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Original Article

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Exposures to Volatile Organic Compounds among Healthcare Workers: Modeling the Effects of Cleaning Tasks and Product Use

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Abstract

Objectives: Use of cleaning and disinfecting products is associated with work-related asthma among healthcare workers, but the specific levels and factors that affect exposures remain unclear. The objective of this study was to evaluate the determinants of selected volatile organic compound (VOC) exposures in healthcare settings.

Methods: Personal and mobile-area air measurements (n = 143) from 100 healthcare workers at four hospitals were used to model the determinants of ethanol, acetone, 2-propanol, *d*-limonene, α-pinene, and chloroform exposures. Hierarchical cluster analysis was conducted to partition workers into groups with similar cleaning task/product-use profiles. Linear mixed-effect regression models using log-transformed VOC measurements were applied to evaluate the association of individual VOCs with clusters of task/product use, industrial hygienists' grouping (IH) of tasks, grouping of product application, chemical ingredients of the cleaning products used, amount of product use, and ventilation.

Results: Cluster analysis identified eight task/product-use clusters that were distributed across multiple occupations and hospital units, with the exception of clusters consisting of housekeepers and floor strippers/waxers. Results of the mixed-effect models showed significant associations between selected VOC exposures and several clusters, combinations of IH-generated task groups and chemical ingredients, and product application groups. The patient/personal cleaning task using products containing chlorine was associated with elevated levels of personal chloroform and α-pinene exposures. Tasks associated with instrument sterilizing and disinfecting were significantly associated with personal *d*-limonene and 2-propanol exposures. Surface and floor cleaning and stripping tasks were predominated by housekeepers and floor strippers/waxers, and use of chlorine-, alcohol-, ethanolamine-, and quaternary ammonium compounds-based products was associated with exposures to chloroform, α-pinene, acetone, 2-propanol, or *d*-limonene.

Conclusions: Healthcare workers are exposed to a variety of chemicals that vary with tasks and ingredients of products used during cleaning and disinfecting. The combination of product ingredients with cleaning and disinfecting tasks were associated with specific VOCs. Exposure modules for questionnaires used in epidemiologic studies might benefit from seeking information on products used within a task context.

Keywords: cleaning and disinfecting; healthcare; hierarchical clustering; modeling; volatile organic compounds

Introduction

Work-related asthma (WRA) is a common, chronic, but preventable respiratory disease, which affects millions of workers in the USA (Dodd and Mazurek, 2016). Previous studies report that 15–22% of adult asthma can be attributed to work (Balmes et al., 2003; Henneberger et al., 2011). Surveillance studies have reported the highest prevalence of current asthma in the healthcare and social assistance industry (10.7%) and healthcare support occupations (12.4%) (Wiszniewska and Walusiak-Skorupa, 2014; Dodd and Mazurek, 2016; Mazurek and Weissman, 2016). Epidemiologic studies have reported an increased risk of asthma, rhinitis, and respiratory symptoms associated with cleaning and disinfecting tasks, such as cleaning surfaces and sterilizing instruments (Delclos et al., 2007; Gonzalez et al., 2014), floor stripping and waxing (Obadia et al., 2009), and use of spray products (Obadia et al., 2009; Dumas et al., 2012; Le Moual et al., 2012). Increased risk of asthma and respiratory symptoms have also been associated with the use of specific products, including general purpose cleaning chemicals (Zock et al., 2010), detergent enzymes (Adisesh et al., 2011), and products containing volatile organic compounds (VOCs) (Quirce and Barranco, 2010). Cleaning and disinfecting tasks have particular significance in healthcare settings because of the need for maintaining infection control. Thus, the need to prevent WRA must be balanced with the requirement of preventing healthcare-associated infections.

Despite the high prevalence of WRA in healthcare industry workers, the specific cleaning and disinfecting tasks, and types and levels of exposures that pose a health risk remain unclear. Comprehensive exposure assessments have rarely been done in healthcare settings, in part, due to the complex nature of exposures and significant challenges of conducting personal sampling for multiple agents. Cleaning and disinfecting products usually comprise complex chemical mixtures, which impart different aesthetic (e.g. scents and perfumes) and functional (e.g. biocides, preservatives) properties to the products (DeLeo et al., 2018). Furthermore, a variety of cleaning and disinfecting tasks can be performed using multiple products by various occupations, e.g. general cleaning by housekeepers or patient care and surface cleaning by nurses (Saito et al., 2015). The handful of exposure assessment studies conducted in healthcare settings reported exposure to alcohols (ethanol and isopropyl alcohol); ketones (acetone); terpenes; aliphatic, aromatic, and halogenated hydrocarbons; and peroxygen compounds using personal or mobile-area, time-integrated measurements for occupations (LeBouf et al., 2014; Hawley et al., 2017) and stationary measurements at various locations within hospitals (Bessonneau et al., 2013). Personal exposures to monoethanolamine, a mixture of glycol ethers, benzyl alcohol, and formaldehyde, were measured during cleaning tasks performed by professional cleaners in different settings including patient rooms in hospitals (Gerster et al., 2014). In a quasi-experimental study, collected short-duration (10 min) task samples and quantified exposure to total volatile organic compounds (TVOCs) and 2-butoxyethanol for typical tasks (e.g. cleaning toilets and mirrors) and modeled determinants of 2-butoxyethanol exposures (Bello et al., 2013). However, workplace studies characterizing the determinants of exposure, such as cleaning and disinfecting tasks or products, are lacking but are essential to understanding the risk of WRA relative to cleaning and to inform intervention and prevention (Heederik, 2014).

A better understanding of factors affecting exposure to cleaning and disinfecting chemicals will allow identification and prioritization of controls and development of task exposure matrices for use in epidemiologic studies (Heederik, 2014; Quinn et al., 2015). In our previous work, we characterized multiple exposures associated with occupations and the frequency and duration of performing cleaning and disinfecting tasks and product use across various healthcare occupations (LeBouf et al., 2014; Saito et al., 2015). Comprehensive exposure characterization can generate a large number of exposure and predictor variables that are often correlated. Hierarchical clustering is a systematic and reproducible data reduction approach that groups observations with similar profiles across the variables of interest, which also minimizes the potential issue of multiple testing. This approach has been widely applied in various disciplines (Johnson, 1997; Gambin and Slonimski, 2005; Henry et al., 2005; Do and Choi, 2008; Kavuri and Liu, 2014), but also has utility in occupational exposure assessment (Hines et al., 1995; Wu et al., 1999; Friesen et al., 2015). In this study, our main objective is to identify the determinants of exposures to selected VOCs present in cleaning products used in healthcare settings.

Materials and methods

Sampling and analysis

Healthcare workers from 14 occupations were recruited from four US Veterans Affairs (VA) hospitals and teaching hospitals. These occupations, clinical laboratory technician, nursing assistant, dental assistant, dental laboratory technician, endoscopy technician, floor stripper/waxer, housekeeper, licensed practical nurse, medical appliance technician, medical equipment preparer, pharmacist/pharmacy technician, registered nurse, respiratory therapist, and surgical technologist, were selected based on their association with WRA or the potential for VOC exposures (Saito et al., 2015). Verbal informed consent was obtained from each worker prior to participating. Participants were monitored for one to three shifts over a period of 1 week (LeBouf et al., 2014; Saito et al., 2015). Mobile-area and personal samples were collected using 6-l and 0.4-l Silonite™-evacuated canisters, respectively (Entech Instruments, Inc., Simi Valley, CA), with an inlet tube near the workers' breathing zone for the latter samples. Additionally, to estimate background VOC levels, a total of 22 daily ambient air samples were collected using the 6-l Silonite™-evacuated canisters placed outside the hospital and away from automobile traffic on each day of sampling. During VOC sampling, systematic observations of participants were conducted by trained technicians using standardized data collection forms to record information at 5-min intervals on tasks, activities, materials or products used and their amounts (low, high), work location, engineering controls, and personal protective equipment use, including cleaning tasks and product use by other workers in the same area ('secondhand exposure').

