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RESEARCH ARTICLE

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Eye and airway symptoms in hospital staff exposed to a product containing hydrogen peroxide, peracetic acid, and acetic acid

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Abstract

Background: Sporicidal products containing hydrogen peroxide (HP), peracetic acid (PAA), and acetic acid (AA) are used widely in multiple industries, including healthcare. Despite widespread use in healthcare, few studies have assessed associations between exposures to HP, PAA, and AA, and work-related symptoms in these settings.

Methods: In 2018, we performed a health and exposure assessment at a hospital where a sporicidal product consisting of HP, PAA, and AA, was used as the primary cleaner on hospital surfaces. We collected 56 personal and mobile air samples for HP, PAA, and AA on participants while they performed their regular cleaning duties; collected area samples for HP ($n = 28$), PAA ($n = 28$), and AA ($n = 70$) in multiple hospital locations where cleaning was performed; and administered a postshift survey to assess eye, skin, and upper and lower airway symptoms that occurred cross-shift or in the previous 4 weeks.

Results: Full-shift exposure levels for HP (range: <3–559 ppb), PAA (range: <0.2–8 ppb), and AA (range: <5–915 ppb) were all below US occupational exposure limits. We observed positive associations ($p < 0.05$) between shift, departmental average, and departmental 95th percentile exposures to HP, PAA, and AA vapors, and work-related acute (cross-shift) and chronic (previous 4 weeks) eye, upper airway, and lower airway symptoms after adjusting for age, gender, smoking status, use of other cleaning products containing sensitizers and irritants, allergic status, and stress.

Conclusions: Our observations of work-related upper and lower airway symptoms among hospital workers exposed to vapors from a sporicidal product containing HP, PAA, and AA indicate a need for a combination of engineering, administrative, and PPE controls to reduce exposure. Additionally, alternative nonchemical disinfection technologies should be further investigated as a means to simultaneously reduce healthcare workers' exposure to disinfectants while also minimizing costly healthcare-acquired infections.

KEYWORDS
healthcare, hydrogen peroxide, peracetic acid, peroxygen, respiratory

1 | INTRODUCTION

Cleaning and disinfectant products are used widely in healthcare settings to minimize healthcareacquired infections (HAIs). HAIs among patients in US hospitals are estimated to have direct medical costs of at least $28.4 billion annually, and indirect costs to society of $12.4 billion due to early deaths and lost productivity.[1] Consequently, demand has increased for effective cleaning and disinfection products that can reduce infectious bacteria like methicillin-resistant *Staphylococcus aureus* (MRSA), vancomycin-resistant *Enterococcus* (VRE), and *Clostridium difficile* (*C. diff*) in healthcare environments in an effort to reduce costly HAIs.[2] Further, intensified cleaning protocols during the COVID-19 pandemic also contributed to increased demand for effective cleaning and disinfection products.[3] Concerns about *C. diff* spores specifically, and HAIs from *C. diff* that cost the healthcare industry $1–5 billion annually, have led to increased demand for cleaning and disinfecting products with sporicidal activity.[4] Sporicidal products composed of chlorine compounds, or mixtures of hydrogen peroxide (HP) and peroxy acids, are often used as surface cleaners and disinfectants in all areas of healthcare facilities.[2,5,6] Sporicidal products containing a mixture of HP, peracetic acid (PAA), and acetic acid (AA) have gained popularity in the last decade as a surface cleaner in healthcare settings due to their rapid-acting disinfectant properties and purported minimal damage to surfaces with no residual salts or films.[7]

Previous studies observed an increased risk for dermatitis, work-related rhinitis, work-related asthma, and chronic obstructive pulmonary disease (COPD) in workers exposed to cleaning and disinfectant chemicals in many different occupational settings.[8–16] Healthcare workers can potentially be exposed to high levels of many different cleaning and disinfecting products.[17–20] Many cleaning and disinfection products used in healthcare settings contain asthmagens, and the use of bleach, quaternary ammonium compounds, ammonia, spray cleaning products, and HP and PAA mixtures have been associated with asthma and respiratory symptoms among healthcare workers.[12,13,21–25] Additionally, the recent increase in cleaning and disinfection product use associated with the outbreak of COVID-19 infections resulted in an increase in uncontrolled asthma among adults with current asthma.[26] Further, a recent longitudinal study of US nurses observed an association between exposure to disinfectants and COPD and suggested that regular use of chemical disinfectants among healthcare workers might be a risk for COPD.[15] Although respiratory effects are well documented in healthcare workers exposed to cleaning and disinfecting products, few studies have evaluated quantitative exposures and the levels at which adverse health effects occur.

Despite widespread use of products containing a mixture of HP, PAA, and AA among U.S. hospitals, only a few assessments of hospital workers' exposure to HP, PAA, and AA have been performed to date.[27,28] The objectives of this study were to evaluate healthcare workers' (i) full-shift personal exposures to cleaning and disinfectant chemicals and work-related upper and lower airway symptoms reported during the shift, and (ii) departmental exposures to cleaning and disinfectant chemicals and work-related upper and lower airway symptoms in the previous 4 weeks.

2 | METHODS

2.1 | Study population

In 2018, the National Institute for Occupational Safety and Health (NIOSH) conducted a health hazard evaluation at a hospital where a sporicidal product (Product A), consisting of HP, PAA, and AA, was used as the primary surface cleaner on surfaces throughout the hospital. Hospital staff cited concerns about exposure to Product A, and described respiratory distress, eye and throat irritation, skin problems, headaches, chest tightness, and nausea. Cleaning staff in all hospital departments were invited to participate in the air sampling and post-shift surveys. Patient care and administrative (non-cleaning) staff working in units where cleaning with Product A was performed were also invited to participate in the post-shift survey. The study was determined not to be human subjects research but to be public health practice as part of the health hazard evaluation program and thus was not subject to IRB review. Participation was voluntary. Workers gave informed consent before participating in the air sampling and post-shift surveys. Demographic information was collected in the post-shift survey.

2.2 | Exposure assessment

We collected 56 full-shift time-weighted average (TWA) personal or mobile samples on cleaning staff employees across all three shifts (day, evening, and night). Twenty-nine of the full-shift samples were collected from workers' breathing zones while they performed regular work duties and 27 of the samples collected were mobile samples. For the mobile samples, we followed employees while they performed cleaning duties and placed the samplers near cleaning staff in the rooms while they cleaned or on their carts near staff while they were cleaning. Participants included workers assigned to the following hospital areas: emergency department (ED), intensive care unit (ICU), labor and delivery, pediatrics, step down unit, medical surgical (floors A and B), float (staff assigned to clean discharged patient rooms in multiple departments), and public restrooms and discharged patient rooms (staff assigned to clean public restrooms and discharged patient rooms in multiple departments). We also observed workers while they performed their regular cleaning duties

and noted task duration, cleaning product use and duration, and personal protective equipment (PPE) use.

Additionally, we collected 70 AA, 28 HP, and 28 PAA full-shift TWA area samples from multiple locations including the ED, ICU, ICU pre-op, anesthesia administration, labor and delivery, pediatrics, step down unit, medical surgical (floors A and B), diagnostic imaging, and pharmacy.

All air samples were analyzed for the three chemicals found in the sporicidal product: HP, PAA, and AA. HP and PAA were collected simultaneously on a cassette in-line with a glass tube sampler at a flow rate of 1 L/min and analyzed according to the methods specified by Hecht et al.[29] AA was collected and analyzed according to the Occupational Safety and Health Administration (OSHA) Method PV2119 (OSHA, 2003). The LODs were 2 µg of HP per sample, 0.2 µg of PAA per sample, and 1 µg of AA per sample.

