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Respiratory quaternary ammonium and volatile organic compound exposures experienced by home care aides during residential bathroom cleaning using conventional and green products

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Abstract

Introduction: US home care (HC) aide visits to clients' homes typically involve cleaning and disinfecting (C&D) environmental surfaces, particularly in bathrooms. Some ingredients in C&D products are associated with respiratory illness: sodium hypochlorite (bleach), quaternary ammonium compounds (QACs), and volatile organic compounds (VOCs). This study assessed and compared aides' respiratory exposures to specific VOCs and QACs while using 2 conventional and 1 "green" household C&D spray products during bathroom cleaning. Measured exposures were compared to ingredients listed on publicly available sources.

Methods: Three C&D products were selected with principal active disinfecting ingredients: 1% to 5% sodium hypochlorite by weight ("bleach-based"); 0.1% to 1% QACs ("QACs-based"); and 0.05% thymol ("green"). Twenty-two aides were recruited to perform C&D tasks in a simulated residential bathroom constructed in an environmental monitoring laboratory. A balanced experimental study design involved each aide visiting the lab 4 times to perform typical cleaning tasks with the 3 products and distilled water (as a control), randomly assigned across the 4 visits. Aides wore air sampling equipment for breathing zone samples: canisters to collect whole air for VOC analyses and filter cassettes for QACs analyses.

Results: Aides performed 84 cleaning visits contributing approximately 20 air samples each for VOCs and QACs, for each of the 3 products and distilled water. In total, 38 unique VOCs were identified in the canister whole air samples: 20 in the QACs-based product samples, 15 in the bleach-based, and 10 in the green. Most VOCs were not listed in publicly available sources of cleaning product ingredients. Toxicity information was limited. Few VOCs had occupational exposure limits. The QACs-based product generated QACs aerosol: benzalkonium chloride (BAC)12 (geometric mean (GM) = 6.98 μg/m^3), BAC14 (GM=2.97 μg/m^3), BAC16 (GM=0.78 μg/m^3); and the 3 QACs summed (GM=10.86 μg/m^3).

Discussion: The use of C&D spray products for residential cleaning can generate respiratory exposures to complex mixtures of volatile and nonvolatile compounds. Notably, we measured aerosols containing QACs during the use of the QACs-based product. Dermal is usually considered the main route of exposure because QACs are nonvolatile salts. This study provides evidence that QACs inhalation exposure should be recognized and minimized in addition to the well-accepted dermal exposure routes. The green product generated the fewest VOCs. However, more toxicity information is needed on the health impacts of green C&D products. Spraying of C&D products, conventional and green, should be avoided.

Conclusions: Aides' respiratory health should be protected from chemical exposures while performing C&D in home care.

Key words: cleaning product chemical exposures; healthcare cleaning and disinfection; home healthcare; household cleaners; occupational exposure assessment.

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What's important about this paper?

This paper shows that respiratory exposures to quaternary ammonium compounds (QACs) aerosols were generated during typical household bathroom cleaning with a ready-to-use QACs-based cleaning and disinfecting (C&D) spray product. Airborne exposure to QACs is often overlooked, however both airborne and dermal exposures should be controlled when spray cleaning with a QACs-based product. Many respiratory exposures to volatile organic compounds are generated during spray cleaning with ready-to-use conventional and green C&D products.

Introduction

This study is part of a larger initiative on respiratory health among home care (HC) aides called the Safe Home Care Cleaning and Disinfecting Project. Previously, we characterized chlorine gas and total volatile organic compound (TVOC) breathing zone exposures experienced by HC aides while performing environmental surface cleaning in a residential bathroom using 3 liquid products dispensed in consumer packaged, hand-held trigger spray bottles: a product with bleach as the active disinfecting ingredient, a product with quaternary ammonium compounds (QACs, also termed "quats"), and a "green" product with plant-derived thymol (Lindberg et al. 2021). Using direct reading instruments with sample intakes located in the aides' breathing zone, we found that aides using the bleach-based product experienced chlorine gas exposures exceeding the U.S. Occupational Safety and Health Administration (US OSHA) Permissible Exposure Limit (PEL), a ceiling limit (1 ppm) not to be exceeded. Furthermore, the TVOC concentrations of all three products substantially exceeded indoor air quality guidelines (LEED—Leadership in Energy and Environmental Design) (Lindberg et al. 2021) (Figure 1). Specific ingredients in the TVOC mixtures were not identified because TVOC measurements with a direct reading instrument only represent a composite of volatile organic compounds (VOCs). Additionally, nonvolatile ingredients such as QACs, are not measured. This study assessed and compared respiratory exposures to specific VOCs and QACs associated with aides' use of the 2 conventional and 1 green cleaning and disinfecting (C&D) products while performing residential bathroom cleaning. Measured exposures were compared to ingredients listed on publicly available sources.

Background

Home care aides assist people ("clients") in private homes with health and personal care services and with household tasks including cleaning (PHI 2023; U.S. BLS 2024). In the USA, most HC clients are adults aged 65 years or older who may live in single-family houses, apartment buildings, or other multiunit housing, including those designed as "elder housing"(Binette and Farago, 2021).

Aides hired by private businesses ("agencies") typically conduct visits to multiple clients per day (Quinn et al. 2016). Increasingly, these visits involve cleaning for the purposes of infection prevention, especially since the start of the coronavirus disease (2019) COVID-19 pandemic (Markkanen et al. 2014; Goodyear et al. 2018; Sama et al. 2021). In HC, the most intensive C&D tasks involve bathroom fixtures (tub/shower, toilet, sink) using premixed "ready-to-use" consumer products. Residential bathrooms in all types of housing are typically small spaces with low or no mechanical ventilation and often lack windows.

Infection prevention good practice recommendations for environmental surfaces usually specify that cleaning, the removal of visible soil, and disinfecting, the elimination of pathogens, be performed sequentially because surface soil can interfere with the disinfectant's efficacy (Goodyear et al. 2015). However, commercial products for home use are increasingly formulated with multiple chemical ingredients that perform C&D in one step (Goodyear et al. 2018). The US Federal Insecticide Fungicide and Rodenticide Act (FIFRA), administered by the US Environmental Protection Agency (EPA) (US EPA 2024a), requires registration of any commercial product labeled as an antimicrobial or disinfectant. Product manufacturers claiming disinfectant properties must list on consumer product labels the "active" disinfecting ingredient(s) and "other" ingredients, expressed as percent by weight. The US OSHA Hazard Communication Standard (US OSHA 2024) requires manufacturers of products containing chemical ingredients to produce a Safety Data Sheet containing, among other information, a section listing ingredients with health hazards or other hazards contributing to a specific hazard classification and their concentrations by weight unless a trade secret is claimed. While Safety Data Sheets provide important information, they are often incomplete for health protection (LeBouf et al. 2019; Lee et al. 2021).