The analytical method targeted 14 specific VOCs (ethanol, acetone, 2-propanol, methylene chloride, hexane, chloroform, benzene, methyl-methacrylate, toluene, ethylbenzene, m,p-xylene, o-xylene, α-pinene, and *d*-limonene) based on a pilot study done at one of the three VA hospital as previously described by LeBouf (2012). The percentage of measurements below the limits of detection (LODs) ranged from 84.6% (α-pinene in personal samples) to 0% (acetone and toluene in personal, and acetone in mobile-area samples). Measurements below the LODs were replaced by imputations, which were randomly simulated from 0 to the corresponding LODs (Ganser and Hewett, 2010).

Data analyses

A total of 100 participants with 143 pairs of mobile-area and personal VOC samples and systematic observations were used in the present analyses. Concentrations of the 14 VOCs were summed to create a total 14 VOCs (TVOC14) group. We also summed 11 VOCs (excluding the three most dominant compounds: ethanol, acetone, and 2-propanol) to create a total 11 VOCs group (TVOC11). VOC measurements, cleaning tasks, and most common product ingredients were summarized and their distributions were plotted by occupation. We combined all individual non-cleaning-related tasks into one variable (i.e. overall non-cleaning task). We also created a product application group that is a combination of the types of cleaning products [e.g. quaternary ammonium compounds (QAC), chlorine-based products] with product applications (e.g. used for skin preparation and surface cleaning). This grouping is consistent with questions used in exposure modules of epidemiologic questionnaires.

Principal component analysis was first explored to reduce data dimensionality but did not yield interpretable principal components. Therefore, hierarchical cluster analyses were applied to agnostically partition workers into groups with similar cleaning task/product-use time profiles (Friesen et al., 2015). Similarity of clusters was estimated by Euclidean length, and Ward's minimum variance method was chosen as the linkage criterion to select the most similar pair of clusters (Ward, 1963). Because clustering and Ward's method have been found to be sensitive to data scale and outliers (Milligan, 1980; Hennig and Liao, 2013), time spent performing cleaning tasks and product use (in minutes) were standardized by subtracting the mean time and dividing by the respective standard deviation. A scree plot was used to determine the numbers of clusters, which shows the distance between two clusters when they are joined together at each step. Considering the potential underlying pattern (i.e. 14 occupations) and practical use of clusters in further analyses (i.e. the size of the data set and minimum desired observations per group), the number of clusters used to group the workers was limited to 10 or fewer. After clustering was complete, the distributions of occupations, hospital unit, and average time spent on tasks and product use were computed to describe each cluster's characteristics.

As an alternative to clustering, similar tasks were grouped by NIOSH industrial hygienists (IH) to generate groups that are easy to interpret for identifying factors amenable to intervention and control (e.g. clean beds, furniture, counters, blood, carts, walls, toilets, sinks, windows, glass, mirrors, and spills were grouped as surface cleaning). Indicator variables (1/0; cut-off = 15 min) of the seven personal task groups included: (i) clean equipment, (ii) clean instruments, (iii) mix chemicals, (iv) clean floors, (v) clean surfaces, (vi) clean patient and personal cleaning, and (vii) non-cleaning tasks. Because every participant spent at least 50 min per day on non-cleaning tasks, the indicator variable for non-cleaning tasks was not included in further models.

Linear mixed-effect models were applied to identify the determinants of 6 out of 14 VOCs that are related to cleaning product as major ingredients (ethanol, acetone, and 2-propanol) or as signature components (chloroform, α-pinene, and *d*-limonene). All models used log-transformed concentrations and included random effects of location (hospital) and participants nested within locations. A null model was constructed for each outcome variable with no fixed effects and the random effects of location and participants nested within locations to obtain the total, within-worker, between-worker, and between-location variance components. Three types of models were constructed to test the effects of tasks and product use, which included the following predictor variables: (i) clusters for tasks and product use (one variable with eight categories), (ii) IH-generated groups for tasks (six indicator variables), and (iii) product application groups (20 indicator variables). All models also included area task and area product use that were coded as present (i) if any cleaning tasks were performed or any products were used by other workers not being monitored while sampling and observing a worker. Additionally, models using IH-generated task groups also tested the fixed effects of selected chemical ingredients of products listed in the safety data sheets (SDS) (e.g. alcohols and fragrances), controls (e.g. use of local exhaust), tools (e.g. liquid spray), and amount of the agent (e.g. high amount), which were coded as indicators and were only retained in the model if statistically significant.

Hierarchical cluster analyses were conducted using JMP version 12 software (SAS Institute Inc., Cary, NC). Linear mixed-effect models and descriptive analyses were performed in SAS version 9.4 software (SAS Institute Inc.). The bar charts of VOC concentrations were generated in R 3.3.1 using the ggplot2 package. The study reported statistically significant associations ($P < 0.05$), and associations with P value between 0.05 and 0.1 as marginally significant.

Results

Descriptive statistics

The exposure concentrations for TVOC11 and TVOC14 and selected cleaning-related VOCs, time spent (in minutes) on cleaning tasks, and ingredients of products by occupation are shown in Supplementary Table 1 (available at *Annals of Work Exposures and Health* online). Median concentrations for personal and mobile-area VOCs show different patterns by occupation (Fig. 1). Nursing assistants had higher personal exposures to most VOCs while clinical laboratory technicians and licensed practical nurses had higher exposures to more than half of the personal VOCs compared with other occupations. Some exposures were specific to occupations, e.g. dental assistants had the highest concentrations among all occupations for mobile-area methyl-methacrylate (which were also elevated among dental laboratory technicians). Other exposures such as 2-propanol and acetone were common across all occupations. Median concentrations for personal and mobile-area VOCs by hospital unit are presented in Supplementary Fig. 1 (available at *Annals of Work Exposures and Health* online). Many units had relatively high concentrations for specific personal VOCs but not necessarily for mobile-area VOCs. Most chemicals were present in all hospital units albeit at varying concentrations.

Field observations of the healthcare workers as they performed their duties revealed unique patterns of the average time spent performing specific cleaning tasks among occupations. As illustrated in Fig. 2, the longest durations of cleaning tasks performed by occupation included the following: medical equipment preparers and equipment cleaning (109 min); housekeepers and surface cleaning (89.5 min); floor strippers/waxers and floor cleaning and mixing (84.2 and 5.38 min, respectively); endoscopy technicians and instrument cleaning (65.0 min); and nursing assistants and patient and personal cleaning tasks (31.3 and 20.6 min, respectively). Most occupations performed at least one cleaning task, with several occupations such as endoscopy technicians and housekeepers performing multiple cleaning tasks. However, some occupations such as dental laboratory technicians and medical appliance technicians spent <5 min on any cleaning task.