2.3 | Post-shift survey of health outcomes and cleaning product use

We administered a voluntary post-shift survey ($n = 77$) of health outcomes and cleaning product use among 67 hospital employees at the end of their shift; 10 employees completed the post-shift survey on two occasions after two different work shifts. We offered the post-shift survey to all cleaning staff who participated in the air sampling survey and to non-cleaning (patient care, pharmacy, and administrative) staff working in departments where air samples were collected. All staff who participated in the air sampling survey also participated in the post-shift survey. Questions addressed eye, respiratory, and skin symptoms; nasal allergies, skin allergies, chronic bronchitis, emphysema, COPD, asthma, and other diagnoses; smoking history; cleaning product use; hospital department assignment; stress outside of work; stress at work; and demographic information. Stress outside of work and stress at work were included as questions in the survey because recent studies indicate a potential association between psychosocial stress and respiratory symptoms.[30,31] The survey was professionally translated into Spanish and offered in English or Spanish.

For eye, respiratory, and skin symptoms, we asked if employees had experienced any of the following symptoms during their shift: (1) nasal irritation (burning, itchy, runny nose); (2) sneezing; (3) throat irritation (burning, dry, sore throat); (4) eye irritation (burning, itchy, watery eyes); (5) cough; (6) wheezing or whistling in the chest; (7) chest tightness; (8) shortness of breath; (9) difficulty breathing; and (10) skin symptoms. When employees reported symptoms that occurred during their work shift, we asked (1) if their symptom had worsened during their shift; (2) what they were doing when the symptom first began; and (3) if they had that symptom upon arrival at work that day. Acute work-related (cross-shift) symptoms were defined as symptoms that occurred during the participants' shift that were not present upon arrival at work that day.

We also asked if employees had experienced any of the same symptoms in the previous 4 weeks. When employees reported symptoms that occurred in the previous 4 weeks, we asked if their symptoms were the same, worse, or better when away from work, either on their days off or when they were on vacation. Symptoms that improved when the employees were away from work, were defined as work-related.

2.4 | Statistical analyses

All statistical analyses were performed using PC-SAS version 9.4 and JMP version 13.0 (SAS Institute) and all plots were prepared in SigmaPlot (Version 14.0; Systat Software Inc.). Because plots of the full-shift TWA exposure data for HP, PAA, and AA indicated the distributions were not normal, full-shift TWA exposure measurements were log-transformed for all analyses. The NLMIXED procedure in SAS, which accounts for measurements below the limit of detection (LOD) was used to summarize the personal and area exposure data. The minimum variance unbiased estimator (MVUE) of the arithmetic mean (AM) and its standard deviation (SD), geometric mean (GM), geometric standard deviation (GSD), and 95th percentile (P95), overall and by department and sample type (i.e., personal, mobile, and area), were calculated. The MVUE AM and SD were calculated utilizing methods described by Gilbert.[32]

For area samples in four departments (ICU Pre-Op, Anesthesia Admin, Diagnostic Imaging, and Pharmacy), only AA measurements were collected. In these situations, relationships between AA and PAA or HP were developed using data from areas where all three exposure measurements were collected to predict area exposures to HP and PAA. The PROC REG procedure in SAS was used to model these relationships with measurements for AA as the predictor variable and HP or PAA as the outcome variable (Supporting Information: Figure 2). Predicted values were used to calculate the HP and PAA summaries (i.e., AM, P95, SD, GM and GSD) by department as described above.

2.4.1 | Assessment of mixture exposures

We used the American Conference of Governmental Industrial Hygienists' (ACGIH®) Additive Mixture Formula to estimate mixture exposures for the total mixture (TM) of HP, PAA, and AA as well as the oxidant exposure mixture (OM) of HP and PAA (ACGIH, 2016). Concentrations in parts per million (ppm) of HP and AA were divided by their established OSHA Permissible Exposure Limit (PEL) and NIOSH Recommended Exposure Limit (REL) of 1 ppm for HP and 10 ppm for AA (Equations 1 and 2). Concentrations of PAA in ppm were divided by 0.2 ppm, the occupational exposure limit proposed by multiple researchers.[33–35] TM and OM exposure was determined using the following equations:

$$TM = \frac{[HP]}{1\,ppm} + \frac{[PAA]}{0.2\,ppm} + \frac{[AA]}{10\,ppm}, \quad (1)$$

$$OM = \frac{[HP]}{1\,ppm} + \frac{[PAA]}{0.2\,ppm}, \quad (2)$$

where [HP], [PAA], and [AA] represent the assigned concentrations for HP, PAA, and AA for each participant.

2.4.2 | Individual level exposure assignments

Cleaning staff participating in air sampling were assigned exposures from their individual personal or mobile air sampling results. Cleaning staff with no air sampling results ($n = 3$) were assigned the average personal exposure for HP, PAA, and AA of cleaning staff employees working in their same department during their shift. Non-cleaning staff were assigned the averages of area measurements for HP, PAA, and AA collected or predicted in their department during their shift.

2.4.3 | Departmental level exposure assignments

Cleaning staff were assigned the AM and P95 of personal exposures by department. In departments with no personal exposure measurements, cleaning staff were assigned the AM and P95 of mobile exposures by department. Non-cleaning staff were assigned the AM and P95 of area measurements for HP, PAA, and AA collected in their department. TM and OM exposure were determined as described above.

2.4.4 | Exposure to other cleaning and disinfection products

Use of cleaning products containing sensitizers or irritants such as quaternary ammonium compounds, bleach, phosphoric acid, sodium xylenesulfonate, or ethanolamines was obtained from reported product use in the post-shift survey. Up to six different products containing sensitizers or irritants were reported, with two different products reported containing quaternary ammonium compounds, one product containing bleach, one product containing phosphoric acid, two products containing sodium xylenesulfonate, and one product containing ethanolamines. An index value for sensitizer and irritant products used during a worker's shift (0–4) was calculated by adding the number of products containing sensitizers and irritants that an employee reported using during their shift on the day of sampling. For sensitizer and irritant products used in the previous 4 weeks, a weighting factor was applied to account for frequency of product used in the previous 4 weeks. The following factors were applied to weight reported product use by frequency: *frequently* = 1, *rarely* = 0.1, and *never* = 0. An index value for other sensitizer and irritant product used in the previous 4 weeks (0–4.1) was calculated by multiplying sensitizer and irritant products used by a factor for frequency of product used in the previous 4 weeks and summing the weighted products together.

2.4.5 | Associations between acute work-related health outcomes and exposure metrics: Individual level exposure

We explored associations between employee's shift-specific exposure to HP, PAA, AA, TM and OM and acute work-related symptoms using logistic regression. Since there were repeated measurements on some participants, the SAS GENMOD procedure with a repeated statement which invokes a General Estimating Equations approach, was used to examine associations of individual level exposure to HP, PAA, AA, TM, and OM with work-related eye, upper airway, lower airway, and skin symptoms reported during an employee's shift; age, gender, smoking status, sensitizers and irritants exposure index, allergic status, and total stress were included as covariates in the models. An independence working correlation structure was utilized because there were too few repeat measures ($n = 10$) to accurately estimate a covariance structure. However by using the empirical or robust variance estimates, correlations among the responses can be largely accounted for in the General Estimating Equations calculations. Allergic status was defined as reporting a previous diagnosis of nasal or sinus allergies (including hay fever) or skin allergy (eczema or any kind of skin allergy). Total stress was defined as the average reported stress at work and stress outside of work in the previous 4 weeks, on a continuous scale from 0 to 10, where a score of 0–3 indicates low stress, 4–6 moderate stress, and 7–10 high stress.[36,37] Smoking status was defined as never and ever smokers.

2.4.6 | Associations between chronic health outcomes and exposure metrics: Departmental level exposure

We assessed associations between the AM and P95 departmental exposure and work-related symptoms in the previous 4 weeks. The GENMOD procedure in SAS was used to examine associations of departmental level exposure to HP, PAA, AA, TM, and OM with work-related eye, upper airway, lower airway, and skin symptoms in the previous 4 weeks, controlling for age, gender, smoking status, sensitizers and irritants exposure index, allergic status and total stress. For the 10 staff who participated in the air sampling and post-shift survey twice, only their first survey responses for symptoms in the previous 4 weeks were utilized in analysis (repeat measures were removed).

