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Analysis of Residual Chemicals on Filtering Facepiece Respirators After Decontamination

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The N95 filtering facepiece respirator (FFR) is commonly used to protect individuals from infectious aerosols. Health care experts predict a shortage of N95 FFRs if a severe pandemic occurs, and an option that has been suggested for mitigating such an FFR shortage is to decontaminate and reuse the devices. Before the effectiveness of this strategy can be established, many parameters affecting respiratory protection must be measured: biocidal efficacy of the decontamination treatment, filtration performance, pressure drop, fit, and toxicity to the end user post treatment. This research effort measured the amount of residual chemicals created or deposited on six models of FFRs following treatment by each of 7 simple decontamination technologies. Measured amounts of decontaminants retained by the FFRs treated with chemical disinfectants were small enough that exposure to wearers will be below the permissible exposure limit (PEL). Toxic by-products were also evaluated, and two suspected toxins were detected after ethylene oxide treatment of FFR rubber straps. The results provide encouragement to efforts promoting the evolution of effective strategies for decontamination and reuse of FFRs.

Keywords decontamination, disinfection, influenza, N95, residual, respirator

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INTRODUCTION

Pandemic influenza outbreaks historically occur every 40 to 50 years and have been responsible for millions of deaths worldwide. The Hong Kong Flu of 1968 had been the most recent pandemic until the H1N1 pandemic was realized in the spring of 2009 with the appearance of the swine flu (H1N1).[1,2] On June 11, 2009, the World Health Organization (WHO) raised the pandemic alert level to 6, which indicated the onset of a pandemic. As of June 8, 2009, WHO reported almost 30,000 confirmed cases of H1N1 and 145 deaths worldwide.[3] More than 13,000 cases and 27 deaths were reported in the United States alone.[3] WHO's December 2009 update[4] reported H1N1 infections in more than 209 countries and attributed over 12,220 deaths to H1N1 infections. Although this outbreak did not have the virulence of earlier pandemics, it was sufficiently similar to previous pandemics to merit concern. It is not certain that the current H1N1 strain will mutate into a more virulent form, but health care workers are taking the possibility very seriously.

A primary barrier used to protect health care workers and the general public from airborne infections is the National Institute for Occupational Safety and Health (NIOSH)-approved filtering facepiece respirator (FFR). (Note that although many types of FFRs are available, this report focuses on six models of N95 FFRs. All references to FFRs in this manuscript specify N95 FFRs). The FFR is rated to capture $\geq$95% of airborne 300-nm particles and has been proven to remove infectious microorganisms from the airstream.[5–10]

The modes for human-to-human transmission of influenza are actively debated,[11–16] but data have been reported that support aerosol transmission.[11,15] This information led the Occupational Safety and Health Administration (OSHA) and the Centers for Disease Control and Prevention (CDC) to recommend that workers wear a properly fitted NIOSH-approved FFR during a pandemic influenza outbreak.[17,18] The Food and Drug Administration (FDA) also demonstrated their support of FFRs by issuing an Emergency Use Authorization (EUA), which approves release of FFRs from the Strategic National Stockpile (SNS) for use by the general public.[19]

The CDC estimated that during a pandemic lasting 42 days, more than 90 million FFRs would be required for health care workers alone.[20] These projections indicate that a shortage of FFRs is likely to occur, which would leave health care workers exposed and might aggravate the severity of the pandemic. A possible solution for alleviating an FFR shortage is to decontaminate and reuse the FFRs,[20] and Cal/OSHA has set a relevant precedent by issuing guidelines for extended use and re-donning as conservation measures recommended by the California Department of Public Health.[21]

FFRs are labeled as "single-use" devices and have not been approved for reuse. Consequently, very few data are available that describe how FFRs behave following treatment with decontamination agents. Many properties must be studied before FFR decontamination and reuse would be allowed: filtration efficiency, pressure drop, fit, residual chemicals, and overall durability are key questions that must be addressed. NIOSH has reported initial studies that suggest that some technologies can be used to decontaminate FFRs without affecting performance.[22] However, other technologies tested—for example, autoclaving—rendered the FFRs unusable.[22] These tests were performed on a limited number of FFR models, and more research is needed on a larger number of FFRs to properly evaluate decontamination technologies.