Occupational patterns in relation to 19 selected chemical ingredients in products based on the SDS are presented in Fig. 3. Alcohol was present in products used

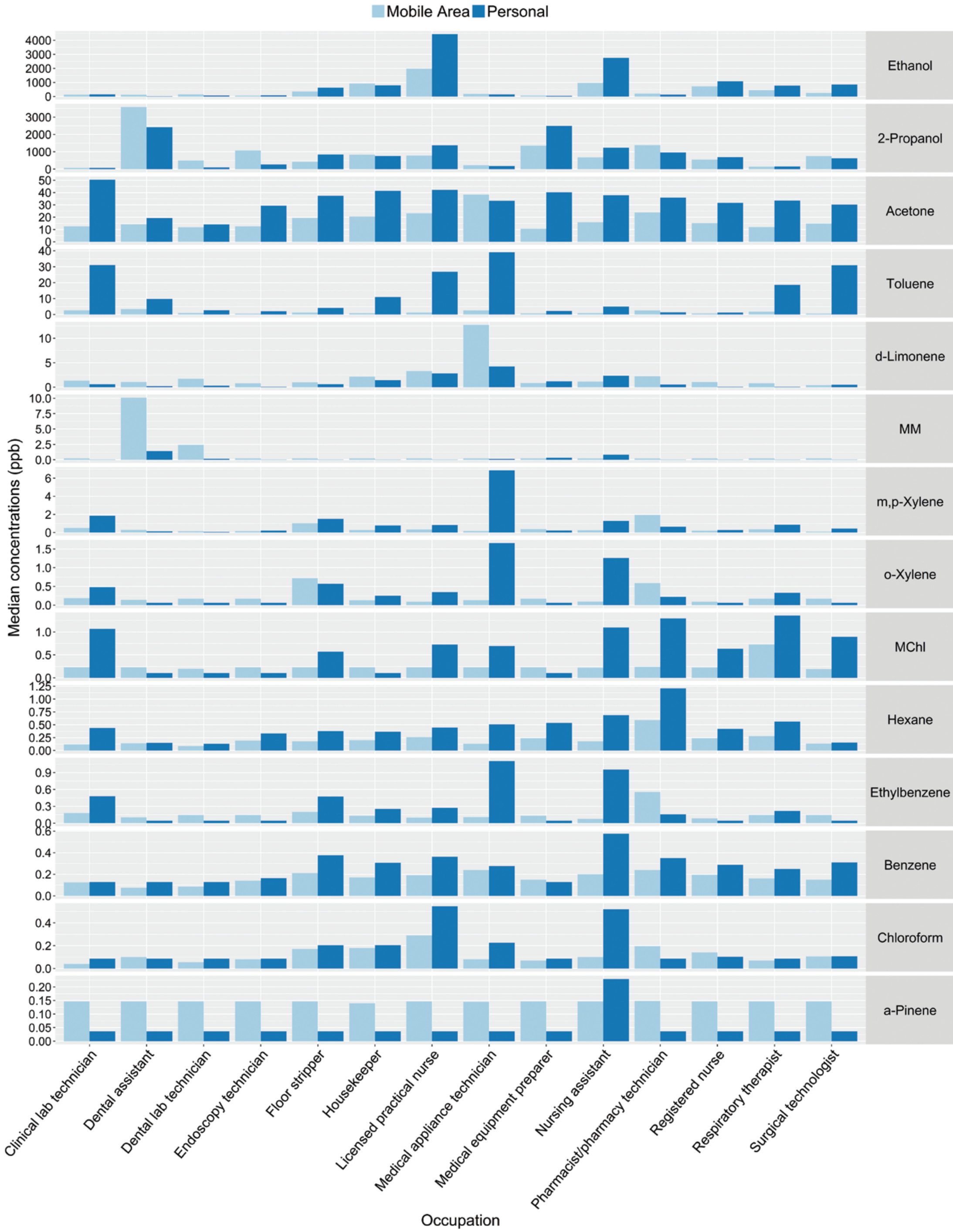

Figure 1. Median concentrations (ppb) for personal and mobile-area VOCs by occupation. VOC, volatile organic compound; MChl, methylene chloride; MM, methyl-methacrylate. Scale is different for each chemical, and chemicals arranged in a descending order of concentration range.

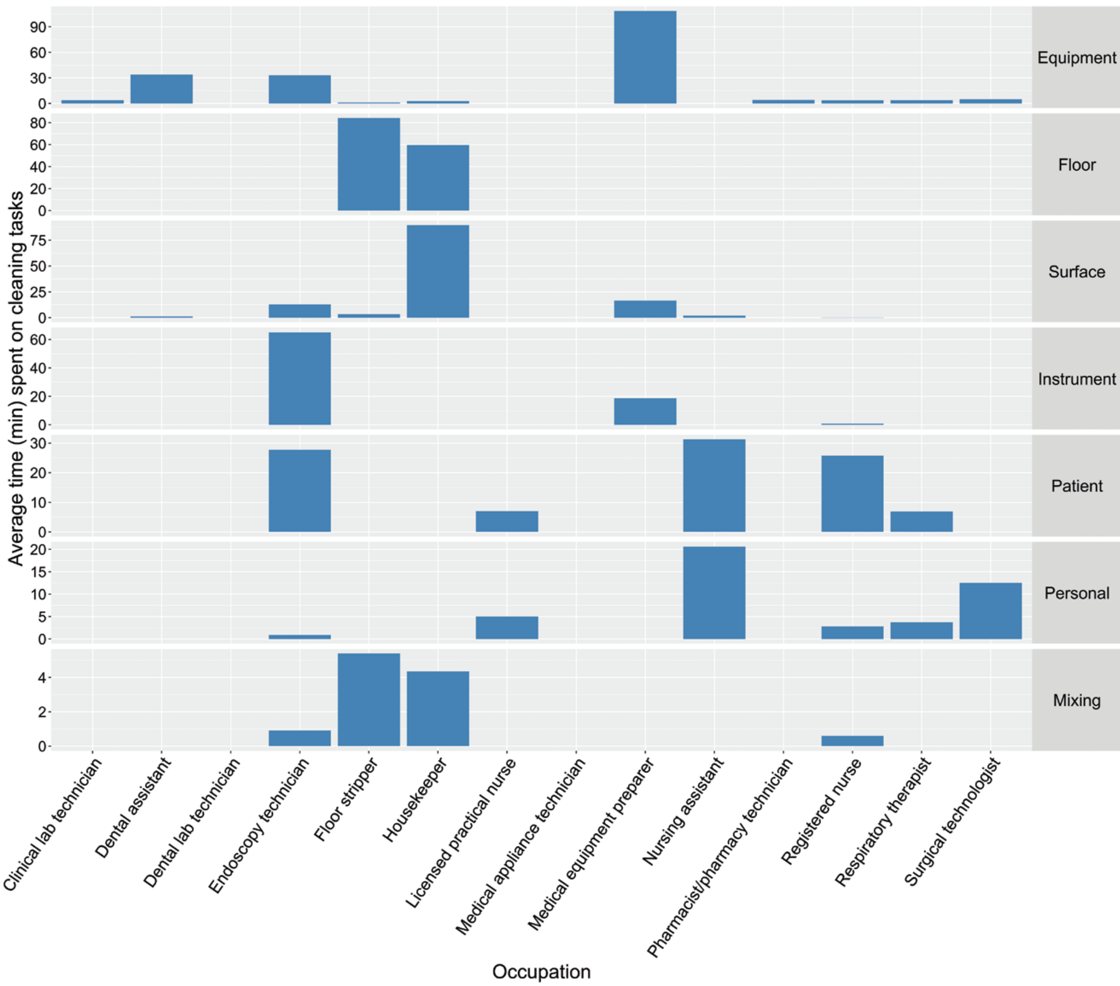

Figure 2. Average time (min) spent on personal cleaning tasks by occupation. Scale is different for each task, and tasks arranged in a descending order of time.

for at least 5 min per shift by 10 out of 14 occupations. Housekeepers on average used alcohol-containing products for >2 h per day. Twelve to 13 different chemicals were present in cleaning products used by endoscopy technicians, floor strippers/waxers, and housekeepers. Some ingredients were unique to occupations, e.g. ammonia was present in products used only by floor strippers/waxers, and aldehydes were present in products used only by clinical laboratory and endoscopy technicians.