3 | RESULTS

3.1 | Exposure assessment

Full-shift exposure levels ranged from <3 parts per billion (ppb) to 559 ppb for HP, <0.2 to 28 ppb for PAA, and <5 to 915 ppb for AA (Supporting Information: Figure 1). Summary of the air concentrations measured on hospital cleaning staff in each department are provided in Table 1. The highest personal exposures to the TM of HP,

TABLE 1 Average (AM) and geometric mean (GM) for cleaning staff exposures to hydrogen peroxide, peracetic acid, acetic acid, oxidant mixture (OM), and total mixture (TM), and 95th percentile concentrations (ppb) of hydrogen peroxide, peracetic acid, and acetic acid, by hospital work area (i.e., departmental exposures).

		Hydrogen peroxide (ppb)			Peracetic acid (ppb)			Acetic acid (ppb)			OM		TM	
Hospital area	Sample (N)	AM (SD)	GM (GSD)	95%ile	AM (SD)	GM (GSD)	95%ile	AM (SD)	GM (GSD)	95%ile	AM (SD)	GM (GSD)	AM (SD)	GM (GSD)
Emergency department	Personal (n = 6)	29.5 (±19.2)	24.9 (1.9)	81.7	1.4 (±1.4)	1.0 (2.7)	3.6	35.2 (±36.7)	22.9 (2.9)	84.3	0.04 (±0.02)	0.03 (1.82)	0.04 (±0.02)	0.04 (1.76)
	Mobile (n = 3)	68.5 (±19.6)	66.6 (1.3)	96.6	1.9 (±0.3)	1.8 (1.1)	2.2	31.04 (±23.0)	25.4 (2.2)	54.3	0.08 (±0.02)	0.08 (1.30)	0.09 (±0.04)	0.08 (1.5)
ICU	Personal (n = 0)	–	–	–	–	–	–	–	–	–	–	–	–	–
	Mobile (n = 6)	61.0 (±16.1)	59.2 (1.3)	89.5	2.6 (±1.4)	2.3 (1.7)	5.4	126.2 (±231.0)	36.2 (6.5)	915.1	0.08 (±0.02)	0.07 (1.34)	0.09 (±0.03)	0.08 (1.45)
Labor and delivery	Personal (n = 4)	90.5 (±30.5)	86.7 (1.4)	127.7	5.3 (±1.5)	5.0 (1.5)	8.6	102.5 (±137.7)	46.9 (4.7)	134.1	0.12 (±0.03)	0.11 (1.34)	0.13 (±0.04)	0.12 (1.37)
	Mobile (n = 5)	63.1 (±38.5)	54.3 (1.9)	131.9	3.9 (±1.5)	3.6 (1.5)	5.3	30.4 (±42.6)	13.7 (4.5)	50.8	0.09 (±0.04)	0.08 (1.66)	0.09 (±0.04)	0.08 (1.62)
Pediatrics	Personal (n = 5)	89.3 (±89.3)	59.7 (2.8)	283.6	6.0 (±2.2)	5.7 (1.4)	10.7	25.2 (±48.4)	5.4 (8.9)	74.4	0.12 (±0.09)	0.09 (2.22)	0.12 (±0.09)	0.10 (2.15)
	Mobile (n = 0)	–	–	–	–	–	–	–	–	–	–	–	–	–
Step down unit	Personal (n = 5)	63.4 (±69.4)	39.1 (3.1)	113.4	13.0 (±14.2)	8.1 (3.1)	28.4	83.4 (±197.6)	7.0 (19.1)	207.1	0.13 (±0.14)	0.08 (3.11)	0.14 (±0.15)	0.09 (3.12)
	Mobile (n = 1)	[A]308.0	—	–	[A]9.9	–	—	[A]416.0	–	–	[A]0.36	–	[A]0.40	–
Medical surgical, Floor A	Personal (n = 0)	–	–	–	–	–	–	–	–	–	–	–	–	–
	Mobile (n = 3)	23.5 (±3.0)	23.4 (1.1)	26.1	1.9 (±0.4)	1.9 (1.2)	2.3	31.5 (±33.9)	19.5 (3.6)	69.1	0.03 (±0.00)	0.03 (1.15)	0.04 (±0.00)	0.04 (1.06)
Medical surgical, Floor B	Personal (n = 0)	–	–	–	–	–	–	–	–	–	–	–	–	–
	Mobile (n = 4)	25.9 (±11.0)	24.2 (1.5)	42.6	1.5 (±0.8)	1.4 (1.8)	3.4	17.7 (±22.4)	8.9 (4.2)	37.9	0.03 (±0.01)	0.03 (1.48)	0.04 (±0.01)	0.04 (1.42)
Float: Discharges	Personal (n = 6)	168.1 (±150.3)	122.0 (2.5)	558.8	3.3 (±1.7)	3.0 (1.7)	5.7	140.1 (±75.2)	124.5 (1.7)	292.2	0.19 (±0.15)	0.14 (2.26)	0.20 (±0.16)	0.16 (2.21)
	Mobile (n = 2)	[A]6.9–13.1	–	–	[A]1.4–1.7	–	–	[A]16.7–29.9	–	–	[A]0.01–0.02	–	[A]0.03–0.06	–
Public restrooms and discharges	Personal (n = 3)	44.0 (±26.7)	38.6 (1.9)	93.8	4.1 (±2.1)	3.8 (1.7)	5.8	67.8 (±95.7)	24.7 (7.1)	110.1	0.07 (±0.04)	0.06 (1.74)	0.07 (±0.04)	0.06 (1.79)
	Mobile (n = 3)	28.5 (±12.7)	26.6 (1.6)	42.4	3.5 (±1.2)	3.4 (1.4)	4.5	8.8 (±12.0)	3.5 (6.4)	31.4	0.05 (±0.02)	0.04 (1.50)	0.05 (±0.02)	0.05 (1.42)

Note: "–" indicates hospital departments where no samples or insufficient numbers of samples >LOD were collected to calculate MVUE, SD, GM, GSD, or 95%tile.

Abbreviations: Float: discharges, cleaning staff assigned to clean discharged patient rooms in multiple departments; GM, geometric mean; GSD, geometric standard deviation, ± one geometric standard deviation shown in parentheses; ICU, intensive care unit; MVUE, minimum variance unbiased estimate; OM, oxidant mixture defined by Equation (2); public restrooms and discharges, cleaning staff assigned to clean public restrooms and discharged patient rooms in multiple departments; SD, one standard deviation, ± one standard deviation shown in parentheses; TM, total mixture defined by Equation (1); 95%ile, 95th percentile.

[A]Indicates employee departments with <2 measurements. In these departments, the minimum and maximum measurements replace the average (MVUE) calculations.

[B]Indicates employee departments where >70% of samples were <LOD. In these departments, the minimum and maximum measurements replace the average (MVUE) calculations.

PAA, and AA were observed for cleaning staff performing cleaning duties in labor and delivery, pediatrics, step down unit, and float employees performing cleaning of discharged patient rooms (Table 1).

We observed cleaning staff employees using the sporicidal product containing HP, PAA, and AA (Product A) on surfaces throughout the hospital, including patient rooms, patient bathrooms, and public bathrooms. To use the product, cleaning staff dispensed Product A from an automated dispenser into a bottle that they then used to pour the product into a container with submerged cloth wipes. The container was equipped with a lid that was opened only when cleaning staff needed to access cloth wipes. Cleaning staff were also observed using, or reported occasionally using, other products containing substances capable of causing or worsening eye and respiratory symptoms, including products containing ethanolamines, bleach, phosphoric acid, sodium xylenesulfonate, or quaternary ammonium compounds (Supporting Information: Tables 1 and 2). We observed nitrile gloves being used frequently by staff when they worked with cleaning products. Staff occasionally chose to also wear safety goggles, a surgical mask, or a MOLDEX 2800N95 Series Particulate Respirator (Moldex®) when dispensing or working with cleaning products Table 2.