Many household C&D products contain ingredients that are known respiratory irritants or sensitizers and are associated with acute and chronic health effects, including asthma, asthma-like symptoms, decline

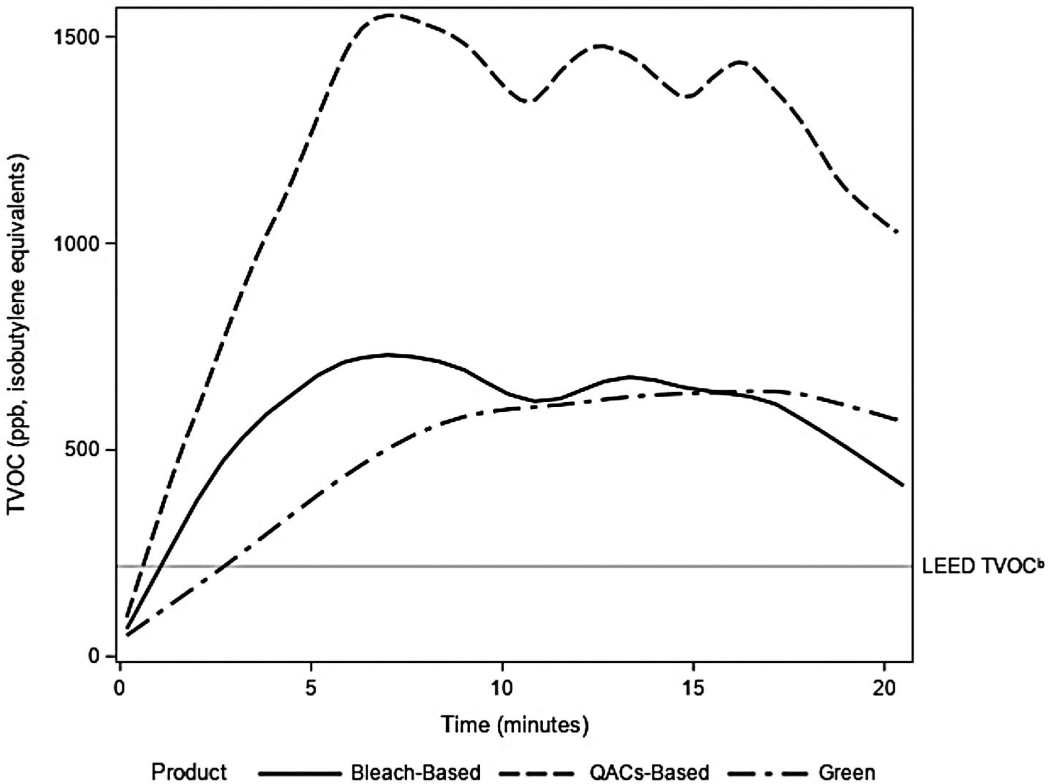

Figure 1. Total volatile organic compounds (TVOC) concentration–time curves[a] by product, all home care aides' residential bathroom cleaning sessions combined. [a]Each curve represents the average of all direct reading TVOC concentration–time profiles generated during cleaning sessions using a specific product. TVOC concentrations are presented in isobutylene equivalents for comparison across products. The curve for the bleach-based product is based on 38 sessions; for the QACs-based product, 40 sessions; for the green product, 44 sessions (see Lindberg et al. 2021). [b]LEED TVOC = Leadership in Energy and Environmental Design indoor air TVOC concentration reference value (500 μg/m^3) converted to a volume concentration in isobutylene equivalents (218 ppb) for comparison.

in lung function, and chronic obstructive pulmonary disease (COPD) (Quinn et al. 2015; Svanes et al. 2018; Clausen et al. 2020; De Matteis et al. 2020; Fazen et al. 2020; Archangelidi et al. 2021; Lemire et al. 2022; Wilson et al. 2023; Mwanga et al. 2024). In the United States, the 2 most common disinfecting ingredients in household C&D products are sodium hypochlorite (bleach) and quaternary ammonium compounds (QACs), which are organic salts of ammonium with aryl and alkyl substitutes (Zheng et al. 2021). Bleach- and QACs-based products specifically have been associated with symptoms of respiratory illness (Rosenman et al. 2020; Migueres et al. 2021; Zheng et al. 2021; De Troeyer et al. 2022; Arnold et al. 2023; Mwanga et al. 2024). Additional C&D product ingredients of respiratory concern include hydrogen peroxide, alcohols, peracetic acid, and VOCs such as ketones, terpenes, aldehydes, and fragrances (Carder et al. 2019; Walters et al. 2019; Weinmann et al. 2019; Dumas et al. 2020; Henneberger et al. 2020; Wolkoff 2020; Pastor-Nieto and Gatica-Ortega 2021; Blackley et al. 2023; Radis-Baptista 2023; Mwanga et al. 2024). Studies among domestic cleaners show increased respiratory illness (Arif et al. 2008; Svanes et al. 2018; Whitworth et al. 2020; De Troeyer et al. 2022); additionally, the work-related respiratory symptoms experienced by domestic cleaners have been associated with self-reported mental and physical ill health (Baron et al. 2022). Occupational health surveillance data show that healthcare workers are at increased risk of asthma (Rosenman et al. 2020; Dang et al. 2022; Patel et al. 2024) and COPD (Dumas et al. 2019). Only a few studies have assessed C&D exposures quantitatively among hospital workers (Virji et al. 2019). Quantitative C&D exposure data on HC workers are lacking.

Products advertised as safer for the environment, sometimes called environmentally preferable or "green" C&D products, are now widely available in retail stores. Many of these are certified by third parties attesting to less harmful environmental impacts, such as reduced biopersistence. However, there are limited quantitative evaluations of the respiratory health risks related to green C&D products (Harley et al. 2021). Due to the spray application of all types of C&D products in small, poorly ventilated spaces there is concern that some airborne chemical exposures may be sufficient to increase respiratory health risks for HC aides, especially if they clean multiple bathrooms and kitchens in a day.

Methods

Details of the study design for the quantitative assessment, exposure setting construction, population recruitment, product selection, and direct reading instrument measurements of chlorine gas and TVOC exposures are reported elsewhere (Lindberg et al. 2021). A summary is presented here, followed by details of the time-integrated air sampling and analyses for specific VOCs and QACs which were conducted at the same time as the real-time measurements.

Ethics approval

All study protocols and materials were approved by the University of Massachusetts, Lowell, USA Institutional Review Board 14-126-QUI-XPD. Study participants were at least 18 years old and written informed consent was obtained before their participation.

Study design

The exposure assessment was conducted while aides performed environmental surface cleaning tasks in a simulated residential bathroom constructed within the University of Massachusetts Lowell environmental monitoring laboratory (the "university lab"). The air sampling data for this study were collected from July 2016 through April 2017. A balanced experimental study design involved HC aides visiting the university lab 4 times to perform typical bathroom cleaning tasks with 1 of 3 C&D products or distilled water as a control. Use of the 3 products and water was randomly assigned across an aide's 4 visits. Products were dispensed in their original 946.4 ml (32 ounces) hand-held plastic bottles with trigger nozzles having a pinhole-sized orifice that produced a conical spray. To disguise product identity, the labels were removed; water was in a similar, clean trigger nozzle spray bottle.