The Air Force Research Laboratory (AFRL) is currently leading an effort that examines the effects of several decontamination technologies on six commonly distributed models of FFRs from the SNS (Table I). The six models represent both common particulate FFRs and those cleared by the FDA as medical devices. The focus of this article is the presence of residual chemicals following decontamination; the other performance parameters will be the topic of future reports.

Decontamination technologies selected for this study comprise energetic, gaseous, and liquid agents (Table II). The gaseous technologies selected were vaporized hydrogen peroxide (VHP) and ethylene oxide (EO) sterilizers. The achievable throughput using these technologies is questionable, but since many hospitals already utilize these devices for low-heat sterilization, they were logical choices for evaluation in this study. Both VHP and EO sterilizers are relatively expensive technologies; however, organizations that own these devices would experience only a small burden of added operational costs.

The energetic device selected for the study was ultraviolet (UV) light. UV devices for surface sterilization are commercially available (Ultra Violet Products, Upland, Calif.); however, distribution of these devices in hospitals and other clinical/first-responder organizations is unknown. The commercially available aqueous (aq) solutions selected for the study were bleach (diluted to 0.6% hypochlorite) and 3% hydrogen peroxide. Mixed oxidants and dimethyldioxirane (DMDO) were both developed as part of Department of Defense (DoD) projects and represent emerging technologies that are not widely distributed.[23,24] They were included in this study in case both bleach and peroxide performed unsatisfactorily. The technologies of primary concern as possible sources of toxic chemical residues are the liquid and gaseous decontamination agents. FFRs exposed to ultraviolet (UV) irradiation (at both 254 nm and 302 nm) were tested for possible byproducts from UV-initiated radical reactions.

TABLE I. Filtering Facepiece Respirators Selected for Decontamination Study

Model Number	Class	Shape
S1	NIOSH- and	Cup-shaped
S2	FDA-approved N95	Flat-fold
S3	Surgical FFR	Duck-bill
P1	NIOSH-approved N95 Particulate FFR	Cup-shaped
P2		Cup-shaped
P3		Cup-shaped

TABLE II. Disinfection Technologies

Gaseous	Ethylene oxide
	Vaporized hydrogen peroxide
Energetic	Ultraviolet light (254 and 302 nm, $\sim 2.7X10^5$ J/m^2)
Liquid	Hydrogen peroxide (3%)
	Sodium hypochlorite (0.6%)
	Mixed oxidants (10% Oxone, 6%, sodium chloride, 5% sodium bicarbonate)
	Dimethyl dioxirane (10% Oxone, 10% acetone, 5% sodium bicarbonate)

MATERIALS AND METHODS

Selection of Analytical Methods

Analytical methods used to measure residual chemicals (Table III) were selected to match the physical properties of each analyte. For volatile contaminants, headspace solid-phase microextraction (HSSPME) analysis using gas chromatography-mass spectrometry (GC-MS) is the method of choice, as this detects vapors emitted from the FFR and those vapors are expected to be respirable. EO was analyzed by GC-MS using guidance provided in ISO 10993-7, an international standard for the biological evaluation of medical devices.[25] FFRs treated with a chemical disinfectant or with UV light were extracted with pentane, which was then analyzed by GC-MS to look for organic hazards that were created during the decontamination process.