3.2 | Participant demographics and post-shift survey results

Demographic information for hospital staff who participated in the air sampling or post-shift surveys can be seen in Table 3. The job group of the non-cleaning staff participants ($n = 22$) included nursing staff (Staff Nurses and Registered Nurses; $n = 13$), other patient care staff (Case Managers, Respiratory Technicians, Radiology Technicians, Radiology Assistants; $n = 4$), administrative staff (Unit Secretaries and Clerks; $n = 3$), and pharmacists ($n = 2$). The median age for both cleaning and non-cleaning staff participants were similar with a median age among cleaning staff participants of 47 years (range: 23–70 years) and a median age among non-cleaning staff participants of 42 years (range: 28–58 years) (Table 3). Most participants were Hispanic (71% cleaning staff and 45% non-cleaning staff). Median tenure at the hospital was 5.9 years and 12.0 years for cleaning and non-cleaning staff participants, respectively. Gender and smoking history were similar between the two groups. Most participants were female (76% cleaning staff and 82% non-cleaning staff) and never smokers (78% cleaning staff and 82% non-cleaning staff).

All participants' responses to questions about symptoms and diagnoses can be seen in Table 4. The most common work-related symptoms occurring during their shift, or in the previous 4 weeks, were mucous membrane irritation symptoms (defined as nasal or eye irritation). Acute work-related mucous membrane symptoms occurred in 48% ($n = 37/77$) of all participants and 62% ($n = 34/55$) of cleaning staff. Work-related mucous membrane symptoms in the previous 4 weeks occurred in 58% ($n = 39/77$) of all participants and 73% ($n = 39/45$) of cleaning staff. Acute work-related lower airway symptoms such as cough, wheeze, chest tightness, shortness of breath or difficulty breathing occurred in 36% ($n = 28/77$) of all participants and 45% ($n = 25/55$) of cleaning staff. Work-related lower airway symptoms in the previous 4 weeks, including cough, wheeze, chest tightness, shortness of breath or difficulty breathing, occurred in 43% ($n = 29/67$) of all participants and 56% ($n = 25/45$) of cleaning staff.

Eye and upper airway irritation (i.e., nasal and throat irritation), and shortness of breath were the most common symptoms in the post-shift survey of acute work-related symptoms. Frequency of acute work-related nasal, throat, and eye irritation was 32%, 27%, and 40% respectively. Additionally, 21% of participants had work-related shortness of breath during their shift. Similarly, nasal irritation (45%), sneeze (36%), throat irritation (36%), and eye irritation (45%) were the most common work-related symptoms in the post-shift survey of symptoms occurring in the previous 4 weeks. Frequency of work-related cough, wheeze, or shortness of breath in the previous 4 weeks was 25%, 22%, and 25%, respectively. Almost three-quarters of (17 of 23; 74%) participants who reported acute work-related lower respiratory symptoms also reported acute work-related nasal symptoms and three-quarters (22 of 29; 76%) of participants who reported work-related lower respiratory symptoms in the previous 4 weeks also reported work-related nasal symptoms in the previous 4 weeks.

Among staff with acute work-related symptoms who were asked what they were doing when their symptoms first began, 46% of workers with nasal irritation, 40% of workers with sneeze, 36% of workers with throat irritation, 50% of workers eye irritation, 25% of workers cough, 38% of workers with wheeze, 50% of workers with chest tightness, 29% of workers shortness of breath, 40% of workers with difficulty breathing, and 40% of workers with skin symptoms described performing cleaning tasks, or cleaning tasks occurring nearby when their symptoms first began. Additionally, 31% of workers with work-related nasal irritation, 33% of workers with work-related sneeze, 23% of workers with work-related throat irritation, 27% of workers with eye irritation, 17% of workers with work-related cough, 8% of workers with work-related wheeze, 25% of workers with work-related chest tightness, and 7% of workers with work-related shortness of breath described working with the sporicidal product specifically when their symptoms first began.

Among medical diagnoses, current asthma was reported by 7% of all participants ($n = 5/67$) and 7% of cleaning staff ($n = 3/45$). Nasal or sinus allergies was reported by 30% ($n = 20/67$) of all participants and 24% ($n = 11/45$) of cleaning staff. Eczema or any kind of skin allergy was reported by 11% ($n = 7/67$) of all participants and 7% ($n = 3/45$) of cleaning staff. Chronic bronchitis was reported in 9% ($n = 6/67$) of all participants and 11% ($n = 5/45$) of cleaning staff.

3.3 | Acute work-related symptoms and exposure to HP, PAA, AA, OM, and TM

Acute work-related mucous membrane irritation symptoms, specifically nasal and eye irritation, as well as wheeze and shortness of

TABLE 2 Average (AM), geometric mean (GM), and 95th percentile area concentrations of hydrogen peroxide, peracetic acid, acetic acid, oxidant mixture (OM), and total mixture (TM) by hospital area.

	Hydrogen peroxide (ppb)				Peracetic acid (ppb)				Acetic acid (ppb)				OM			TM	
Hospital area	*N*	AM (±SD)	GM (GSD)	95% ile (ppb)	*N*	AM (±SD)	GM (GSD)	95% ile (ppb)	*N*	AM (±SD)	GM (GSD)	95% ile (ppb)	*N*	AM (±SD)	GM (GSD)	N	AM (±SD)	GM (GSD)
Emergency department	12	4.4 (±1.3)	4.6 (1.3)	7.3	12	0.2 (±0.2)	0.1 (2.5)	0.6	12	8.9 (±6.1)	7.3 (1.9)	20.7	12	0.01 (±0.0)	0.006 (±1.34)	12	0.01 (±0.0)	
ICU	2	[A]4.4–8.1	–	–	2	[A]0.2–1.1	–	–	6	11.6 (±7.2)	9.9 (1.9)	20.1	2	[A]0.005–0.014	–	2	[A]0.007–0.016	–
ICU Pre-Op	0	–	–	–	0	–	–	–	4	8.0 (±2.2)	7.7 (1.3)	10.7	0			0		
Anesthesia admin	0	–	–	–	0	–	–	–	4	17.0 (±9.3)	15.2 (1.7)	29.7	0	–	–	0	–	–
Labor and delivery	6	6.9 (±2.8)	6.4 (1.5)	12.0	6	0.6 (±1.1)	0.2 (5.1)	2.4	12	11.2 (±7.2)	9.4 (1.9)	31.4	6	0.01 (±0.01)	0.008 (1.81)	6	0.01 (±0.01)	0.009 (1.75)
Pediatrics	2	[A]6.8–16.6	–	–	2	[A]0.2–2.4	–	–	6	11.3 (±7.4)	9.5 (1.9)	23.6	2	[A]0.018–0.019	–	2	[A]0.019–0.021	–
Step down unit	2	[A]6.7–42.1	–	–	2	[A]0.5–5.7	–	–	6	12.8 (±6.8)	11.4 (1.7)	25.4	2	[A]0.009–0.07	–	2	[A]0.011–0.073	–
Medical-surgical, Floor A	2	[A]7.5-16.8	–	–	2	[A]0.2–0.6	–	–	6	12.2 (±6.6)	10.8 (1.7)	22.1	2	[A]0.009–0.02	–	2	[A]0.010–0.022	–
Medical-surgical, Floor B	2	[A]7.0–8.7	–	–	2	[A]0.3–0.7	–	–	6	9.2 (±1.7)	10.5 (5.8)	21.4	2	[A]0.009–0.012	–	2	[A]0.010–0.014	–
Diagnostic imaging	0	–	–	–	0	–	–	–	4	[B]5.4–9.7	–	9.7	0	–	–	0	–	–
Pharmacy	0	–	–	–	0	–	–	–	4	6.7 (±3.3)	6.2 (1.6)	9.8	0	–	–	0	–	–

Note: "–" indicates areas where no samples or insufficient numbers of samples >LOD were collected to calculate MVUE, SD, GM, GSD, or 95%tile.