Hierarchical clustering

Eight clusters were identified using time spent on cleaning tasks and product use (Table 1). The clusters were distributed across occupations and hospital units with some exceptions, and using additional information on task/product use, were assigned a label to enable interpretation. Cluster 1 is labeled a general cleaning cluster and included housekeepers, dental assistants, registered nurses, and respiratory therapists performing cleaning and patient-care tasks, mostly using QAC-based surface cleaners and multiple skin preparation wipes. Cluster 2 was represented by most occupations and hospital units but was dominated by registered nurses (17 out of 52 observations) and included all clinical laboratory technicians (n = 8) and pharmacists/pharmacy technicians (n = 6), and most of the licensed practical nurses (4 out of 5). Non-cleaning tasks were most dominant in Cluster 2, but it also included some patient-care and cleaning tasks using alcohol-based skin preparation wipes and QAC-based surface cleaners. Cluster 2 was the largest cluster (n = 55) and could not be further

Figure 3. Average time (min) spent on selected chemicals in cleaning products used by occupation. Scale is different for each chemical ingredient in products used, and chemical ingredients arranged in a descending order of time.

subdivided meaningfully using hierarchical clustering. Cluster 3 was labeled a patient and personal cleaning cluster and consisted mainly of nursing occupations and respiratory therapists working in patient-care settings like operating rooms/gastroenterology, critical care, and wards. Common tasks and product use included patient care, hand washing, and using alcohol-based and other skin preparation wipes. Cluster 4 was dominated by

Table 1. Clusters for time spent on cleaning tasks and product use[a].

Cluster (no. of observation)	Overall	Cluster 1 (16)	Cluster 2 (55)	Cluster 3 (11)	Cluster 4 (8)	Cluster 5 (7)	Cluster 6 (12)	Cluster 7 (22)	Cluster 8 (12)
Count of occupational characteristics (*n*)									
Unit									
Critical care	15	2	8	2	0	1	0	2	0
Clinical laboratory	8	0	8	0	0	0	0	0	0
Dental clinic	4	3	0	0	1	0	0	0	0
Dental laboratory	4	0	2	0	1	0	0	1	0
Dialysis unit	6	1	0	0	4	0	0	1	0
Emergency room	8	2	3	0	0	1	0	2	0
Floor	13	0	2	0	0	0	0	0	11
Operating room/ gastroenterology	42	4	14	7	0	5	8	3	1
Orthopedic laboratory	2	0	1	0	0	0	0	1	0
Pharmacy	6	0	6	0	0	0	0	0	0
Sterile processing	7	1	2	0	0	0	4	0	0
Ward	28	3	9	2	2	0	0	12	0
Occupation									
Clinical laboratory technician	8	0	8	0	0	0	0	0	0
Nursing assistant	8	0	6	1	0	1	0	0	0
Dental assistant	4	3	0	0	1	0	0	0	0
Dental laboratory technician	4	0	2	0	1	0	0	1	0
Endoscopy technician	11	0	3	0	0	3	5	0	0
Floor stripper/waxer	13	0	2	0	0	0	0	0	11
Housekeeper	31	7	2	0	0	0	1	20	1
Licensed practical nurse	5	0	4	1	0	0	0	0	0
Medical appliance technician	2	0	1	0	0	0	0	1	0
Medical equipment preparer	7	1	2	0	0	0	4	0	0
Pharmacist/pharmacy technician	6	0	6	0	0	0	0	0	0
Registered nurse	34	3	17	3	6	3	2	0	0
Respiratory therapist	8	2	2	4	0	0	0	0	0
Surgical technologist	2	0	0	2	0	0	0	0	0
Task (average minute)									
Pour/mix product	2.73	0.63	1.09	0.00	2.50	1.43	1.67	9.32	5.42
General cleaning	20.6	42.8	4.45	4.09	0.63	0.00	28.3	67.3	11.7
Wash equipment	6.57	0.00	1.27	0.00	0.00	0.00	72.5	0.00	0.00
Sterilize/disinfect	2.80	0.00	1.91	0.00	0.00	0.00	24.6	0.00	0.00
Wipe with alcohol	0.03	0.00	0.00	0.00	0.63	0.00	0.00	0.00	0.00
Clean bathroom	4.13	3.13	0.36	0.00	0.00	0.00	0.00	23.4	0.42
Mop floor	15.3	19.1	1.18	0.00	0.00	0.00	17.1	53.4	36.3
Clean spill	0.42	0.00	0.00	0.00	0.00	0.00	0.00	0.23	4.58
Clean window	1.43	0.94	0.09	0.00	0.00	0.00	0.00	8.41	0.00
Clean scope	1.54	0.00	0.09	0.00	0.00	0.00	17.9	0.00	0.00
Disinfect machine	0.49	0.00	0.00	0.00	8.75	0.00	0.00	0.00	0.00
Tear down equipment	2.17	0.00	0.55	0.91	0.00	29.3	5.42	0.00	0.00

Table 1. *Continued*

Cluster (no. of observation)	Overall	Cluster 1 (16)	Cluster 2 (55)	Cluster 3 (11)	Cluster 4 (8)	Cluster 5 (7)	Cluster 6 (12)	Cluster 7 (22)	Cluster 8 (12)
Prepare procedure room	2.20	0.00	0.18	0.00	0.00	26.4	10.0	0.00	0.00
Hand wash	0.70	0.00	0.00	7.73	1.25	0.71	0.00	0.00	0.00
Patient care	27.6	93.1	12.3	46.8	18.1	105	32.5	0.00	0.00
Buff/strip floor	5.94	2.19	0.45	0.00	0.00	0.00	0.00	2.50	61.3
Non-cleaning-related tasks	241	152	325	286	324	186	118	160	175
Product application (average minute)									
Alcohol-based skin preparation	10.7	1.25	6.73	26.8	30.0	25.7	33.3	0.68	0.42
Alcohol-based surface cleaner	1.29	0.00	0.18	0.00	19.4	0.00	1.67	0.00	0.00
Chlorine-based surface cleaner	1.99	1.25	0.09	0.00	9.38	0.00	0.00	8.41	0.00
Chlorine-based skin preparation	2.73	1.25	0.91	2.73	8.75	31.4	0.00	0.00	0.00
Chlorine-based waste treatment	2.45	0.00	0.00	0.00	0.00	0.00	29.2	0.00	0.00
Detergent bathroom cleaner	1.78	2.81	0.64	0.00	0.00	0.00	0.00	7.95	0.00
Detergent instrument cleaner	2.24	0.94	0.00	0.00	0.00	0.00	24.2	0.00	1.25
Detergent surface cleaner	1.43	2.19	0.00	0.00	0.00	0.00	0.00	6.59	2.08
Ethanolamine-based floor stripper	7.38	0.00	0.45	0.00	0.00	0.00	0.00	1.14	83.8
Ethanolamine-based glass cleaner	3.01	2.81	0.00	0.00	0.00	0.00	0.00	17.5	0.00
Ethanolamine-based surface cleaner	2.73	0.00	0.00	0.00	0.00	0.00	0.00	12.5	9.58
Enzyme cleaner	8.67	0.00	2.27	0.91	0.00	0.00	92.1	0.00	0.00
High-level instrument disinfectant	0.35	0.00	0.00	0.00	0.00	0.00	4.17	0.00	0.00
High-level disinfectant-oxidizer	1.85	0.00	0.00	0.00	0.00	0.00	22.1	0.00	0.00
Iodine-based skin preparation	3.53	0.31	0.82	0.91	2.50	60.7	0.00	0.00	0.00
Phenolic-based surface cleaner	4.13	0.00	1.09	0.00	0.00	16.4	34.6	0.00	0.00
QAC-based bathroom cleaner	1.50	0.00	0.00	0.00	0.00	0.00	0.00	9.77	0.00
QAC-based floor cleaner	12.7	2.81	0.00	0.00	0.00	0.00	0.00	77.1	5.83
QAC-based skin preparation	0.80	0.00	0.00	0.00	14.4	0.00	0.00	0.00	0.00
QAC-based surface cleaner	19.3	55.9	1.73	2.73	3.75	0.71	40.0	51.4	8.33