However, several disinfectants—hydrogen peroxide agents (VHP and 3% liquid), hypochlorite, and DMDO—in this study are reactive and thus incompatible with separation by GC. Also, inorganic decontaminants used in this study do not readily evaporate. The active species for bleach is a hypochlorite salt that will not elute from—and in practice will destroy—a GC column, and that can react with chloride to liberate chlorine as Cl_2 (g). In the mixed oxidant (6% sodium bicarbonate, 5% sodium chloride, and 10% potassium peroxymonosulfate (Oxone) in water), the initial oxidative capacity is provided by the nonvolatile, reactive Oxone, but the persulfate mainly oxidizes sodium chloride to form hypochlorite. Both oxidizers are salts and thus incompatible

TABLE III. Analytical Methods for Quantifying Decontamination Agents on FFRs

Decontamination Agent	Concentration	Analysis Method
Untreated	N/A	Iodometric back-titration, GC-MS HSSPME, pentane extraction
Hydrogen peroxide	3%	Iodometric back-titration, pentane extraction
Sodium hypochlorite	0.6%	Iodometric back-titration, pentane extraction
Mixed oxidants	10% Oxone, 6% sodium chloride, 5% sodium bicarbonate	Iodometric back-titration, pentane extraction
Dimethyldioxirane	10% Oxone, 10% acetone, 5% sodium bicarbonate	Iodometric back-titration, pentane extraction
Ethylene oxide	Amsco Eagle 3017	GC-MS HSSPME, pentane extraction
Vaporized hydrogen peroxide	Sterrad 100S System	Iodometric back-titration, pentane extraction
Ultraviolet light (254 and 302 nm)	$\sim 2.7 \times 10^5 J/m^2$	Pentane extraction

with GC-MS methods. Residual quantities of reactive chemicals left on the FFR by these technologies were extracted into water and measured as oxidizing equivalents by addition of a standard quantity of sodium thiosulfate and iodometric back titration (IBT) of the unreacted thiosulfate. IBT is a standard technique for quantifying oxidative capacity[26–28] and was used without modification.

Liquid Decontaminants

Three FFRs of each model were submerged in liquid decontamination agents (Table II) in a chemical fume hood for 30 min at room temperature. A volume of 200 mL of decontaminant per FFR was used. After a 30-min soak, the FFRs were removed from the solutions, placed on trays, and allowed to off-gas for 18 hr in a chemical fume hood.

Following the off-gassing period, 10 14-mm-diameter samples were punched from areas equally spaced on each respirator and separately weighed in 20-mL glass scintillation vials. In addition, the straps, nose cushions, and metal nosepieces were cut into ~12-mm pieces and separately weighed in scintillation vials. IBTs were conducted as previously described.[26–28] Three additional 14-mm samples were removed from each FFR and extracted with 10 mL of *n*-pentane (HPLC grade, Fisher Scientific, Pittsburgh, Pa.) for 3 hr. Extracts were analyzed in a Thermo–Finnigan Trace GC (Thermo Scientific, Waltham, Mass.) with a Programmed Temperature Vaporization (PTV) injector in splitless mode and fitted with a 30-m × 0.32-mm × 0.25-μm DB-5 column. The GC was interfaced to a Trace DSQ MS with a Leap Technologies CTC CombiPAL autosampler (Carrboro, N.C.).

For the analysis, 2-mL aliquots were added to standard GC vials and loaded on the autosampler. The helium flow rate was 1.5 mL/min, the ion source was heated to 225°C, and the column temperature was held at 40°C for 4 min, then ramped to 270°C at 20°C/min and held for 2 min before cooling to 40°C to prepare for the next injection. MS scans were taken from mass-to-charge ratio (m/z) 30.0–300.0 at five scans per second and a scan rate of 1807 (m/z)/s.