Population recruitment

Home care aides who performed cleaning as part of their jobs were recruited from private agencies in Massachusetts, United States. In addition to a small monetary incentive for participation, aides were paid their regular hourly salary for their time in the study.

Product selection

Three ready-to-use C&D spray products were selected from brands available at local retail stores. The C&D product selection was informed by focus groups of aides to characterize HC work (Markkanen et al. 2014); a microbiology laboratory comparative evaluation of conventional versus green C&D products to remove soil and eliminate pathogens (Goodyear et al. 2015), and a microbiology field study for the effectiveness of conventional and green C&D products to eliminate pathogens in elder housing (Goodyear et al. 2018). The active disinfecting ingredient in the first conventional product was 1–5% sodium hypochlorite by weight according to the product's Safety Data Sheet (the "bleach-based product"). The second conventional product contained 0.1–1% by weight QACs (benzyl-C12-16-alkyldimethyl chlorides (BAC)—the "QACs-based" product). The active disinfecting ingredient in the "green" product was 0.05% by weight thymol, a monoterpene and component of botanical thyme oil.

Preparation of the simulated bathroom

The simulated bathroom (volume 8.8 m^3) built in the university lab (155.4 m^3) was constructed and fitted with fixtures typical of US residential bathrooms: a combination bathtub and shower with a shower stool; toilet; and cabinet with a sink and metal faucets. The bathroom had one entrance with an open doorway for the only source of ventilation. Fixtures, shower walls, and chair surfaces were marked with washable crayons to simulate a soiled surface in a similar manner for all cleaning sessions. Between each air sampling session, the bathroom was ventilated with a portable fan and the same direct reading instrument used to obtain the real-time TVOC concentration measurements during the cleaning tasks was used to determine when the TVOC concentrations had returned to background [a ppbRAE 3000 photoionization detector (PID) (RAE Systems/Honeywell, San Jose CA) and associated ProRAE Studio II, v.1.11.0 software].

Cleaning tasks and timing

During each visit, 2, 20-min cleaning sessions were performed by the aide using one of 3 C&D products or distilled water to remove bathroom surface soil. Both sessions within a visit involved cleaning with the same product. Aides were shown a study protocol training video before their first cleaning session to standardize cleaning practices. Each aide was instructed to spray the C&D product on the soiled bathroom surfaces as she would during a typical home visit and wipe the surface clean using paper towels. The sequence of tasks and times that comprised each 20-min cleaning session included 10 min for the tub/shower/chair; 5 min cleaning the toilet; 3 min cleaning the sink and faucets;

and 2 min remaining in the bathroom after the spray cleaning stopped to gather materials before exiting the bathroom.

To obtain greater accuracy in the quantitative VOCs and QACs analyses described here, the air samples collected during the 2 sessions were combined. Thus, the unit of analysis for the exposure assessment was an aide's 40-min visit (comprising 2 identical 20-minute sessions).

Qualitative assessment of cleaning product ingredients

A review of publicly available data sources identified the ingredients in the 3 C&D products. The information was specific to the date the products were manufactured because product formulations can vary over time. All ingredients by product were researched to ascertain compound names and synonyms, Chemical Abstract Service (CAS) numbers, ingredient function within the C&D product formulation, toxicity, and whether an occupational exposure limit (OEL) exists for the ingredient. Sources of information included: labels from the C&D products used in the study; product manufacturers' websites; product Safety Data Sheets from the United States and European Union; the SmartLabel® digital platform maintained by US brands and retailers to search product names, including household cleaners, for detailed information on ingredients (Consumer Brands Association 2024); and PubChem, a US National Library of Medicine public repository for information on chemical substances and their biological activities (US NLM 2024). Substances detected in canister whole air samples (see below) were researched using the US EPA Computational Toxicology (CompTox) database of over 1 million chemicals listing environmental fate and transport, use, and hazard information (US EPA 2024b). The available toxicity data on each compound was summarized for this study as: none = compound is not listed in CompTox; minimal = CompTox lists results from one to three basic toxicity tests, such as the LD_{50} via ingestion, LC_{50} via inhalation, or tests for skin or eye irritation in one or more experimental animal species; good = results from basic toxicity tests plus one or more risk assessment measures such as the No Adverse Effect Level, Lowest Adverse Effect Concentration, or a cancer slope factor. When CompTox noted positive findings for tests of genotoxicity or cancer in animals, these were coded as (g) or (ca) respectively in Table 2.

Air sampling and analysis

Preparation. Prior to performing cleaning tasks, aides were fitted with a vest with pockets and a belt to hold multiple devices for simultaneous air sampling with intake probes secured in their breathing zone: 2 direct reading instruments, the PID to provide TVOC concentration-time curves; a chlorine gas meter (Dräger Pac 7000 passive diffusion sampler and associated Dräger CC-Vision Basic, v.7.1.0 software, Dräger Safety, Lübeck, Germany); a canister to sample whole air to analyze for specific VOCs; and a pump attached by tubing to a cassette with a filter for personal breathing zone aerosol samples for QACs analysis (Figure 2). The VOCs and QACs analyses described here were performed in the US National Institute for Occupational Safety and Health (NIOSH) Field Studies Branch Organics Laboratory, Morgantown, WV, USA (the "NIOSH lab").

Whole air sampling and analyses for volatile organic compounds

Evacuated 450 mL Silonite-coated MiniCans ("canisters") (Part: 29-MC450QT—Entech Instruments, Inc., Simi Valley, California, USA) were used to obtain time-integrated whole air personal samples during cleaning sessions and background air grab samples. All canister sampling components were prepared by the NIOSH lab and shipped to the university lab in batches consisting of 5 canisters (3 for air sampling during aides' cleaning, 1 background, and 1 field blank) 3 flow controllers, and 1 rapid flow valve. The initial operating pressure for the canisters was a 50 mTorr vacuum. The canister flow rate during cleaning sessions was regulated by a restrictive flow controller at 5 cm^3/minute. Air flow was started and stopped at the beginning and end of each 20-min cleaning session for a total sample duration of 40 minutes. A new flow controller was used for each aide's visit to avoid cross-contamination. Prior to use for cleaning sessions or background sampling, the vacuum level in each canister was confirmed by attaching a MicroValve Vacuum Test Gauge (Part: -01-29-70010QT Entech Instruments, Inc., Simi Valley, CA, USA).