Abbreviations: GM, geometric mean; GSD, geometric standard deviation, ±one geometric standard deviation shown in parentheses; ICU, intensive care unit; MVUE, minimum variance unbiased estimate; OM, oxidant mixture defined by Equation 2; SD, one standard deviation, ±one standard deviation shown in parentheses; TM, total mixture defined by Equation 1; 95%ile, 95th percentile.

[A]Indicates areas with <2 measurements. In these areas, the minimum and maximum measurements replace the average (MVUE) calculations.

[B]Indicates areas where >70% of samples were <LOD. In these areas, the minimum and maximum measurements replace the average (MVUE) calculations.

TABLE 3 Demographic characteristics of survey participants.

Characteristic	All staff (*n* = 67)	Cleaning staff (*n* = 45)	Non-cleaning staff (*n* = 22)
Age, years, median (range)	43 (23–70)	47 (23–70)	42 (28–58)
Tenure, years, median (range)	6.4 (0.1–28.8)	5.9 (0.1–28.8)	12 (0.3–21.7)
Male, *n* (%)	15 (22)	11 (24)	4 (18)
Race, *n* (%)			
Hispanic	42 (63)	32 (71)	10 (45)
White	13 (19)	6 (13)	7 (32)
Asian	6 (9)	4 (9)	2 (9)
Unknown[a]	4 (6)	2 (4)	2 (9)
Black	2 (3)	1 (2)	1 (5)
Smoking status, *n* (%)			
Current	5 (7)	4 (9)	1 (5)
Former	9 (13)	6 (13)	3 (14)
Never	53 (79)	35 (78)	18 (82)

Note: Non-cleaning staff = Case manager, staff nurses, registered nurses, respiratory technicians, unit secretaries, clerks, radiology technicians, radiology assistants, pharmacists.

[a]Includes participants who did not indicate a race.

breath, were significantly associated with exposure to HP, OM, and TM, in logistic models adjusting for all covariates (Figure 1, Supporting Information: Table 3). Acute work-related chest tightness and skin symptom results are not reported in Figure 1 and Supporting Information: Table 3 because the logistic regression model could not reliably estimate odds ratios and confidence intervals for these health outcomes due to too few survey participants reporting these symptoms during their shift. Odds ratios for all model covariates (age, gender, smoking status, allergic status, sensitizer and irritant exposure index, and total stress) can be seen in Supporting Information: Table 4

3.4 | Work-related symptoms in the previous 4 weeks and average and P95 departmental exposure to HP, PAA, AA, OM, and TM

Work-related mucous membrane irritation symptoms (nasal and eye irritation) and wheeze in the previous 4 weeks were significantly associated with AM departmental exposure to OM, and TM, in logistic models adjusting for all covariates listed above (Figure 2,

TABLE 4 Symptoms, self-reported diagnoses, and total stress reported by all post-shift survey participants.

Health outcome	Overall symptoms, *n* (%)	Work-related[a], *n* (%)
Symptoms during shift (*n* = 77)		
Nasal irritation	30 (39)	25 (32)
Eye irritation	33 (43)	31 (40)
Sneeze	18 (23)	14 (18)
Throat irritation	26 (34)	21 (27)
Cough	15 (19)	10 (13)
Wheeze or whistling in the chest	10 (13)	8 (10)
Chest tightness	6 (8)	4 (5)
Shortness of breath	16 (21)	16 (21)
Difficulty breathing	5 (6)	5 (6)
Lower airway symptoms[b] (cough, wheeze, chest tightness, shortness of breath, or difficulty breathing)	31 (40)	28 (36)
Skin symptoms	6 (8)	4 (5)
Symptoms in previous 4 weeks (*n* = 67)		
Nasal irritation	39 (58)	30 (45)
Eye irritation	43 (64)	30 (45)
Sneeze	37 (55)	24 (36)
Throat irritation	34 (51)	24 (36)
Cough	23 (34)	17 (25)
Wheeze or whistling in the chest	21 (31)	15 (22)
Chest tightness	14 (21)	10 (15)
Shortness of breath	22 (33)	17 (25)
Difficulty breathing	16 (24)	11 (16)
Lower airway symptoms[b]	35 (52)	29 (43)
(cough, wheeze, chest tightness, shortness of breath, or difficulty breathing)		
Skin symptoms	17 (25)	15 (22)
Diagnoses (*n* = 67)		
Asthma		
Ever	9 (13)	
Current	5 (7)	
Nasal or sinus allergies	20 (30)	
Eczema or any kind of skin allergy	7 (11)	
Chronic bronchitis	6 (9)	
Emphysema	0 (0)	

TABLE 4 (Continued)

Health outcome	Overall symptoms, *n* (%)	Work-related[a], *n* (%)
COPD	0 (0)	
Total stress	5.0[c]	

Abbreviation: COPD, chronic obstructive pulmonary disease.

[a]Work-related acute, cross-shift symptoms defined as symptoms that occurred during the participants' shift that were not present upon arrival at work that day. Work-related symptoms in the previous 4 weeks were defined as symptoms that improved away from the facility, either on days off or on vacation.

[b]Lower airway symptoms include any of the lower airway symptoms (cough, wheeze, chest tightness, shortness of breath, or difficulty breathing).

[c]Total stress is reported as the average for all participants, on a scale of 0–10.

Supporting Information: Table 4). Additionally, work-related nasal irritation, eye irritation, wheeze, and chest tightness in the previous 4 weeks were significantly associated with increases on average departmental exposure to PAA, indicating an increase in symptoms with increasing exposure to PAA, one of the constituents in the sporicidal product (Figure 2, Supporting Information: Table 5). Work-related eye irritation and wheeze in the previous 4 weeks were also associated with average departmental exposure to HP. Associations between exposure to HP, PAA, OM, or TM and shortness of breath in the previous 4 weeks approached significance (Supporting Information: Table 5). Odds ratios for all model covariates (age, gender, smoking status, allergic status, sensitizer and irritant exposure index, and total stress) can be seen in Supporting Information: Table 6.

Similarly, work-related mucous membrane irritation (nasal and eye irritation) and wheeze in the previous 4 weeks, were also significantly associated with average departmental P95 exposure to the OM or TM in logistic models adjusted for all covariates listed above (Figure 3, Supporting Information: Table 7). An increase in symptoms was also observed with increasing P95 exposures to HP and PAA (Figure 3, Supporting Information: Table 7). Work-related nasal irritation, sneeze, eye irritation, and chest tightness in the previous 4 weeks were also significantly associated with increases in P95 departmental exposure to PAA and work-related eye irritation, wheeze, and shortness of breath in the previous 4 weeks were also associated with P95 departmental exposure to HP. Odds ratios for all model covariates (age, gender, smoking status, allergic status, sensitizer and irritant exposure index, and total stress) can be seen in Supporting Information: Table 8.

4 | DISCUSSION

Few studies have assessed occupational exposure to HP, PAA, and AA and health outcomes among workers in a healthcare setting.[27,28] In this study, and in a previous study at another multispecialty hospital, we observed health effects among hospital staff at exposure levels below established occupational exposure limits.[28] Exposures to HP (<3–559 ppb HP), PAA (<0.2–28 ppb PAA), and AA (<5–915 ppb AA) were similar to exposures measured in a previous study at another hospital where Product A was also used widely throughout the hospital, with exposures in the previous study measuring from <11 to 511 ppb HP, <2.2 to 48 ppb PAA, and <8.8 to 319 ppb AA. Both HP and PAA are strong oxidants, and the mixture of these strong oxidants potentially contributed to eye, upper airway, and lower airway symptoms reported by cleaning staff at relatively low levels of measured exposures.