[a]Cluster analysis was conducted using standardized time (minute) spent on tasks and product use; average time shown here used original data (non-standardized).

registered nurses working in the dialysis unit who mainly performed non-cleaning tasks but who were also doing patient care and machine disinfection and using multiple different skin preparation wipes and surface cleaners. Cluster 5 was labeled a patient-care and procedure preparation/takedown cluster, included tasks of patient care, tearing down equipment, and preparing procedure rooms, using chlorine-, iodine-, and alcohol-based skin preparation products. This cluster comprised two occupations—endoscopy technicians and nurses—and most of them were in the operating rooms/gastroenterology unit. Cluster 6, labeled instrument sterilizing and disinfecting cluster, included two main occupations—endoscopy technicians and medical equipment preparers in the operating rooms/gastroenterology and sterile processing areas. The main tasks were washing equipment, sterilizing/disinfecting, and cleaning scopes using multiple products including detergents, enzymatic cleaners, alcohol-based wipes, high-level disinfectants, and QAC- and phenolics-based surface cleaners. Cluster 7 was labeled a floor, bathroom, and general cleaning cluster and consisted mainly of housekeepers, and included tasks of mixing products, mopping floors, general cleaning, cleaning bathrooms and windows, and product use of detergents, QAC-, bleach-, and ethanolamine-based surface and floor cleaners that were conducted across several hospital units. Cluster 8 labeled floor cleaning, buffing, and stripping cluster, mostly had floor strippers/waxers, and included tasks of mixing products, buffing, mopping, and stripping floors using ethanolamine-based floor cleaner and stripper and some QAC-based surface cleaners.

Associations between VOC exposures and cleaning tasks and product use

Task-product clusters

The effects of clusters of cleaning tasks and product use on cleaning-related VOC exposures are presented in Table 2. The reference group in all models was the non-cleaning cluster (Cluster 2), which had the least amount of time on most of cleaning-related tasks/product use. Negative estimates for clusters indicate lower exposure for the cluster compared with the non-cleaning cluster. Multiple clusters were significant or marginally significant predictors of various VOC exposures. The instrument disinfection cluster (Cluster 6) had lower exposures for both personal and mobile-area ethanol than the reference cluster, though dialysis (Cluster 4) and floor stripping/waxing (Cluster 8) had higher mobile-area ethanol exposures. Personal acetone exposure was significantly associated with general cleaning (Cluster 1) and instrument disinfection (Cluster 6). Personal 2-propanol was associated with floor stripping/waxing (Cluster 8) while mobile-area 2-propanol was associated with general cleaning (Cluster 1) and instrument disinfection (Cluster 6). Personal chloroform was associated with general cleaning (Cluster 1) and patient care (Cluster 3). Models for α-pinene showed associations with general cleaning (Cluster 1), patient care (Cluster 3), patient care in procedure (Cluster 5), and floor stripping/waxing (Cluster 8) for personal or mobile-area measurements. Instrument disinfection (Cluster 6), housekeeping (Cluster 7), and floor stripping/waxing (Cluster 8) were associated with higher personal *d*-limonene exposures. The total variance explained by fixed effects in models ranged from 4% (2-propanol) to 43% (ethanol) for personal VOCs and 8% (acetone) to 56% (TVOC14) for mobile-area VOCs.

IH-generated groups

The associations between IH-generated groups of personal cleaning tasks and selected VOCs are shown in Table 3. In these models, negative estimates for tasks indicate that performing a task was associated with lower exposure compared with not performing that task. There were several notable findings of significant or marginally significant associations between VOC exposures and task groups or product ingredients. Personal acetone exposure was associated with patient/personal cleaning task, while ethanol and 2-propanol exposures were associated with using products containing alcohol. The use of a local exhaust ventilation hood had a significant association with decreased mobile-area ethanol exposure; local exhaust ventilation hoods were mainly present in the clinical laboratory and pharmacy. Personal chloroform exposure was associated with patient/personal cleaning and floor cleaning tasks, and mobile-area chloroform was associated with floor cleaning, surface cleaning, and the presence of chlorine in products. Both personal and mobile-area *d*-limonene exposures were associated with using products containing fragrances and terpenes. The total variance explained by fixed effects in models ranged from 7% (2-propanol) to 45% (*d*-limonene) for personal VOCs and 4% (acetone) to 56% (*d*-limonene) for mobile-area VOCs. Models for TVOC14 and TVOC11 showed some associations with tasks but were not notably different from the individual VOCs (data not shown).

Product application groups

The associations between product application groups and selected VOCs are shown in Table 4. None of the product application variables were significantly associated with either personal or mobile-area ethanol exposure, while mobile-area 2-propanol exposure was associated with use of high-level disinfectants in sterile processing. In univariate models, many product application groups were associated with personal acetone exposure (Supplementary Table 2, available at *Annals of Work Exposures and Health*

Table 2. Results of multiple linear mixed-effect models for selected and total VOCs and cleaning task-product clusters identified by hierarchical clustering.

Variable	Count	Ethanol			Acetone			2-Propanol			Chloroform			α-Pinene			*d*-Limonene			TVOC14			TVOC11		
		β	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ
Personal Samples																									
Variance explained by fixed effects			0.43			0.30			0.04			0.19			0.24			0.13			0.16			0.06	
Intercept		**5.81**	**0.55**		**3.41**	**0.16**		**5.49**	**0.55**		**−1.90**	**0.28**		**−3.11**	**0.18**		*−1.20*	*0.47*		**7.11**	**0.26**		**2.53**	**0.39**	
Task-product clusters																									
Cluster 1: General cleaning	16	0.90	0.70	147	**0.57**	**0.24**	**76.1**	0.89	0.72	143	*0.54*	*0.28*	*71.9*	**0.60**	**0.28**	**81.7**	0.63	0.55	88.6	**0.90**	**0.36**	**145**	0.35	0.37	41.5
Cluster 3: Patient care	11	1.31	0.85	270	0.36	0.28	43.0	−1.28	0.84	−72.1	*0.63*	*0.33*	*87.9*	**0.95**	**0.34**	**159**	0.64	0.64	89.6	0.65	0.45	90.8	0.67	0.43	94.6
Cluster 4: Dialysis unit	8	−0.81	0.88	−55.6	−0.01	0.32	−0.68	0.43	0.95	53.7	0.20	0.35	21.6	0.01	0.35	1.16	−1.09	0.73	−66.4	0.42	0.45	51.8	−0.31	0.49	−26.7
Cluster 5: Patient care in procedure	7	0.36	0.97	43.5	0.13	0.35	13.9	0.26	1.02	29.3	0.04	0.38	3.68	0.44	0.39	55.9	−0.47	0.78	−37.3	0.24	0.50	27.6	−0.28	0.53	−24.6
Cluster 6: Instrument disinfection	12	**−1.76**	**0.83**	**−82.7**	**0.63**	**0.28**	**88.2**	1.26	0.82	251	0.29	0.32	34.1	0.10	0.33	11.0	*1.12*	*0.62*	*207*	0.33	0.44	38.8	0.69	0.43	99.4
Cluster 7: Housekeeping	22	0.52	0.68	68.0	0.28	0.23	32.8	0.28	0.69	32.3	0.31	0.27	36.9	0.03	0.27	2.72	**1.13**	**0.52**	**210**	0.04	0.35	4.46	−0.12	0.36	−11.3
Cluster 8: Floor stripping/ waxing	12	0.52	0.85	68.8	0.33	0.29	39.7	*1.46*	*0.85*	*331*	0.00	0.33	0.31	0.26	0.34	30.2	*1.27*	*0.64*	*256*	0.44	0.45	55.8	*0.77*	*0.44*	*116*
Cluster 2: Non-cleaning	55													Reference											
Mobile Area Samples																									
Variance explained by fixed effects			0.51			0.08			0.45			0.18			0.16			0.15			0.56			0.12	
Intercept		**5.59**	**0.38**		**2.97**	**0.17**		**5.07**	**0.65**		**−2.08**	**0.24**		**−2.03**	**0.11**		0.20	0.18		**6.92**	**0.26**		**1.93**	**0.12**	
Task-product clusters																									
Cluster 1: General cleaning	16	−0.27	0.53	−23.9	−0.14	0.24	−13.2	*1.59*	*0.84*	*389*	0.30	0.19	34.5	**0.39**	**0.15**	**47.9**	0.01	0.32	0.51	0.50	0.31	65.7	0.25	0.26	27.9