The VOC analyses of the canister whole air samples involved: (i) identification of VOCs present in the whole air and (ii) quantification of a subset of VOCs previously identified in healthcare facilities while C&D tasks were performed by workers (Virji et al. 2019). The canister air samples were shipped to the NIOSH lab weekly and analyzed using a preconcentrator/gas chromatograph/mass spectrometer system according to a method development and validation study (LeBouf et al. 2012). To identify whether a specific VOC was present in the canisters, the mass spectral data were interrogated for chemical peaks found in the chromatograms using the National Institute for Standards and Technology 2008 mass spectral library. When the library match reported a subjective quality factor of 75% or greater, the identified compound was reported as present. The quantitative analysis using GC/MS focused on 14 analytes that are abundant in healthcare

Figure 2. Home care aide wearing air sampling equipment to assess respiratory exposures while she performs cleaning in the residential bathroom built in the university environmental monitoring laboratory. Front (2a) and back (2b) views.

settings or have the potential for health risks previously identified by NIOSH researchers during cleaning tasks performed in healthcare facilities: acetone, benzene, chloroform, *d*-limonene, ethanol, ethylbenzene, isopropyl alcohol, methyl methacrylate, methylene chloride, toluene, α-pinene, *m*,*p*-xylene, n-hexane, and *o*-xylene (LeBouf et al. 2012, 2014).

Cleaning and disinfecting product bulk sample headspace analysis for VOCs

One liquid bulk sample of each C&D product was stored in a partially filled, closed vial and the air above the surface of the liquid (the "headspace") was analyzed quantitatively for the same 14 VOCs as the canister whole air samples. The objective of this headspace analysis was to identify additional VOCs not found in the canister whole air samples (Supplementary File 1).

Quaternary ammonium compounds sampling and analysis

Time-integrated, breathing zone aerosol samples were collected for all products and water and analyzed for QACs using a personal air sampling pump and collection media during each aide's cleaning session. A weekly background sample was obtained with the same apparatus. The sampling pump (Leland Legacy Part: 100-3002, SKC, Eighty-Four, PA) was calibrated to a flow rate of 5.5 l/min with a dedicated flow calibration filter cassette. The collection media included a 37-mm diameter, 1.0 µm pore size polytetrafluoroethylene (PTFE) filter (Part: 225-17-1 SKC, Eighty-Four, PA) housed in a 37-mm closed-face conductive cassette (Part: 225-309 SKC, Eighty-Four, PA), to minimize particle adhesion to walls. The filter cassette was connected to the sampling pump with silicone tubing using a tapered luer adapter (Part: 225-13-3 SKC, Eighty-Four, PA). The total sampling duration was 40 min: the pump was started and stopped at the beginning and end of each 20-minute cleaning session. The sampling pump flow rate was checked at the end of the second cleaning session using the same process described for the pump calibration. All collection media was prepared by the NIOSH lab, shipped to the university lab in batches of 5 sealed cassettes (3 for air sampling during aides' cleaning, 1 background, and 1 field blank), and returned to the NIOSH lab for analysis.

The QACs analysis was conducted by ultra-performance liquid chromatography tandem mass spectrometry (UPLC–MS–MS). The method for sampling and analyzing QACs in the air was selective for benzethonium chloride (BEC), didecyldimethylammonium bromide (DDAB), benzyldimethyldodecylammonium chloride, (BAC12), benzyldimethyltetradecylammonium chloride (BAC14), and benzyldimethylhexadecylammonium chloride (BAC16) (LeBouf et al. 2017).

Background air samples and field blanks

Weekly time-integrated background samples were collected with the canisters and filter media. The background samples were obtained in the simulated bathroom following 15 min of dilution ventilation. The background sampling procedures followed similar methods used during the aides' visits to the lab except that the sampling equipment was suspended in the breathing zone within the bathroom. Field blanks for the integrated sampling media accompanied each media shipment and sample return shipment. Blanks were handled and stored in the same manner as the sample media.

Data analysis

Volatile organic compounds. Not all 14 VOC analytes were quantified in every canister of whole air; for a given analyte, some results were below the limit of detection (LOD) of the method. To reduce bias in statistical summary measures of the concentrations of analytes in the whole air canister samples, the geometric mean (GM) of an analyte's concentration and its geometric standard deviation (GSD) were calculated using the Beta-Substitution method to impute measurement values below the method LOD (Ganser and Hewett 2010).

Quaternary ammonium compounds. Summary statistics were calculated for detected QACs including the arithmetic mean and standard deviation, geometric mean and geometric standard deviation, and the range. Additionally, for each air sample with more than one QAC detected, the concentrations of QACs were summed to develop a measure called "sum of QACs" and the same summary statistics were calculated. All data analysis was performed using SAS 9.4 (SAS Institute Inc., Cary, NC, USA).

Results

Population and air sampling visits

Twenty-two female aides participated in the study, age range 21 to 69 years, an average age of 41 years. At the time of the study, all aides were currently performing cleaning as part of their job; 55% cleaned 9 or more hours per week, and 23% cleaned more than 20 h per week. The aides contributed a total of 84 visits to perform C&D tasks in the simulated bathroom; only 4 visits could not be completed due to aides' health or unavailability. Nineteen visits were completed using the bleach-based product; 20 visits using the quats-based product; 22 visits using the green product; and 23 visits using distilled water.

Qualitative assessment of cleaning product ingredients

Product labels, Safety Data Sheets, and other publicly available data sources yielded a list of numerous volatile and nonvolatile ingredients by product (Table 1). Within each product formulation was a mixture of ingredients constituting the product's fragrance according to manufacturer and SmartLabel® database information. The fragrance compounds in the green product were plant-derived, while the fragrance compounds of the conventional products were both plant-derived and synthetic. In all, the QACs-based product contained the highest number of ingredients, including the highest number of compounds listed as contributing to the fragrance, followed by the bleach-based and green products, respectively. The SmartLabel® database was the most complete source of information about the function of ingredients within a particular C&D product formulation.

Volatile organic compounds in whole air

Analyses of aides' breathing zone whole air samples from the canisters (including the spectral and GC/MS analyses) identified the presence of 38 VOCs in 1 or more of the products, excluding VOCs found in the canisters collected during cleaning with distilled water, lab or field blanks, and background samples (Table 2). Of the 38 VOCs found in the aides' breathing zone, 20 VOCs were identified during the use of the QACs-based product; 15 VOCs using the bleach-based product; and 10 VOCs using the green product. These VOC numbers are consistent with the relative concentrations of TVOCs measured by product in the previous study, using the direct-reading instrument (Figure 1). Only 3 of the 38 VOCs identified in the product canisters were listed as ingredients on the product labels, Safety Data Sheets, or other publicly available data sources. Toxicity information was not available for more than one-third (37%) of the VOCs and 39% had only minimal information. Despite the limited toxicity data overall, there was evidence of genotoxicity or carcinogenicity for 32% of the VOCs. Only one-third (34%) of the VOCs had an established OEL (Table 2).

Table 1. Cleaning and disinfecting product ingredients listed on labels, manufacturers' Safety Data Sheets and other publicly available sources.