In our current study, hospital staff using the product containing HP, PAA, and AA, or working in areas where the product containing HP, PAA, and AA was used, reported work-related upper and lower airway symptoms occurring during their shift and in the previous 4 weeks. Work-related eye irritation, nasal irritation, and wheeze during the shift or in the previous 4 weeks, as well as acute work-related shortness of breath was associated with exposure to the OM, or TM mixture of vapors from Product A. Similarly, increasing departmental P95 exposures, a surrogate for peak exposures, for the OM and TM were associated with significant increases in nasal irritation, eye irritation, and wheeze. Increasing departmental P95 exposures to HP and PAA were also associated with significant increases in nasal irritation (P95 PAA), sneeze (P95 PAA), eye irritation (P95 HP and P95 PAA), wheeze (P95 HP), chest tightness (P95 PAA), and shortness of breath (P95 HP). Our results demonstrate that exposure to vapors from the sporicidal product containing HP, PAA, and AA contributed to acute work-related eye, upper airway, and lower airway symptoms as well as work-related eye, upper airway, and lower airway symptoms in the previous 4 weeks in hospital staff.

Overall, nasal and eye irritation were the most commonly reported work-related symptoms among hospital staff in the present study. Occupational upper respiratory disease such as allergic rhinitis (hay fever, nasal allergies) and sinusitis is often more prevalent than occupational asthma.[38] Further, several studies indicate that rhinosinusitis might precede or occur with lower respiratory symptoms and asthma.[38–42] Additionally, the common airway hypothesis suggests that occupational upper airway disease indicates a risk for lower airway involvement, and upper respiratory involvement such as rhinitis or sinusitis can result in suboptimal control of asthma.[43–46] Despite associations between occupational rhinosinusitis and occupational asthma, occupational upper airway disease is often not considered serious.[46] In the present study, almost three-quarters of (74%) participants who reported acute work-related lower respiratory symptoms also reported acute work-related nasal symptoms and three-quarters (76%) of participants who reported work-related lower respiratory symptoms in the previous 4 weeks also reported work-related nasal symptoms in the previous 4 weeks, indicating an overlap between work-related nasal symptoms and work-related lower respiratory symptoms.

Our observation of significant associations between acute work-related eye irritation, nasal irritation, wheeze, and shortness

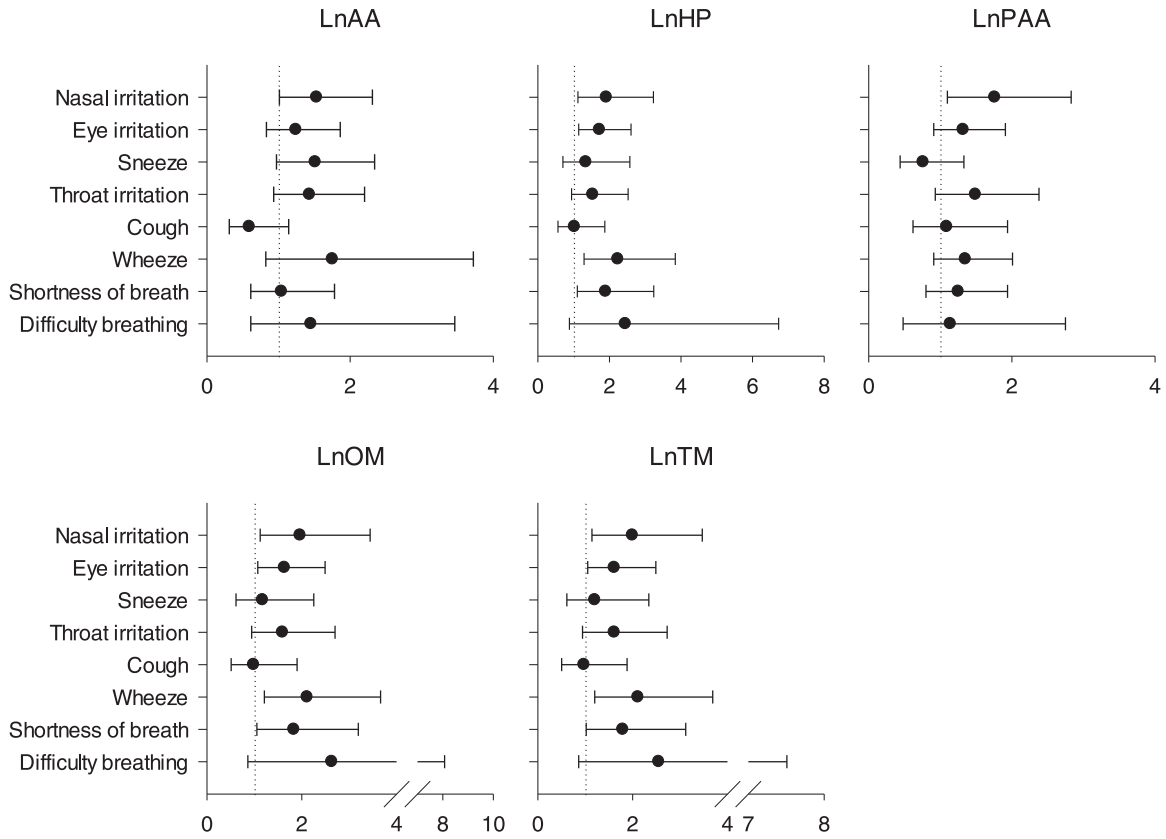

FIGURE 1 Adjusted odds ratios and 95% confidence intervals for acute work-related eye, upper airway, and lower airway symptoms reported as occurring during hospital employees' shift per increase in exposure to LnAA, LnHP, LnPAA, LnOM, and LnTM. Ln indicates natural log-transformed measurements of AA, HP, PAA, OM, and TM respectively. OM indicates the mixture of HP and PAA using the ACGIH mixture formula. TM indicates the mixture of HP, PAA, and AA using the ACGIH mixture formula. AA, acetic acid; HP, hydrogen peroxide; OM, oxidant mixture; PAA, peracetic acid; TM, total mixture.

of breath and exposure to the OM and TM is similar to results in our previous study of hospital cleaning staff using the same sporicidal product at another hospital[28]; however, in that study we were unable to fully explore associations between exposures and cross-shift lower airway symptoms because the sample size and number of workers reporting acute cross-shift lower airway symptoms was too small to reliably calculate prevalence ratios for lower airway symptoms. We were able to assess chronic (usual or previous 12 months) symptoms however, and we observed significant associations between chronic shortness of breath on level ground and increases in exposure to the OM and TM, similar to our observation in this study of increases in acute work-related shortness of breath and exposure to the OM and TM. We also observed in this study that increases in chronic (previous 4 weeks) wheeze and chest tightness with increasing exposure to HP, PAA, OM, or the TM, which we did not observe in our previous study; however, previously we observed associations that approached significance for wheeze in the previous 12 months and increases in HP exposure. The larger sample size in the current study may have contributed to our ability to detect additional significant positive associations between exposures to vapors from the sporicidal product and lower airway symptoms.

Significant increases in nasal irritation, wheeze, chest tightness, and shortness of breath symptoms reported by hospital staff in our study are consistent with previous studies that have reported an increased risk for work-related rhinitis and asthma in workers exposed to cleaning and disinfectant chemicals.[8,10,47,48] Additionally, several case studies have reported occupational asthma caused by exposure to the mixture of HP and PAA and the Association of Occupational and Environmental Clinics (AOEC) listed this sporicidal product as an asthmagen in 2015.[23,24,49] Although the prevalence of current asthma in this study (7%) is lower than prevalence reported in other healthcare studies, we did observe significant associations between increasing exposure to vapors from the sporicidal product and acute work-related wheeze and shortness of breath, as well as chronic (previous 4 weeks) work-related wheeze, chest tightness, and shortness of breath.