Table 2. *Continued*

Variable	Count	Ethanol			Acetone			2-Propanol			Chloroform			α-Pinene			*d*-Limonene			TVOC14			TVOC11		
		β	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ
Cluster 3: Patient care	11	1.33	0.93	276	−0.33	0.27	−28.4	−0.85	1.00	−57.3	−0.05	0.25	−4.73	0.02	0.17	2.05	−0.12	0.38	−11.3	0.36	0.39	43.3	−0.04	0.32	−3.52
Cluster 4: Dialysis unit	8	*1.08*	*0.62*	*195*	0.18	0.32	19.9	0.80	1.07	123	0.02	0.22	1.95	0.08	0.20	8.27	−0.22	0.42	−19.7	0.36	0.38	43.8	0.12	0.32	12.8
Cluster 5: Patient care in procedure	7	−0.85	0.75	−57.2	−0.26	0.34	−23.3	−1.69	1.17	−81.6	0.20	0.25	21.5	**0.54**	**0.21**	**72.2**	−0.25	0.45	−21.7	**−0.94**	**0.43**	**−60.8**	−0.23	0.35	−20.3
Cluster 6: Instrument disinfection	12	*−1.60*	*0.81*	*−79.7*	−0.31	0.27	−26.7	**2.78**	**0.98**	**1509**	0.12	0.24	12.7	0.04	0.16	4.23	−0.25	0.37	−21.7	**1.12**	**0.38**	**208**	−0.43	0.31	−35.0
Cluster 7: Housekeeping	22	0.48	0.55	60.9	−0.09	0.22	−8.54	0.74	0.81	110	0.24	0.19	27.4	−0.06	0.14	−5.86	0.35	0.30	41.4	0.19	0.31	20.5	−0.28	0.24	−24.3
Cluster 8: Floor strip-ping/ waxing	12	*1.38*	*0.74*	*297*	0.45	0.28	56.2	1.40	1.01	308	0.19	0.24	20.8	**0.38**	**0.17**	**45.8**	0.34	0.38	39.9	0.38	0.39	45.6	*0.62*	*0.31*	*85.3*
Cluster 2: Non-cleaning	55	Reference																							

The linear mixed-effect models for individual VOCs and TVOCs (8 models for personal VOCs and 8 models for mobile-area VOCs) included random effects of hospital and participants nested within hospitals, and fixed effects of 1 variable with 8 task-product categories (i.e. clusters), and bystander cleaning tasks and product use (yes/no). Mobile-area ethanol model also included the use of local hood (yes/no).

VOC, volatile organic compound; TVOC14, sum of total 14 VOCs; TVOC11, sum of 11 VOCs (excluding 3 most dominant compounds: ethanol, acetone, and 2-propanol); β, regression model estimate; SE, standard error; % Δ, percentage change was estimated by the following equation: $(\exp(\beta) - 1) \times 100\%$; P value < 0.05 shown in bold, $0.05 < P$ value < 0.1 shown in italics.

Table 3. Results of multiple linear mixed-effect models for selected VOCs and groups of cleaning tasks generated by IH.

Variable	Count	Ethanol			Acetone			2-Propanol			Chloroform			α-Pinene			*d*-Limonene		
		β	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ	*β*	SE	% Δ
Personal Samples																			
Variance explained by fixed effects			0.09			0.12			0.07			0.15			0.19			0.45	
Intercept		**5.78**	**0.42**		**3.25**	**0.09**		**4.98**	**0.37**		**−2.02**	**0.19**		**−3.11**	**0.12**		*−0.99*	*0.41*	
Task groups (≥15 min)																			
Equipment	22	**−1.54**	**0.59**	**−78.6**	-	-	-	**1.24**	**0.59**	**245**	-	-	-	-	-	-	-	-	-
Instrument	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mixing	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Floor	38	-	-	-	-	-	-	-	-	-	*0.44*	*0.25*	*55.7*	-	-	-	-	-	-
Surface	36	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Patient/personal	25	**1.13**	**0.56**	**211**	**0.66**	**0.17**	**93.2**	-	-	-	**0.51**	**0.21**	**66.9**	**0.46**	**0.21**	**57.7**	-	-	-
Chemical ingredients in products used (≥15 min)																			
Alkane	11	-	-	-	-	-	-	*1.38*	*0.78*	*298*	-	-	-	-	-	-	-	-	-
Fragrance	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**2.45**	**0.63**	**1056**
Terpene	13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1.82**	**0.76**	**517**
Mobile Area Samples																			
Variance explained by fixed effects			0.54			0.04			0.38			0.12			0.06			0.56	
Intercept		**5.27**	**0.37**		**2.98**	**0.13**		**4.76**	**0.55**		**−2.25**	**0.27**		**−1.93**	**0.09**		0.20	0.22	
Task groups (≥15 min)																			
Equipment	22	-	-	-	-	-	-	**1.73**	**0.73**	**461**	-	-	-	-	-	-	-	-	-
Instrument	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**−0.87**	**0.38**	**−58.0**
Mixing	6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Floor	38	-	-	-	-	-	-	-	-	-	**0.42**	**0.19**	**52.3**	**0.27**	**0.13**	**30.9**	-	-	-
Surface	36	-	-	-	-	-	-	-	-	-	*0.29*	*0.17*	*33.1*	**−0.38**	**0.14**	**−31.6**	**−0.65**	**0.28**	**−48.0**
Patient/personal	25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chemical ingredients in products used (≥15 min)																			
Alcohol	79	**1.06**	**0.36**	**190**	-	-	-	*1.07*	*0.61*	*192*	-	-	-	-	-	-	-	-	-
Bleach	7	-	-	-	-	-	-	-	-	-	*0.44*	*0.22*	*54.9*	-	-	-	-	-	-
Fragrance	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1.60**	**0.32**	**395**
Terpene	13	-	-	-	-	-	-	-	-	-	-	-	-	**0.45**	**0.19**	**57.1**	**1.46**	**0.41**	**329**
Controls (≥15 min)																			
Use of local hood	8	**−3.64**	**0.64**	**−97.4**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

The linear mixed-effect models for individual VOCs (6 models for personal VOCs and 6 models for mobile-area VOCs) included random effects of hospital and participants nested within hospitals, and fixed effects of 6 variables for IH-generated task groups (yes/no, reference group = no), multiple variables for chemical ingredients in products (yes/no) and controls (yes/no), and bystander cleaning tasks and product use (yes/no).

VOC, volatile organic compound; β, regression model estimate; SE, standard error; % Δ, percentage change was estimated by the following equation: $(\exp(\beta) - 1) \times 100\%$; P value < 0.05 shown in bold, $0.05 < P$ value < 0.1 shown in italics; '-' is variable not included in the model or not significant.

Table 4. Results of multiple linear mixed-effect models for selected and total VOCs and product application groups.