Ingredient	CAS No.	Amount in product (% weight)	Function in product	Source[a]
Bleach-based product				
Water	7732-18-5	…	Solvent, carrier	3, 4
Sodium hypochlorite	7681-52-9	1 – 5[b]	Active disinfecting ingredient, antimicrobial, whitener	1,2,4
Sodium chloride	7647-14-5	…	Stabilizer, thickener	4
Sodium hydroxide	1310-73-2	0.1 to 1[b]	pH adjuster and soil remover	1,2,4
Dimethicone/silica/PEG Distearate antifoam	-	…	NA	3
Lauramine oxide	1643-20-5	…	Cleaning agent, foam enhancer, stabilizer, thickener	3, 4
Sodium carbonate	497-19-8	…	Alkalinity buffer, cleaner, divalent cation removal (water softener), soap scum remover	4
Myristamine oxide	3332-27-2	…	Cleaning agent, surfactant, thickener, stabilizer	4
Sodium chlorate	7775-09-9	…	Product of sodium hypochlorite equilibrium and breakdown	4
Sodium silicate	1344-09-8	…	Corrosion inhibitor for washing equipment, cleaning agent	3, 4
Fragrance including:			To create a scent that remains in clothing, to mask other odors	3, 4
Benzophenone	119-61-9	…	Fragrance	4
Other fragrance(s)	CAS withheld		Fragrance(s)	4
Dodecyldimethylamine oxide	1643-20-5	0.025 to <0.25	NA	2
Bornan-2-one	76-22-2	<0.025	NA	2
Benzene	71-43-2	<0.025	NA	2
QACs-based product				
Water	7732-18-5	…	Diluent to adjust concentration	7
(QAC) Benzyl-C12-16-alkyldimethyl chlorides	68424-85-1	0.1 to 1	Active disinfecting ingredient	5, 7
(QAC) Alkyl (50% C14, 40% C12, 10% C16) dimethyl benzyl ammonium chloride	68424-85-1	…	Active disinfecting ingredient	7
(QAC) Alkyl (67% C12, 25% C14, 7% C16, 1% C8-C10-C18) dimethyl benzyl ammonium chloride	63449-41-2	…	Active disinfecting ingredient	7
Phenoxyisopropanol	770-35-4	…	Solvent to dissolve other ingredients into solution	7
Dipropylene glycol dibutyl ether	-	…		6
Lauramine oxide	1643-20-5	…	Surfactant	7
Dodecyldimethylamine oxide	1643-20-5	0.1 to 1		5
Ethanolamine	141-43-5	…	pH adjuster	7

Table 1. Continued

Ingredient	CAS No.	Amount in product (% weight)	Function in product	Source[a]
Fragrances including:		...		7
Alcohols, C9-11, ethoxylated	68439-46-3	...	Fragrance component: component of a fragrance oil	7
Citronellyl nitrile	51566-62-2	...	Fragrance component: component of a fragrance oil	7
d-Limonene	5989-27-5	...	Fragrance component: component of a fragrance oil	7
Dihydromyrcenol	18479-58-8	...	Fragrance component: component of a fragrance oil	7
Dipropylene glycol	25265-71-8	...	Fragrance component: component of a fragrance oil	7
Terpinolene	586-62-9	...	Fragrance component: component of a fragrance oil	7
Tetrahydrolinalool	78-69-3	...	Fragrance component: component of a fragrance oil	7
Tetrahydromyrcenol	18479-57-7	...	Fragrance component: component of a fragrance oil	7
Trisodium dicarboxymethyl alaninate	164462-16-2	...	Complexing/sequestering agent	7
Acid Yellow 23	1934-21-0	...	Colorant	7
FD&C yellow #5 (synonym for Acid Yellow 23)	-	...		6
Ethanol	64-17-5	...		7
Decanol	-	...		6
Green product				
Water	7732-18-5	...	Diluent	8, 9
Thyme oil (essential oil contains thymol)	8007-46-3	0.05	Antimicrobial active agent	8
Thymol	89-83-8	0.05	Antimicrobial active agent	9
Sodium lauryl sulfate	151-21-3	<1	Cleaning agent	8
Copper sulfate pentahydrate	7758-99-8	...	Water mineralizer	8, 9
Citric acid	77-92-9	...	Water softener	8, 9
Sodium citrate (dihydrate)	6132-04-3	...	Water softener	8
Sodium citrate	68-04-2	...	Water softener	9
Origanum vulgare (oregano) oil	8007-11-2	...	Fragrance	8
Fragrance—essential oil mixture, including:				
Cymbopogon nardus (citronella) oil	8000-29-1		Fragrance	8,9
Cymbopogon schoenanthus (lemongrass) oil	8007-02-1		Fragrance	8,9
Citral	5392-40-5		Fragrance	8,9

CAS number = Chemical Abstracts Service number; QAC = Quaternary ammonium compound; SDS = Safety Data Sheet.
[a]Sources of ingredient information:.
1 = US SDS, Clorox Company, January 5, 2015; 2 = EC/EU SDS, Clorox Company, April 4, 2014; 3 = Clorox website 2014; 4 = https://smartlabel.labelinsight.com/product/6091200/ingredients; 5 = SDS, Lysol Brand II All Purpose Cleaner Complete Clean Lemon Breeze Scent, Reckitt Benckiser LLC, April 4, 2015; 6 = Lysol website 2016; 7 = http://www.rbnainfo.com/product.php?productLineId=2854; 8 = SDS, Disinfecting Multi-Surface Cleaner, Seventh Generation Inc, May 28, 2015; 9 = https://smartlabel.seventhgeneration.com/732913228102-0001-en-US/index.html.
[b]European Union requires a narrower range. See Source 2.

Table 2. Volatile organic compounds detected in breathing zone air of home care aides performing bathroom cleaning, by product. List excludes compounds found in canister whole air samples collected during cleaning with distilled water, or in lab and field blanks or background samples.