Due to sampling limitations, we were unable to directly assess short-duration or peak exposures. However, we were able to utilize the departmental P95 as a surrogate for increased exposure intensity. The departmental P95 was used as a surrogate for exposure intensity because it captures exposure variability and short-duration high intensity exposures will contribute to higher full-shift exposures and greater variability. Similar significant associations were observed

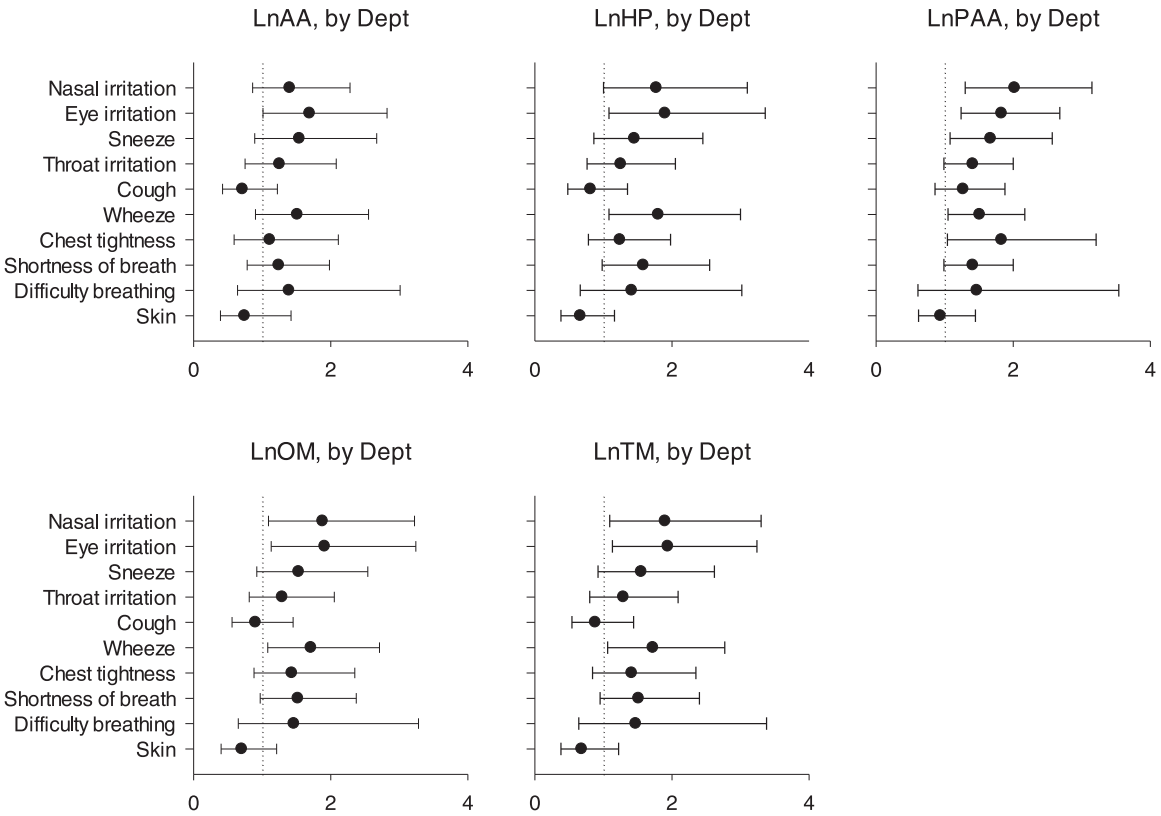

FIGURE 2 Adjusted odds ratios and 95% confidence intervals for work-related eye, upper airway, lower airway, and skin symptoms reported by hospital employees as occurring in the previous 4 weeks per increase in departmental AM exposure to LnAA, LnHP, LnPAA, LnOM, and LnTM. Ln indicates natural log-transformed measurements of AA, HP, PAA, OM, and TM respectively. OM indicates the mixture of HP and PAA using the ACGIH mixture formula. TM indicates the mixture of HP, PAA, and AA using the ACGIH mixture formula. AA, acetic acid; HP, hydrogen peroxide; OM, oxidant mixture; PAA, peracetic acid; TM, total mixture.

between departmental average and P95 exposures and symptoms in the previous 4 weeks, however odds ratios for upper and lower airway symptoms were larger with departmental P95 PAA exposure compared with departmental AM PAA exposure, suggesting that greater intensity in PAA exposures contributed to higher ORs for airway symptoms. Additionally, departmental P95 HP exposure was associated with significant increases in shortness of breath in the previous 4 weeks while departmental average HP exposure was not, suggesting that greater intensity in HP exposures contributed to shortness of breath in the previous 4 weeks. Our observation of significant associations between P95 exposures and upper and lower airway symptoms indicate a need to mitigate exposure intensity to the oxidant vapors (HP and PAA) in the sporicidal product.

The CDC's Guideline for Disinfection and Sterilization in Healthcare Facilities acknowledges that irritant and allergic effects can occur with disinfectant chemical air concentrations at levels below OSHA or NIOSH exposure limits.[50] The Healthcare Infection Control Practices Advisory Committee (HICPAC) recommends that controls be used to minimize exposure to disinfectants, including elimination or substitution of the chemical, engineering or administrative controls, or the use of PPE.[50] We observed some cleaning staff using surgical masks or N95 respirators for the purpose of respiratory protection while dispensing or working with cleaning products; however, these types of masks are not appropriate respiratory protection while working with products that release gases or chemical vapors. As described previously, substitution with a low-level disinfectant for routine cleaning of surfaces in nonpatient areas is one option for reducing exposures; however, this might not be possible for surfaces in areas with isolation precautions in place and substitution with another low-level disinfectant containing phenolic, iodophors, alcohols, or chlorine compounds can also potentially cause upper airway irritation and asthma in exposed workers.[28] As Dumas et al. highlight in their recent study of COPD among US nurses exposed to disinfectants, additional studies are needed to investigate potential safer alternatives such as non-chemical means of disinfection such as steam or ultraviolet light.[15] Where substitution with less hazardous cleaning products or nonchemical alternatives is not possible, engineering, administrative, and appropriate PPE controls can be used to mitigate exposure to HP, PAA, and AA.

Recent studies indicate the irritant characteristics of many chemicals found in cleaning and disinfection products can potentially contribute to a range of respiratory effects, including lower airway disease.[15] Studies in the last decade have reported an increased risk of COPD, accelerated lung function decline, and higher rates of COPD deaths among cleaning workers.[51–53] Additionally, occupational