Gaseous Decontaminants

Triplicate FFRs of each model were exposed to EO in an Amsco Eagle 3017 EO sterilizer (Steris Corp., Mentor, Ohio) according to supplier directions, for 3 hr at 54°C, followed by a 12-hr aeration cycle at 54°C. FFRs were packaged individually in sterilization pouches that contained sterilization indicator strips, which verified that the sterilizer performed adequately. Following the aeration period, each respirator was dismantled and the respiratory components were weighed. Ten 14-mm-diameter samples were punched from areas equally spaced on each respirator, placed in separate Supelco (Sigma-Aldrich, St. Louis, Mo.) 20-mL headspace vials and weighed. Straps, nose cushions, and metal nosepieces were cut into ~12-mm pieces and weighed in individual headspace vials. GC-MS analysis for EO used guidance from the ISO standard AAMI/ANSI/ISO 10993–7.[25]

Samples for GC-MS analyses were collected by HSSPME onto a Supelco 65-μm bonded phase polymethylsiloxane-divinylbenzene fiber that was exposed to the headspace for 240 s and inserted into a PTV injector for a desorption time of 900 s. The PTV injector was set to a base temperature of 250°C, and the MS operated in scan mode from m/z 20.0–120.0 at five scans/sec; other GC and MS conditions were as described for liquid decontaminants. Pentane extracts were also prepared and analyzed as described for liquid decontaminants.

Triplicate FFRs of each model, packaged individually in sterilization pouches that contained sterilization indicator strips, were exposed to VHP for 55 min at 45–55°C in a STERRAD 100S system (Advanced Sterilization Products, Irvine, Calif.) according to supplier directions. Following the sterilization cycle, 14-mm-diameter samples were punched from areas equally spaced on each respirator and weighed in a 20-mL scintillation vial. In addition, the straps, nose cushions, and metal nosepieces were cut into ~12-mm pieces and separately weighed in vials. Samples were analyzed by IBT, and pentane extracts were analyzed by GC-MS as described in the liquid decontaminants section.

Energetic Decontaminants

Triplicate 38-mm-diameter circles were cut from each FFR model. A multi-wavelength, 8-watt lamp (Ultra Violet Products) was used to expose triplicate samples of each FFR model to UV light. Samples were placed 1 inch from the lamp source and were irradiated with 4.0 mW/cm^2 of UV-B (302 nm) and 3.4 mW/cm^2 UV-C (254 nm) for 1 hr each. A UV meter (Ultra Violet Products) was used to measure irradiance. After exposure, samples were weighed in 20-mL glass scintillation vials and extracted with pentane as described for liquid decontaminants.

Untreated FFRs

Residual chemicals on untreated FFRs were evaluated using the protocols described above. Triplicate samples for each model of FFR were evaluated.

DATA ANALYSIS

Iodometric Back Titration (IBT)

The data measured by this assay were initially reported in mmol of oxidant per gram of FFR (filtering material, straps, external nosepiece, or nose cushion) that was converted into mg of oxidant per gram of FFR by multiplying by the gram-molecular weight of the decontaminant applied to the FFR. This calculation cannot be performed for oxidant recovered from untreated FFRs because the chemical identity of the native oxidant(s) is unknown, so correction of the data for the background of oxidant on the FFRs was accomplished before converting into concentration units. The calculation to determine net mass of oxidant per FFR is described in Eq. 1. The IBT assay can produce negative numbers that have no physical significance and were treated as below detection limit for the analysis. Prism-5 software (GraphPad, La Jolla, Calif.) was used to calculate 95% confidence intervals.

$$\text{mg of oxidant per FFR} = G * \sum[(T_i - U_i) * W_i] \qquad \textbf{(1)}$$

T_i = Treated mmol of oxidant per gram of component i (FFR respirator material, strap, nose cushion, metal nosepiece)
U_i = Untreated mmol of oxidant per gram of component i
W_i = Weight of FFR component i in grams
G = Gram-molecular weight of the decontaminant

Ethylene Oxide HSSPME Data Analysis

The ISO standard method for biological evaluation of medical devices that injects headspace gas directly into the GC and quantifies by external calibration[25] was modified for this analysis. FFRs treated with EO were analyzed by HSSPME GC-MS as described above. Chromatographic analysis was carried out by manual recognition of symmetrical peaks measured at a signal-to-noise ratio (S/N) of ~3:1 or greater. This sensitivity limit was chosen as a threshold for reliable detection and identification of residual oxidants and of byproducts formed by the FFR components reacting with EO. A detection limit study for EO was used to determine a reasonable threshold value for the technique.

