more work is required to assess whether these results are representative for these industries as a whole. Likewise, this study cannot exclude the possibility of occasional high peak exposures.

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Conflict of interest

The authors declare no conflict of interest relating to the material presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

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