	Volatile organic compound	CAS #	Bleach-based product *N* = 19	QACs-based product *N* = 20	Green product *N* = 22	OEL?[a]	On SDS[b] or other public source?	Toxicity data?[c]
1	(−)-alpha-Pinene (L-alpha-Pinene)	7785-26-4	…	✓	…	Yes (1)[d]	No	Minimal
2	(Z)-difluorodiazene (nitrogen fluoride (N2F2), (Z)-)	13812-43-6	…	✓	…	No	No	None
3	1,2-Benzenediol, o-(4-methoxybezoyl)-o′-(5-chlorovaleryl)-	no CAS	…	…	✓	No	No	None
4	1,2-Dihydro-3H-1,2,4-triazol-3-one	930-33-6	…	✓	…	No	No	Minimal
5	1,4-Cineole	470-67-7	…	✓	…	No	No	Minimal
6	1-Isopropyl-2-methylbenzene (o-Cymene)	527-84-4	…	✓	…	No	No	Minimal
7	2,3-Dimethylbutane	79-29-8	✓	…	…	Yes (1,3,5,6)	No	Minimal
8	2,5-Dimethylpyrazine	123-32-0	…	…	✓	No	No	Minimal
9	2-Methyl-1-nitropropane	625-74-1	✓	…	…	No	No	None
10	2-Methyl-4,6-octadiyn-3-one	29743-33-7	✓	…	…	No	No	None
11	2-Methylfuran	534-22-5	…	…	✓	No	No	Minimal
12	2-Methylnonane	871-83-0	✓	…	…	No	No	Minimal
13	2-Norpinene, 3,6,6-trimethyl-	4889-83-2	…	✓	…	No	No	None
14	3,7-Dimethyloctan-3-ol (tetrahydrolinalool)	78-69-3	✓	✓	…	No	Yes	Minimal
15	3-Carene	13466-78-9	…	✓	…	Yes (1)	No	Minimal
16	4-(1,1,3,3-Tetramethylbutyl)phenyl trimethylsilyl ether	78721-87-6	…	✓	…	No	No	None
17	4-Carene	29050-33-7	…	✓	…	No	No	None
18	Acetaldehyde	75-07-0	✓	✓	✓	Yes (1,3,4,5,6)	No	Good (ca)
19	alpha-Pinene	80-56-8	…	✓	…	Yes (1)	No	Good (g)
20	alpha-Thujene	2867-05-2	…	✓	…	No	No	None
21	aeta-Thujene	28634-89-1	…	✓	…	No	No	None
22	Bis(dichloromethyl) ether	20524-86-1	✓	…	…	No	No	None
23	Chloroform	67-66-3	✓	…	…	Yes (1,3,4,5,6,7)	No	Good (ca)
24	Cyanogen chloride	506-77-4	✓	…	…	Yes (1,4,6)	No	Minimal
25	Dichloroacetonitrile	3018-12-0	✓	…	…	No	No	Minimal (g)
26	d-Limonene	5989-27-5	…	✓	…	Yes (2,3,4)	Yes	Good (g)
27	Ethanol	64-17-5	✓	✓	✓	Yes (1,3,4,5,6)	Yes	Good (ca)
28	Eucalyptol	470-82-6	…	✓	…	No	No	Minimal (g)
29	Furfuryl acetate	623-17-6	…	…	✓	No	No	Minimal (g)
30	Isoterpinolene	586-63-0	…	✓	…	No	For terpinolene	None
31	Linalyl anthranilate	7149-26-0	…	…	✓	No	No	Minimal
32	Methyl methacrylate	80-62-6	✓	…	…	Yes (1,3,4,5,6,7)	No	Good (g)

Table 2. Continued

Volatile organic compound	CAS #	Bleach-based product N = 19	QACs-based product N = 20	Green product N = 22	OEL?[a]	On SDS[b] or other public source?	Toxicity data?[c]
33 Methylene chloride	75-09-2	✓	✓	…	Yes (1,3,4,5,6,7)	No	Good (ca)
34 m-Hydroxymandelic acid, tris(trimethylsilyl)-	68595-69-7	…	✓	…	No	No	None
35 Spiro(2.4)hepta-4,6-diene	765-46-8	✓	…	✓	No	No	None
36 Sulfur dioxide	7446-09-5	…	…	✓	Yes (1,3,4,5,6,7)	No	Good (g)
37 Tert-butyldimethylsilanol	18173-64-3	…	…	✓	No	No	None
38 Vinylidene chloride (also 1,1 Dichloroethene)	75-35-4	✓	…	…	Yes (1,3,4,6,7)	No	Good (ca)

[a]OEL authorities: 1 = American Conference of Governmental Industrial Hygienists; 2 = American Industrial Hygiene Association; 3 = German Research Foundation Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area (MAK); 4 = International Labor Organization/World Health Organization; 5 = US Occupational Safety and Health Administration; 6 = National Institute for Occupational Safety and Health; 7 = European Union Occupational Exposure Limit.
[b]Safety Data Sheet.
[c]Toxicity data: none = not listed in https://comptox.epa.gov/dashboard/ or listed with no toxicity data; minimal = CompTox lists 1 to 3 basic toxicity tests, e.g. LD50, Ames assay for mutagenicity, animal test for skin or eye irritation; good = CompTox lists minimal toxicity data plus additions e.g. chronic exposure No Adverse Effect or Lowest Adverse Effect Concentrations, slope factors for cancer risk assessment; (g) = positive genotoxicity tests; (ca) = positive evidence of cancer in animals.
[d]OEL is for α-Pinene racemic mixture.

The concentrations of 4 (out of 14) VOCs could be quantified reliably in the canister whole air samples, excluding compounds found in samples collected during cleaning with distilled water, or in lab and field blanks or background samples (Table 3). Concentrations above the analytical method LOD were measured in 20% or more of the canister whole air samples for: chloroform, limonene, ethanol, and α-pinene.

Cleaning and disinfecting product bulk sample headspace VOCs

Concentrations of 8 (out of 14) VOCs above the method LOD were quantified in the C&D product headspace analyses, including 4 VOCs not quantified in the canister whole air samples: acetone, benzene, methyl methacrylate, and toluene (Supplementary Table S1).

Quaternary ammonium compounds time-integrated air sampling and analysis

One or more of the QACs listed on the QACs-based product Safety Data Sheet (BAC12, BAC14, BAC 16) were detected in all 20 of the aerosol samples collected in aides' breathing zones while they cleaned with the QACs-based product (Table 4). Eighteen of the 20 air samples contained all 3 QACs. The arithmetic mean and standard deviation of the sum of the 3 QACs in the 18 air samples were: 13.34 μg/m^3 and 8.59 μg/m^3, respectively. Additionally, each of the 18 summary measures were logged, and the geometric mean and geometric standard were calculated: 10.86 μg/m^3 and 2.01, respectively.

Discussion

Recent studies of C&D respiratory health effects identified the need for quantitative exposure assessment (De Matteis et al. 2020; Arnold et al. 2023). Thus far, only a few studies provide personal breathing zone measurements collected while workers are performing their cleaning jobs (LeBouf et al. 2014; Virji et al. 2019; Lindberg et al. 2021; Oyer-Peterson et al. 2022; Schäferhenrich et al. 2023). This study used multiple methods, including personal breathing zone measurements, to assess VOC and QACs respiratory exposures generated while HC aides performed typical bathroom cleaning tasks using 2 conventional and 1 green C&D product.

Strengths and limitations

Strengths of this study include 84 C&D exposure evaluation visits contributing approximately 20 personal breathing zone measurements each for VOCs and QACs by product and distilled water. Participants

Table 3. Volatile organic compound concentrations[a], GM[b] in ppb (GSD[c]) quantified in canister whole air samples collected in the breathing zone of home care aides applying three cleaning products. Excludes compounds found in whole air samples collected during cleaning with distilled water, or in lab and field blanks or background samples.

Volatile organic compound	Bleach-based product (*N* = 19)	QACs-based product (*N* = 20)	Green product (*N* = 22)
Chloroform	21.4 (1.7)	…	…
d-Limonene	…	3.8 (3.9)	…
Ethanol	41.6 (3.7)	89.7 (6.1)	23.6 (2.5)
α-Pinene	…	9.3 (1.5)	…

[a]Includes only compounds for which >20% of canister sample concentrations were >LOD.
[b]GM = geometric mean in parts per billion.
[c]GSD = geometric standard deviation.