Aqueous standards of EO purchased from Accustandard (New Haven, Conn.) were serially diluted to obtain concentrations of 10 ppm, 5 ppm, 1 ppm (PEL), 500 ppb, 50 ppb, 5 ppb, and 0.5 ppb. EO was found to elute at t_R = 5.60 min. FFR samples were analyzed over a window from 4.0–6.5 min to allow for variations in chromatography caused by byproducts from EO alkylation. The detection limit for EO by HSSPME GC-MS was 500 ppb (half of the PEL).

Analysis of GC-MS data for Pentane Extracts

GC-MS analysis of the pentane extracts produced chromatograms for each treated sample plus an untreated sample. Peaks present in the untreated sample or the normal instrument background for pentane were subtracted from the treated samples. Peaks still present were selected for investigation based on a visual comparison against the background signals of the instrument and procedural materials. Peaks measured at S/N ≥3:1 were analyzed using Xcalibur software (Thermo Scientific, Waltham, Mass.). The software identifies a peak by comparing its acquired mass spectrum with several spectral libraries contained within the software. The first match provided by the software is not always the best match for the spectrum in question. Peaks were labeled as the first match that was consistent with species present in the procedure.

RESULTS

Iodometric Back Titrations

The mass of oxidant remaining on the FFRs varied with the FFR model and decontamination technology (Table IV) applied. Similar amounts of oxidant remained after treatment with 3% hydrogen peroxide on all FFRs except S3, on which no oxidant was detected. The S1, S2, P1, and P2 models treated with VHP retained ~3 times as much oxidant as the other two models. All FFR models treated with 0.6% hypochlorite retained similar amounts of oxidant with the exception of S3, on which none was detected. P2 retained more oxidant after hypochlorite and after mixed oxidant decontamination than did the others, but the large confidence intervals for those data show them to be less reliable than corresponding values measured for the other FFRs. P3 treated with mixed oxidants also retained comparatively large quantities of oxidant. All FFR models retained ~5 times more oxidant after DMDO treatment than their counterparts treated with other disinfectants.

GC-MS Analysis of Pentane Extracts

Many unique peaks were identified in the pentane extracts (data not shown); however, most of these were found on fewer than three FFRs, which suggests that they are random events unrelated to the disinfection technologies. For the chemical disinfection agents, a total of 11 unique peaks were identified, one a ubiquitous plasticizer and the remainder attributable to solvent contamination or column background. UV irradiation

TABLE IV. Oxidant (mg) Remaining on FFRs Following Decontamination and Off-Gassing for 18 Hours

Respirators[A]	S1	S2	S3	P1	P2	P3
3% Hydrogen Peroxide						
Average	0.59	0.36	ND	0.43	0.53	0.70
Lower 95% CI	0.14	0.28	—	0.12	0.20	0.38
Upper 95% CI	1.04	0.45	—	0.74	0.87	1.02
Vaporized Hydrogen Peroxide						
Average	1.23	0.43	0.36	1.09	0.81	0.35
Lower 95% CI	0.68	0.29	−0.11	0.64	0.29	0.04
Upper 95% CI	1.77	0.57	0.83	1.53	1.34	0.66
10% Bleach						
Average	0.37	0.70	ND	0.32	1.66	0.45
Lower 95% CI	0.00	0.29	—	−0.31	−2.03	−0.64
Upper 95% CI	0.73	1.11	—	0.95	5.34	1.54
Mixed Oxidants						
Average	0.14	0.08	ND	0.25	1.72	8.10
Lower 95% CI	−0.05	−0.08	—	−1.53	−1.38	3.06
Upper 95% CI	0.32	0.24	—	2.03	4.82	13.14
DMDO						
Average	7.38	7.72	4.53	5.53	7.19	5.14
Lower 95% CI	6.87	−0.09	2.52	5.11	6.50	3.95
Upper 95% CI	7.89	15.53	6.53	5.94	7.87	6.33

Note: ND = none detected (the detection limit (0.02 mL × 0.001 *N* reductant) is ∼0.02 μeq, ∼0.7 μg).
[A]n = 3 for all samples in the table.

produced the greatest number of unique peaks; however, many of these appear to be constituents of the pentane solvent.