Variable	Count	Acetone			2-Propanol			Chloroform			α-Pinene			*d*-Limonene			TVOC14			TVOC11		
		β	SE	% Δ	β	SE	% Δ	β	SE	% Δ	β	SE	% Δ	β	SE	% Δ	β	SE	% Δ	β	SE	% Δ
Personal Samples																						
Variance explained by fixed effects			0.15						0.07			0.18			0.48			0.19			0.12	
Intercept		**3.60**	**0.01**					**−1.76**	**0.17**		**−3.01**	**0.09**		**−1.16**	**0.19**		**7.34**	**0.28**		**2.59**	**0.38**	
Product application groups (≥15 min)																						
Alcohol-based skin preparation	26	-	-	-	-	-	-	-	-	-	**0.45**	**0.19**	**57.4**	-	-	-	-	-	-	-	-	-
Alcohol-based surface cleaner	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*1.27*	*0.63*	*254*	-	-	-
Chlorine-based surface cleaner	7	**0.53**	**0.19**	**69.4**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Chlorine-based skin preparation	9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**0.77**	**0.36**	**117**	-	-	-
Detergent instrument cleaner	4	-	-	-	-	-	-	-	-	-	-	-	-	**2.18**	**0.96**	**784**	-	-	-	**1.91**	**0.65**	**577**
Detergent surface cleaner	4	-	-	-	-	-	-	**1.01**	**0.46**	**174**	-	-	-	-	-	-	-	-	-	-	-	-
Ethanolamine-based surface cleaner	5	-	-	-	-	-	-	-	-	-	-	-	-	**2.80**	**0.76**	**1550**	-	-	-	-	-	-
High-level instrument disinfectant	2	-	-	-	-	-	-	**1.20**	**0.52**	**233**	**1.56**	**0.54**	**374**	**2.61**	**0.98**	**1266**	-	-	-	*1.39*	*0.74*	*301*
QAC-based surface cleaner	27	-	-	-	-	-	-	-	-	-	-	-	-	**1.75**	**0.42**	**476**	-	-	-	-	-	-
Mobile Area Samples																						
Variance explained by fixed effects			0.003			0.21			0.16			0.38			0.50			0.27			0.42	
Intercept		**2.91**	**0.12**		**5.65**	**0.60**		**−2.06**	**0.23**		**−2.03**	**0.14**		0.03	0.17		**6.95**	**0.25**		**1.71**	**0.16**	
Product application groups (≥15 min)																						
Alcohol-based skin preparation	26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**0.47**	**0.23**	**60.5**	-	-	-
Alcohol-based surface cleaner	2	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	**1.37**	**0.42**	**293**
Chlorine-based skin preparation	9	-	-	-	-	-	-	**0.54**	**0.17**	**72.3**	**0.42**	**0.16**	**52.5**	-	-	-	-	-	-	-	-	-
Detergent surface cleaner	4	-	-	-	-	-	-	**1.42**	**0.33**	**312**	-	-	-	-	-	-	-	-	-	-	-	-
Ethanolamine-based floor stripper	13	*0.49*	*0.26*	*63.5*	-	-	-	-	-	-	**0.43**	**0.16**	**53.0**	-	-	-	-	-	-	*0.53*	*0.29*	*69.9*

Table 4. *Continued*

Variable	Count	Acetone			2-Propanol			Chloroform			α-Pinene			*d*-Limonene			TVOC14			TVOC11		
		β	SE	% Δ	β	SE	% Δ	β	SE	% Δ	β	SE	% Δ	β	SE	% Δ	β	SE	% Δ	β	SE	% Δ
Ethanolamine-based surface cleaner	5	-	-	-	-	-	-	0.66	0.22	93.4	0.66	0.22	93.6	2.67	0.39	1339	-	-	-	1.40	0.32	304
High-level instrument disinfectant	2	-	-	-	4.50	1.81	8878	-	-	-	-	-	-	-	-	-	1.82	0.64	520	-	-	-
Iodine-based skin preparation	4	-	-	-	-	-	-	-	-	-	0.66	0.24	93.3	-	-	-	-	-	-	-	-	-
QAC-based floor cleaner	12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	*0.83*	*0.44*	*130*	-	-	-
QAC-based surface cleaner	27	-	-	-	-	-	-	-	-	-	-	-	-	0.57	0.25	77.6	-	-	-	-	-	-

The linear mixed-effect models for individual VOCs and TVOCs (7 models for personal VOCs and 7 models for mobile-area VOCs) included random effects of hospital and participants nested within hospitals, and fixed effects of multiple product-use groups (yes/no, reference group = no; selected from 20 product-use groups), and bystander cleaning tasks and product use (yes/no).

VOC, volatile organic compound; TVOC14, sum of total 14 VOCs; TVOC11, sum of 11 VOCs (excluding three most dominant compounds: ethanol, acetone and 2-propanol); β, regression model estimate; SE, standard error; % Δ, percentage change was estimated by the following equation: $(\exp(\beta) - 1) \times 100\%$; P value < 0.05 shown in bold, $0.05 < P$ value < 0.1 shown in italics; '-' is variable not included in the model.

online), but only the use of chlorine-containing products on surfaces and ethanolamine-based floor stripping products remained significant in the multiple regression models. Personal or mobile-area chloroform exposures were associated with use of detergents and ethanolamine-containing products to clean surfaces, high-level disinfectants in sterile processing, and chlorine-containing antiseptics on skin. Univariate models identified additional product application groups associated with chloroform exposures, e.g. use of chlorine-containing products to clean surfaces. Exposure to α-pinene was associated with alcohol-, chlorine-, and iodine-based skin preparation wipes, ethanolamine-based surface cleaner and floor stripper, and use of high-level disinfectants in sterile processing. Personal and mobile-area *d*-limonene exposures were significantly associated with several product-use groups including use of detergents to clean instruments, ethanolamine- and QAC-based surface cleaners, and use of high-level disinfectants in sterile processing. Of particular interest is the association of personal and mobile-area TVOC11 with use of detergent for instrument cleaning, ethanolamine-based surface cleaner and floor stripper, alcohol-based surface cleaner, and high-level disinfectants in sterile processing. Personal and mobile-area TVOC14 exposure was associated with alcohol-surface cleaners, QAC-based floor cleaner, chlorine- and alcohol-based skin preparation wipes, and high-level disinfectants in sterile processing. The total variance explained by fixed effects in models ranged from 7% (chloroform) to 48% (*d*-limonene) for personal VOCs and 0.3% (acetone) to 50% (*d*-limonene) for mobile-area VOCs.

Discussion

Cleaning and disinfecting-related VOC exposures in healthcare settings

Healthcare settings typically have complex exposure profiles and task scenarios. In this study, we selected 19 chemical ingredients (Fig. 3) based on a review of the SDS, with alcohols, glycol ethers, ammonium chloride, methacrylates, and amines being the most common ingredients in the cleaning products used. Our study showed that measured exposures to some specific VOCs such as acetone, 2-propanol, and ethanol occurred across various occupations and hospital units. Ethanol and 2-propanol are common ingredients in alcohol-based disinfectants (e.g. alcohol-based hand rubs usually consist of >60% ethanol or 2-propanol), which are widely used in hospitals, especially in the patient-care areas (Boyce and Pittet, 2002). Healthcare workers who frequently perform disinfecting and patients-care tasks, such as nurses and instrument disinfection workers, are expected to experience higher exposures to alcohol. Acetone, another dominant compound found in our study, is a solvent that is widely used in products intended to remove oil, grease, paint (ATSDR, 1994), or to clean equipment or instruments, and is present in floor stripping products and adhesive removers. Exposures to acetone, 2-propanol, and ethanol varied depending on ingredients of cleaning products used. Cleaning products use varies depending on facility purchasing policies; thus, it is difficult to identify a unique marker of exposure related to cleaning products.