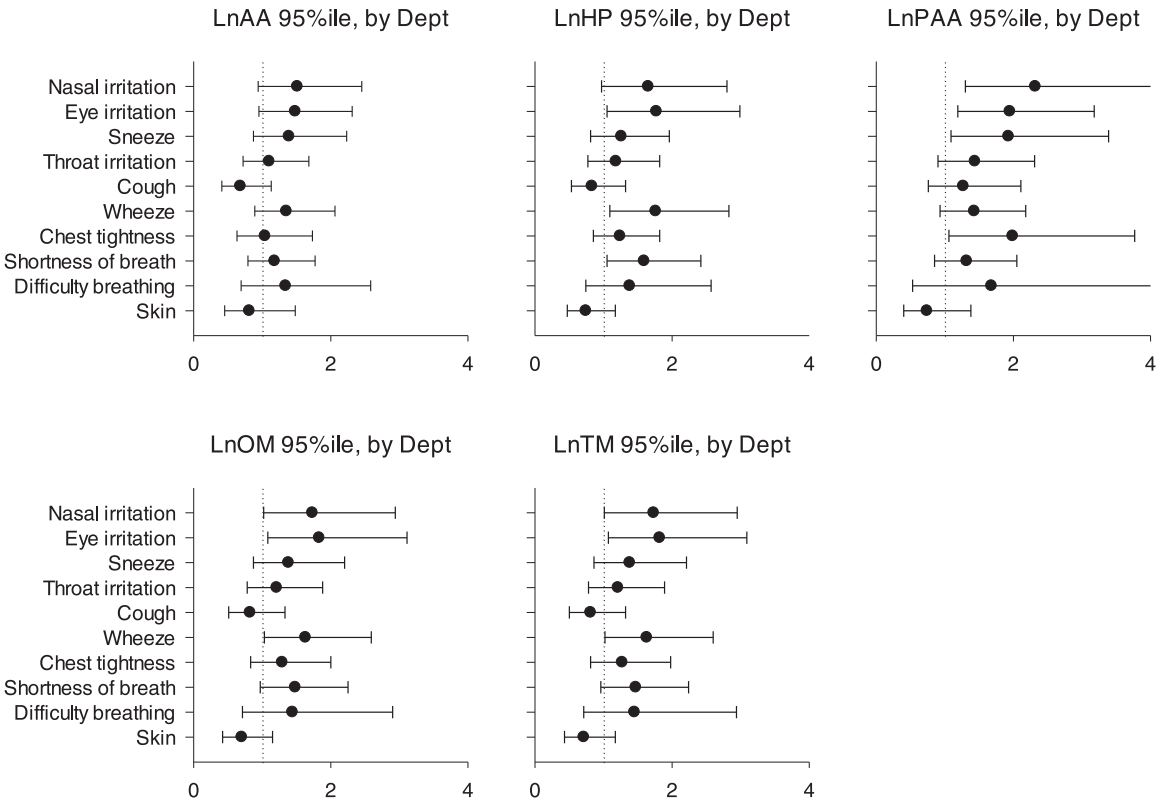

FIGURE 3 Adjusted odds ratios and 95% confidence intervals for work-related eye, upper airway, lower airway, and skin symptoms reported by hospital employees as occurring in the previous 4 weeks per increase in departmental 95th percentile exposure to LnAA, LnHP, LnPAA, LnOM, and LnTM. Ln indicates natural log-transformed measurements of AA, HP, PAA, OM, and TM, respectively. OM indicates the mixture of HP and PAA using the ACGIH mixture formula. TM indicates the mixture of HP, PAA, and AA using the ACGIH mixture formula. AA, acetic acid; HP, hydrogen peroxide; OM, oxidant mixture; PAA, peracetic acid; TM, total mixture.

exposure to cleaning products and disinfectants was recently associated with an increased risk for developing COPD.[15] Our health survey was cross-sectional and limited to reported symptoms. Although in our study only five workers (7%) reported current asthma and only six workers (9%) reported chronic bronchitis (a form of COPD), significant associations were observed between exposure to vapors from the sporicidal product and lower airway symptoms commonly observed in asthma or COPD including shortness of breath, wheeze, and chest tightness.[54] However, our study did not include diagnostic tests such as pulmonary function tests, chest radiographs, or CT scans, limiting our ability to characterize respiratory function among the exposed workers.

Our study, although larger than our previous study of hospital cleaning staff using the same sporicidal product, was small and this could have limited our ability to detect additional significant associations among reported symptoms and exposures to HP, PAA, AA, the OM, and TM. Another limitation of our study is that we only collected full-shift TWA samples for the three chemical constituents, HP, PAA, and AA, found in Product A. Sampling and analytical limitations inhibited our ability to assess short-term exposures and compare short-term exposures with short-term exposure limits established by the ACGIH. Additionally, practical considerations limit the number of samplers a participant can wear during sampling; thus, personal samples were limited to samplers collecting samples for HP, PAA, and AA. However, we were able to record hospital staff's use of other products containing sensitizers and irritants and observed that use of products containing sensitizers and irritants during a worker's shift was significantly associated with acute work-related nasal irritation, sneeze, and difficulty breathing. Additionally, use of products containing sensitizers and irritants in the previous 4 weeks was significantly associated with difficulty breathing in the previous 4 weeks. We adjusted for use of products containing sensitizers and irritants during a worker's shift or in the previous 4 weeks in our models that assessed associations between work-related symptoms and exposure to HP, PAA, AA, the OM, or TM. Another limitation of our study was that PPE use was not systematically measured. Thus, we were unable to assess whether voluntary use of goggles, surgical masks, or N95 respirators affected acute or chronic work-related symptom prevalence. An additional limitation is that sampling and analytical limitations hindered our ability to assess short-term exposures and compare short-term exposures with the established short-term exposure limits established by the ACGIH. Additionally, there was no validated method for full-shift sampling and analysis of PAA at the time of our survey. The sampling method we used to collect HP and PAA utilizes a sampling train that simultaneously collects HP and PAA.[29] We described the limitations of this sampling

method previously.[28] Briefly, previous studies have indicated the potential for small amounts of PAA (3%) to be collected on the quartz filter used for collection and analysis of HP.[55] However, Christensen et al. acknowledge that this effect was minimized when the flow rate is maintained at 1 L/min, which is the flow rate used for our sampling. Small amounts of PAA could potentially have been misclassified as HP on the quartz filter. Thus, some of the associations we observed between exposure to HP and eye and airway symptoms could have been affected by a small misclassification of PAA as HP. Regardless, we attempted to address this potential limitation by summing values of relative HP and PAA concentrations to generate the OM and TM exposure variables used for all analyses.

Although our current and previous studies of occupational exposure to HP, PAA, and AA were limited to healthcare settings, the mixture of HP, PAA, and AA has broad application in other occupational settings outside of healthcare, including food production, agricultural, childcare, and food service industries. Additional studies are needed to 1) develop an improved sampling method for simultaneous HP and PAA collection and analysis, especially in settings where concentrations are anticipated to be relatively low and feasibility of short-term sampling is constrained by detection limits, and 2) characterize the potential eye and respiratory health effects from both acute and chronic occupational exposure to HP, PAA, and AA, across a wide range of potential exposures and occupational settings. Additionally, further study of alternative disinfection technologies is needed to identify potentially safer nonchemical technologies that can be used for infection control in healthcare settings.

5 | CONCLUSIONS

Hospital workers exposed to HP, PAA, and AA reported acute work-related eye, upper airway, and lower airway symptoms at low levels of measured exposure. Increased exposure to the mixture of the two oxidants, HP and PAA, as well as the TM of HP, PAA, and AA, were significantly associated with increases in work-related acute and chronic eye and nasal irritation, wheeze, and shortness of breath. Additionally, increased departmental P95 exposures to vapors from the sporicidal product were associated with eye and nasal irritation, sneeze, wheeze, chest tightness, and shortness of breath. Further, associations between P95 exposures and upper and lower airway symptoms indicate a need to measure short-term exposures potentially contributing to elevated P95 exposures to inform more targeted exposure mitigation efforts. Our observations of work-related upper and lower airway symptoms among hospital workers exposed to vapors from a sporicidal product containing HP, PAA, and AA indicate a need for a combination of engineering, administrative, and PPE controls to reduce exposure. Additional studies are needed to investigate potentially safer nonchemical disinfection technologies as a means to simultaneously reduce healthcare workers' exposure to disinfectants while also meeting the goal of infection control and minimizing costly HAIs.

AUTHOR CONTRIBUTIONS

Brie Hawley Blackley, Randall J. Nett, Jean Cox-Ganser, and Mohammed Abbas Virji participated in the design of the work. Brie Hawley Blackley, Randall J. Nett, and R. Reid Harvey participated in the acquisition of data for the work. Brie Hawley Blackley, Jean Cox-Ganser, and Mohammed Abbas Virji participated in the analysis and interpretation of data for the work. All authors assisted in drafting the work or revising it critically for important intellectual content and agree to be accountable for all aspects of the work in ensuring that questions related to accuracy or integrity of any part of the work are appropriately investigated and resolved.

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CONFLICTS OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DISCLOSURE BY AJIM EDITOR OF RECORD

John Meyer declares that he has no conflict of interest in the review and publication decision regarding this article.

ETHICS APPROVAL AND INFORMED CONSENT

The work was performed at the National Institute for Occupational Safety and Health as part of the Health Hazard Evaluation Program and was determined not to be human subjects research but public health practice, and thus was not subject to NIOSH IRB review. Participation was voluntary. Workers gave informed consent before participating in the air sampling and post-shift surveys. Demographic information was collected in the post-shift survey.

DISCLAIMER

The findings and conclusions in this report 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 the US Government, National Institute for Occupational Safety and Health, or Centers for Disease Control and Prevention.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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