Ethylene Oxide HSSPME Results

The total ion chromatograms were examined in a window from 4.0–6.5 min because time to elution of EO itself gradually decreased from ∼5.6 to 5.2 min as trimming away of contaminated sections at the front of the column progressively decreased its working length. This wide time window also accommodated variations in chromatography, such as retention time shifts or peak fronting/tailing. No residual EO was detected in any of the respirators or respirator components tested. Diacetone alcohol was found in 11 samples, 2-hydroxyethyl acetate (HEA) in 15 samples, and cyclohexanone in 2 samples. All 15 occurrences of HEA were on straps, and all gave an identifiable mass spectrum. However, all were measured in trace amounts (≤3 times the S/N of the baseline), so a more sensitive measurement of concentration will be needed before the significance of these traces can be evaluated.

DISCUSSION

The presence of oxidant on the FFRs following decontamination was not surprising. The critical question, however, was the quantity of residual decontaminant or byproducts on the FFRs as possible health threats to the user. Measured quantities of residual chemicals were compared with median lethal dose and concentration, LD_{50} and LC_{50}, respectively, the level immediately dangerous to life and health (IDLH), the short-term exposure limit (STEL, 15-min time-weighted average [TWA] exposure not to be exceeded at any time during a workday), or NIOSH's recommended exposure limit (REL, TWA concentration for a workday of 10 hr or less during a 40-hr workweek).[29] Two extreme worst cases were assumed for these calculations:

(1) instantaneous volatilization of the entire residue into a single 2-L inhaled volume, or
(2) complete volatilization distributed over a 15-min period into a nominal minute volume of 25 L (375 L net volume).

Values from Assumption 1 correspond to IDLHs for approximately 10 s; the values from Assumption 2 compare directly with STELs. This analysis is conservative because for all materials tested, these calculated values far exceed realistically attainable concentrations.

The MSDS for Clorox lists the REL for sodium hypochlorite (bleach), a nonvolatile salt, as "not established."[30] Formation of hypochlorite from chlorine and sodium hydroxide is partially reversible and causes the smell of chlorine bleach. Respirator P2 retained almost 2 mg of chlorine equivalents; assuming complete reversal to chlorine gas, ∼1 g/m^3 Cl_2 is available in 2 L, and ∼5 mg/m^3 in 375 L. The IDLH for chlorine is 29 mg/m^3, but the calculated concentration would occur during only one inhalation, and much of the gas

would be dissipated when the package containing the respirator was opened. In addition, the LC_{50} for several mammalian species is a *Ct* [product of concentration multiplied by time] of >400 mg-hour/m^3,[31] and the equilibrium constant strongly disfavors formation of chlorine—that is, most of the oxidant will remain on the FFR as a salt and act only as a potential skin irritant—so actual concentrations will present no health risk. Reinforcing this conclusion, the 15-min hypothetical worst-possible concentration is only 3.5 times the REL for chlorine[32] and twice the STEL and OSHA's permissible exposure limit (PEL). The slight residual odor noted could be tolerated by all except a few highly susceptible individuals.

Because DMDO disappears quickly, the oxidizing residue for this treatment must be presumed to be unreacted Oxone. The 7-mg residue of Oxone (50% persulfate) on P3 translates to a dust concentration of 1.8 g/m^3 in 2 L, less than a reported[33] 1-hr LC_{50}, and ~5 mg/m^3 for 15 min—close to the (8-hr TWA) PEL for respirable dusts, as Oxone is classified.[34] The dust adhered through the treatment process, so one can reasonably assume that reaerosolization will be neither complete nor instantaneous into the first inspiration. The active agent in the mixed oxidants technology is hypochlorite, so the discussion of bleach (and of Oxone) applies to this decontaminant.