Some of the VOCs are present in some specific products that are used by certain occupations, thus resulting in a higher likelihood of exposure for those occupations. For example, chlorine, α-pinene, and *d*-limonene are common ingredients in daily-use cleaning products, including chlorine bleach (which can release chloroform), detergents, fresheners, and floor wax (ATSDR, 1997; Nazaroff and Weschler, 2004; Odabasi, 2008). Our results show that cleaning tasks done using products containing these chemicals resulted in elevated exposures to chloroform, α-pinene, and *d*-limonene; occupations that spent a greater percentage of time performing cleaning tasks included housekeepers and floor strippers/waxers. Methyl-methacrylate is widely used in dentistry to make dental fillings, cement or dentures (Leggat and Kedjarune, 2003). Our study measured noticeably higher levels of mobile-area methyl-methacrylate exposure among dental assistants and dental laboratory technician compared with other occupations.

Additionally, the contribution of outdoor sources to personal and mobile-area VOC exposures was evaluated by comparing benzene, toluene, ethylbenzene, and xylene (BTEX) concentrations in the 22 daily ambient samples with the 143 pairs of personal and mobile-area samples. The result showed lower median BTEX levels in ambient samples than in personal and mobile-area samples (data not shown) and suggests that particular occupations in healthcare settings might experience higher BTEX exposures via performing unique tasks or using specific products. A Chinese study that collected VOC samples from four hospitals also reported that on average, indoor BTEX levels were slightly higher than outdoors (Lü et al., 2006).

Determinants of exposure models

Overall, models for task/product-use clusters, IH-generated groups, and product application groups for mobile-area and personal VOC exposures were similar. Some task groups and product ingredients were associated with higher levels of specific VOC exposures, demonstrating the presence of airborne exposures during these activities. Exposures associated with these cleaning task groups are a function of the products used and their ingredients. Use of chlorine-containing products (e.g. bleach) to clean surfaces and chlorine-based skin preparation wipes or surgical scrub (e.g. chlorohexidine) was associated with chloroform exposure. Chloroform exposures were also associated with use of floor and surface cleaning products that contain chlorinated hydrocarbons. Acetone exposures were associated with the use of floor stripping and surface cleaning products, as well as products used on skin for adhesive removal. Exposure to fragrance chemicals such as α-pinene was associated with skin preparation products, and *d*-limonene with a variety of ethanolamine-, QAC-, and alcohol-based surface and floor cleaning products. The combination of these cleaning tasks with products is shown to be important sources of specific VOC exposures, and using these products for cleaning and disinfecting might constitute important risk factors for asthma and respiratory symptoms associated with exposure to cleaning chemicals. Indeed, recent epidemiologic studies have shown associations between asthma symptoms and ammonia, bleach, chloramines, ethylene oxide, formalin, formaldehyde, glutaraldehyde, ortho-phthalaldehyde, cleaning sprays, and other cleaners and disinfectants (Zock et al., 2010; Arif and Delclos, 2012).

Negative estimates obtained in these models indicate that the reference or comparison group had higher exposure than the group performing a task. In the models with clusters, the reference group comprised nursing, clinical, and dental laboratory staff who are likely exposed to VOCs, e.g. ethanol, from multiple sources including use of solvents not related to cleaning, secondhand exposure from other workers using cleaning products, or from the use of hand sanitizers that was not recorded in observations (due to the very short duration of this activity), thus resulting in a negative estimate for some of the remainder of the clusters. In the models for IH-generated groups, the comparison group comprised workers who did not perform that task; however, these workers could also be exposed to the specific VOC from other cleaning tasks or use of solvents in non-cleaning tasks. Likewise, the reference group for some product application categories, e.g. alcohol-based skin or surface or floor cleaning products, is likely also exposed to alcohol as almost all cleaning products contain alcohol. Negative estimates were not obtained in models using ingredients of products used.

The cleaning tasks and product use in hospitals observed in our study were similar to results observed in previous studies. Bello et al. (2009) and Quinot et al.

(2017) reported that surface cleaning (e.g. windows, glass, and counter cleaning) and alcohol were the most common cleaning task and chemical contained in cleaning products, respectively, in hospitals. In addition, Bello et al. (2009) also reported other common cleaning tasks, such as floor cleaning (e.g. mopping, stripping, waxing, and buffing), and chemical ingredients in the cleaning products, such as QACs and amines. In our study, the results of regression models showed the significant effects of both products use (i.e. chemical ingredients) and tasks on VOC exposures. Some chemical ingredients had much stronger effects on certain VOC exposures and therefore attenuated the associations between tasks and VOCs. The models for product application groups combined product type (major ingredient) and application (task) to best describe the cleaning activity. Moreover, the VOC exposure estimates obtained from these models can be applied to epidemiologic studies in which workers report the use of specific products on patients, surfaces, or for instrument cleaning.

Hierarchical clustering-based task clusters versus expert-based task groups

Hierarchical clustering is a systematic and replicable data reduction approach that groups observations with similar responses together (Friesen et al., 2015). Therefore, the issue of collinearity in regression models due to highly correlated variables can be avoided. Observations within identified clusters are mutually exclusive, so the results of hierarchical clustering can be used directly as predictors in statistical models. While hierarchical clustering can disentangle the complex exposure scenario by revealing the relationships among multiple factors and identifying subgroups of correlated observations that might otherwise be missed, it is a data-driven method that results in overlapped variables within clusters, which might diminish the capability to understand the effect of each variable separately. In this study, we also grouped tasks based on the best knowledge of IH, and because this approach is only partially data-driven, it provides more practical ways to control exposure sources. The consistency between the results using hierarchical clusters and expert-based groups suggests that hierarchical clustering partitioned observations in a meaningful way.

Strengths and limitations

This study presents the results of a comprehensive exposure assessment for VOCs in healthcare settings. We collected robust and extensive exposure data, including full-shift personal and mobile-area samples, and corresponding observations of personal and area tasks and product use. We also evaluated multiple methods of grouping tasks and product use to disentangle the complex exposure scenario and to obtain results that can be used to inform exposure control and provide exposure estimates for epidemiologic studies. Despite time-activity observations recorded for each of the full-shift personal and mobile-area samples, the exposure determinant models did not identify a large number of significant exposure determinants. This is in part due to the constant background exposure to alcohols and other VOCs that are present in hand sanitizers and cleaning products, resulting in background secondhand exposure and exposed reference groups. Whereas we recorded activities of other workers using cleaning products, we did not record the general background exposure levels that can overwhelm the individual activities. In addition, the occurrences of (i) multiple tasks or use of multiple products simultaneously, (ii) highly variable duration and frequency of tasks and product application, and (iii) complex and highly variable amount of chemical ingredients in products make it difficult to estimate the effects of tasks, product application, and other factors based on full-shift measurements. The effect of constantly changing tasks and product use are ideally investigated using real-time exposure measurements to identify the sources of short-lasting exposures, as described by Houseman and Virji (2017). Some of the VOCs selected to represent exposure to cleaning products, e.g. fragrances such as terpenes, are aesthetic not functional ingredients, are not unique to cleaning products, and may or may not be present in a product. A frequent concern raised in observational studies is the Hawthorne effect, which causes participants aware of being observed to modify their behavior. However, this is less likely to occur when assessing job functions like tasks and product use, compared with when assessing behavior such as safety practices, use of personal protective equipment, or hand hygiene, as shown in one study (Ampt et al., 2007).

Conclusions

Exposures to various VOCs were associated with mixed cleaning tasks and chemical ingredients of products use. However, high background exposure to VOCs in healthcare settings likely obscured the effect of tasks and product use, based on full-shift measurements. While some cleaning tasks and product-use combinations were specific to some occupations, e.g. using ethanolamine-containing floor stripping product among floor strippers/waxers, other general cleaning tasks and product use were spread across occupations and hospital units. Product ingredients in combination with cleaning and disinfecting tasks were important predictors of specific VOCs. Exposure modules for questionnaires might benefit from seeking information on products use within a task context. In the future, we plan to apply the estimated VOC exposures for tasks/product use to participants in an epidemiologic study of WRA symptoms who report having performed a task or used a product.

Supplementary data

Supplementary data are available at *Annals of Work Exposures and Health* online.

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