Table 4. Airborne concentrations of quaternary ammonium compounds (QACs) measured in the breathing zone of 20 aides performing cleaning with the QACs-based product.

Quaternary ammonium compound (QACs)	*N*[a]	Arithmetic mean (μg/m^3)	Standard deviation (μg/m^3)	Geometric mean (μg/m^3)	Geometric standard deviation	Range min—max (μg/m^3)
BAC12	18	8.58	5.54	6.98	2.02	1.48 to 23.82
BAC14	19	3.67	2.41	2.97	2.01	0.68 to 10.58
BAC16	20	0.97	0.63	0.78	2.05	0.16 to 2.74
Sum of 3 QACs[b]	18	13.34	8.59	10.86	2.01	2.31 to 37.13

[a]Aides contributed 20 time-integrated air samples for QAC sampling. BAC16 was detected in all 20 samples, BAC14 was detected in 19 (out of 20) samples, BAC12 was detected in 18 (out of 20) samples.
[b]Concentration of BAC12 + BAC14 + BAC16 was calculated for each of the 18 air samples containing all three QACs.

were representative of the aide population in eastern Massachusetts, United States, and they all performed cleaning tasks for their jobs. The air samples were collected according to an experimental design which enabled the same aide to use each product and the water, thus minimizing variability in aides' cleaning methods across the products. The air measurements were collected in a realistic, standardized setting with many major exposure determinants well-controlled or documented. Randomization of the product used for each aide's visit controlled for bias that might have been introduced if there were an effect of the order in which the products were used.

Limitations include that only 3 products were evaluated. These products were assessed 1 at a time and aides often use multiple products each time they clean a bathroom; our data likely under-represent aides' actual exposures. While our protocol required aides to wear full cover garments and nitrile disposable gloves, our assessment focused only on respiratory exposures. In practice, aides also experience dermal exposures from over-spray and from unprotected skin contacting liquid C&D products on surfaces or from evaporation. Finally, the sampling duration of the measurements in this study was 40-min, comprising 2, identical cleaning sessions with the same product or water. In practice, 40 min more closely represents cleaning of 2 bathrooms. Many aides, however, clean 2 or more bathrooms per work shift.

Lessons learned

Spray application of a cleaning and disinfecting product containing QACs can produce inhalation exposures to QACs aerosols.

Although there is increasing concern about the health effects of QACs, dermal, rather than respiratory, is often considered the major route of exposure because QACs are nonvolatile salts. This study provides quantitative data (Table 4) demonstrating that a ready-to-use QACs-based product sprayed in a small space with low ventilation, produced QACs aerosol in the aides' breathing zones. The specific QACs and their airborne concentrations corresponded to the relative amounts reported on the QACs-based product Safety Data Sheet: BAC12, BAC14, and BAC16, in highest to lowest amount respectively. Most of the time-integrated air samples (18 of 20) collected in the aides' breathing zones contained all 3 QACs.

Several studies have assessed QACs or other biocide aerosols from spraying C&D products. While exposure determinants differ among them, their findings are generally consistent with our personal breathing zone QACs aerosol measurements. Using the same air sampling and analytic methods applied in this study, LeBouf et al. (2017) collected air samples from a US hospital where C&D products, including QACs-based, were used. Results of a short-duration (15 min) area air sample showed that spraying of a QACs-based product (containing BAC less than 1% by weight) generated liquid aerosol with concentrations of 0.23 μg/m^3 BAC12, 1.5 μg/m^3 BAC14, and 0.96 μg/m^3 BAC16 while a housekeeper actively cleaned a hospital bathroom with the QACs-based spray product. BAC proportions in the air sample were comparable to those in solution, based on the Safety Data Sheet. Clausen et al. (2023) assessed aerosol exposure generated by spraying a biocide containing BAC in a chamber and estimated peak 15-min time-weighted concentrations ranging from 1.3 μg/m^3 to 6.6 μg/m^3. Schäferhenrich et al. 2023 measured 49.9 μg/m^3 of BAC in aerosol samples generated during C&D product spraying in a simulated workplace. While the United States has no health-based exposure limits for airborne QACs, the Danish EPA gives a consumer product health-based limit value of 0.005mg/m^3 for inhalation exposure to BAC (Berthelsen et al. 2000; Clausen et al. 2020). The BAC values we measured are close to or exceed this limit.

LeBouf et al. 2017 identified a second mechanism by which use of a QACs-based C&D product can generate airborne QACs exposures: a short-duration (15 min) area air sample measured 3.5 μg/m^3 of BAC12, 1.2 μg/m^3 of BAC14, 0.15 μg/m^3 of BAC16, and 0.46 μg/m^3 of benzethonium chloride (BEC) while a housekeeper swept a hospital waiting room. Although QACs-based C&D products were used in the hospital, no QACs-based products were used directly during the sweeping task. The latter results provide evidence that QACs can adsorb onto the surface of solid particles that settle onto environmental surfaces and be re-aerosolized when disrupted by mechanical actions such as sweeping. Zheng et al. (2021) measured QACs in dust samples collected in homes and showed that QACs exposures increased post-COVID.

Cleaning and disinfecting in residential bathrooms with common, ready-to-use household spray products generates respiratory exposures to complex mixtures of volatile as well as nonvolatile compounds.

Publicly available information confirmed that all 3 liquid C&D products were complex mixtures of volatile and nonvolatile ingredients (Table 1). The QACs-based product contained the greatest number of ingredients followed by the bleach-based and green products, respectively. When the liquid products were sprayed, they generated numerous VOC respiratory exposures, with the QACs-based producing the most VOCs compared to the bleach-based and green products (Tables 2 and 3). Further, the fragrance mixture in the QACs-based product contained the most components compared to the fragrances in the other two products (Table 1). These findings are consistent with our previous study showing that the QACs-based product generated the highest concentration of TVOCs compared to the bleach-based and green products (Figure 1). Additionally, in controlled chamber studies, Jahn et al. (2023) found a variety of VOCs emitted from lab-grade BAC as well as from commercial QACs-based product formulations. The authors concluded that a solution of BAC and water alone, with no commercial additives, generates a range of VOCs, possibly from contaminants created during synthesis or products of solution chemistry. The latter finding counters the present thinking that BAC has no volatile properties.

Most VOCs detected in the aides' breathing zones were not listed in publicly available data sources for the products they used. Toxicity information for most of the VOCs was limited and only a few VOCs have OELs.

Comparing Tables 1 and 2, there is little overlap between the ingredients listed on the product labels and those detected in air samples. Product labels and Safety Data Sheets, the information sources most accessible to aides and their employers, were particularly limited: only 3 of the 38 VOCs found in the aides' breathing zones were listed on a Safety Data Sheet or other public source (Table 2). Variable and incomplete data sources, combined with the lack of toxicity information and exposure protection guidelines, make it difficult for workers, employers, clients, and other householders to know what they are exposed to and how to limit exposures when using C&D products.

Future quantitative assessments of C&D respiratory exposures for epidemiology may be more time and cost-effective when used in combination with semi-quantitative and qualitative methods.