Both peroxide-based decontaminants (VHP and 3% hydrogen peroxide) left ~1 mg of oxidant on the respirators. VHP treatment of S1 left 1.23 mg of oxidant, which would produce ~600 mg/m^3 in the single 2-L inhalation and ~3.3 mg/m^3 in 375 L. In comparison, the IDLH (75 ppm, ~100 mg/m^3, for 4 hr)[35] is only 6 times the hypothetical 2-L concentration, and the one-breath *Ct* is 30 times less than the *Ct* of the standard. The REL and PEL[36] (both as 8-hr TWAs) are about half the 15-min upper-limit value. As peroxide is slow to evaporate, both sets of calculated concentrations are exaggerated, and we can conclude for all processes tested that residual oxidant will pose no significant health hazard in any realistic scenario.

Plotting the amount of oxidant retained by the various FFR parts on a bar chart (Figure 1) reveals a clear behavioral trend: residual oxidant concentrated in the filter media of all of the particulate FFRs but among the surgical FFRs oxidants collected in significant amount on the filtration medium of only S1. This is a significant finding as the filtering media

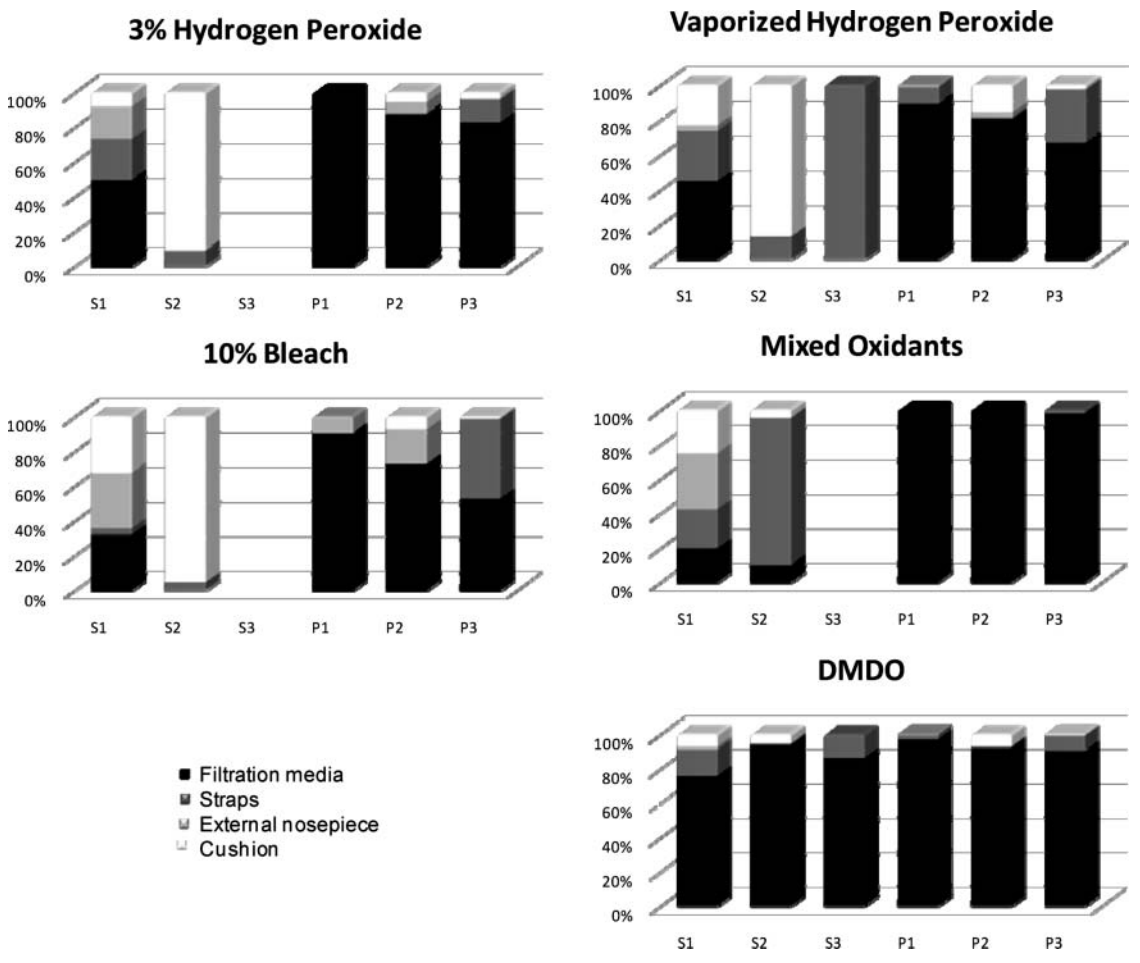

FIGURE 1. Distribution of oxidant recovered from FFR components.

comprise the largest portion of the FFR and thus pose the greatest risk of exposure to the user. Clearly, the two surgical FFRs would provide much less exposure to users than all the P FFRs and the S1 FFR.

The exception is DMDO, which was retained in quantity by all six FFRs and was the only treatment medium that included both an organic chemical and dissolved salts. That S1 accumulates oxidant on the filter medium can be explained if the hydrophobic coating applied to surgical FFRs to provide resistance to blood splatter and other body fluids occurs on the exterior surface but less or none is on the filter medium. That S3 retained very little oxidant (other than DMDO, Table IV) is likely due mainly to its simple design—it does not contain a nose cushion. The nose cushion of S2, which is considerably larger than the nose cushions on the other FFRs tested, retained a majority of the oxidants used in the traditional decontamination methods. Data for most of the mixed-oxidant decontaminant tests are noisy due to low retention of oxidant, making them difficult to interpret.