Because the ingredients in C&D products are in diverse physicochemical forms, a comprehensive quantitative workplace exposure assessment requires multiple air sampling and analytical methods that are technically complex and costly. Despite its complexity, this investigation focused on only 3 products while many products from many manufacturers are used for household C&D, often for the same cleaning session in a single room. Additionally, the formulation of the same product can change over time. Thus, the ingredients in one C&D product do not represent the same ingredients in other products or even in the same products in different time periods. For C&D exposure assessments in future epidemiological studies, more feasible methods may include a combination of quantitative and qualitative methods: including air measurements and biomarkers for specific exposures combined with C&D exposure modeling, worker and citizen science to collect samples and/or identify product ingredients using digital applications, questionnaire surveys, and focus groups (Meesters et al. 2018; Harari et al. 2021; Harley et al. 2021; Zheng et al. 2021; Knox et al. 2023; Suleiman 2023; Lee et al. 2024). For exposure assessment in occupational hygiene practice, real-time TVOC measurements with direct reading instruments, as described in our previous study (Lindberg et al. 2021), can provide initial respiratory exposure screening, but miss the nonvolatile compounds such as QACs.

Spraying of all types of C&D products (conventional and green) should be avoided.

Recent studies show that spraying C&D products produces a wide range of respiratory exposures and that the use of sprays for environmental surface cleaning is an important occupational risk factor for airway disease in healthcare settings (Clausen et al. 2020; Mwanga et al. 2023). Figure 1 shows how rapidly VOCs from spraying can be generated and Table 4 shows the concentrations of QACs in the aerosol generated while spraying the QACs-based product. In this study, the active ingredient in the green product was thymol, a solid at room temperature with low volatility (vapor pressure 0.0022 mmHg). While we did not evaluate thymol in the aerosol samples, it was likely dissolved in the C&D liquid product and dispersed in the aerosol generated during the green product spraying.

We observed that the trigger nozzles on the C&D product bottles were effective aerosol generators that produced small liquid particles. Lovén et al. 2019 characterized the airborne particle size distributions and respiratory deposition fractions of ready-to-use bathroom cleaning products sprayed from bottles in a chamber. They found that up to one-third of the product sprayed out did not reach the intended surface and that the total airborne particles were very small (mass median aerodynamic diameter range 1.9 to 3.7µm), in the relevant size range for nasal, tracheobronchial, and alveolar deposition. Clausen et al. 2023 concluded if spraying cannot be avoided, holding the spray nozzle 1 cm from the cloth or paper towel used for wiping can reduce respiratory exposures.

The most effective way to reduce harmful C&D exposures is to eliminate hazardous ingredients and spray technologies.

This conclusion is consistent with the occupational hygiene hierarchy of controls model which holds that eliminating a hazard at its source is the most effective preventive action (US NIOSH 2023). Lovén et al. 2019 recommend re-designing spray nozzles to minimize airborne exposures. Some spray nozzles have features to dispense C&D liquid in a focused liquid stream and our previous study found that streaming generated lower TVOC concentrations than spraying (Lindberg et al. 2021). Lovén et al. 2023 and Schäferhenrich et al. 2023 show that dispensing a biocide as a foam reduces airborne exposures compared to spraying, although foam does not reduce dermal exposure.

Another approach to reducing C&D exposures is to re-formulate the product with less hazardous ingredients. Government programs with this objective are already underway. For example, the US EPA Safer Choice program is designed to eliminate C&D hazards by assisting consumers and facilities such as schools to find C&D products containing chemical ingredients that are safer alternatives for human health and the environment (US EPA 2024c). Fragrances are associated with irritant and/or allergic contact dermatitis (Pastor-Nieto and Gatica-Ortega 2021) and can trigger or intensify episodic and chronic symptoms of respiratory illness (Radis-Baptista 2023). The SmartLabel® database describes 2 fragrance functions: to produce a scent and to mask other odors (Table 1). Fragrances are not listed as active disinfecting ingredients or as having any role in the removal of soil. Given potential toxicity and no C&D action, this chemical group should be reduced or eliminated in C&D products.

The green product evaluated in this study was designed as a safer alternative and the results of this exposure assessment suggest that the green product might present lower respiratory health risks compared to the 2 conventional products. The green product had the fewest ingredients overall (Tables 1 and 2), the least number of compounds comprising the fragrance (Table 1), and the fewest VOC ingredients with quantifiable concentrations (Table 3). In this study, thymol was not evaluated in the VOC analyses, probably due to low volatility, however, it was likely in the aerosol generated during cleaning with the green product. Use of low- or nonvolatile substances can reduce respiratory exposures, *as long as they are not aerosolized*. Human toxicity data on plant-derived fragrances is limited, although some plant-derived compounds that serve as disinfectant and/or fragrance components, such as terpenes, are recognized respiratory irritants. Further research is needed to evaluate thymol as a potential component of green C&D product aerosols and on the impact of green C&D products and ingredients on respiratory and other health outcomes (Harley et al. 2021; Mwanga et al. 2024).

There are also alternatives to conventional C&D products in different chemical, biological, and physical forms and these should be evaluated for HC. A major challenge to implementing alternatives to conventional disinfecting products is the lack of information about their infection prevention effectiveness. A recent German study provides promising findings from an evaluation of the comparative effectiveness of soap-based and probiotic (*Bacillus* spp.) cleaning of environmental surfaces, compared to conventional disinfection, and the incidence of hospital-acquired infections (HAIs). The investigators conducted a cluster randomized controlled, crossover intervention trial in 18 non-ICU wards in the university hospital of Berlin. Each cleaning strategy (soap, probiotic, conventional disinfection chemical) was used on each ward for 4 consecutive months; the order was randomized for each ward. The results showed that soap-based and probiotic cleaning were as effective at preventing HAIs as routine conventional surface disinfection (Leistner et al. 2023).

Another approach to reducing C&D chemical exposures is to switch to nonchemical alternatives, such as steam or UV light. Currently, these do not seem feasible in most home care settings, however, advances in these technologies (safe, lightweight, portable, user-friendly, low-cost steam cleaners, or UV robotics) could include design for safe HC.

Conclusion

The use of C&D spray products for residential cleaning generates a complex mixture of potentially hazardous respiratory exposures. Aides' respiratory health should be protected during cleaning, especially as C&D activity increases with pandemics. Occupational hygienists and infection preventionists should work together to maximize infection prevention and respiratory health.

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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.

Data Availability

Most of the data underlying this article are available in the paper, its online supplementary material, and the open access article Lindberg *et al.* JOEH 2021. In accordance with IRB approval, to protect the anonymity of the participants, personal identifying data are not publicly available. Additional data may be shared on reasonable request to the corresponding author.

Disclaimer

The findings and conclusions in this paper are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention. Mention of any company or product does not constitute endorsement by NIOSH, CDC.

Supplementary material

Supplementary material is available at *Annals of Work Exposures and Health* online.

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