GC-MS analysis of the pentane extracts revealed many minor components (data not shown), but 20 unique peaks were identified in the spectra of at least 3 of the 18 FFRs evaluated for each decontamination method. Eleven peaks appeared following chemical disinfection, and nine were observed following UV disinfection. All appear to be species related to the solvent (*n*-pentane) and unrelated to the disinfectant. Several more are identified as siloxanes, common artifacts bled from GC columns. The GC also detected ubiquitous contaminants, including butyl phthalate and bis(2-ethylhexyl) adipate, which are used in the manufacture of polymeric materials. These were included in the results to show completeness, but it is important to note that, like the other analytes, they are presumed to be unrelated to the decontamination technologies.

Although background subtraction was performed using negative controls, some treated samples retained residual chemicals similar to those found in the controls. That these peaks were either not seen in the negative controls (untreated FFRs and pentane solvent) or not completely removed by background correction is likely because the quantities are small—many peaks appeared at or near the instrument detection limit—and minor run-to-run variations in response are a normal event. The peaks that are due to column bleed are inherently random, although they consistently increase in concentration as the oven temperature increases. As the study progressed, GC maintenance included progressively trimming several feet from the front end of the capillary column. We have tried to account for shifts in retention time caused by this procedure but might not have precisely tracked all of the peaks through the entire course of the study.

Although no EO was detected on any of the respirators, several of the models and components treated with EO contained diacetone alcohol (4-hydroxy-4-methyl-2-pentanone) and traces of a contaminant identified by the system software as 2-hydroxyethyl acetate (HEA, ethylene glycol monoacetate). Diacetone alcohol is a Class II combustible liquid with both REL and PEL of 50 ppm (240 mg/m^3)[29] that is presumed to have formed by aldol condensation of acetone introduced incidentally as part of the process of preparation and treatment. An adjustment to the procedure or composition of the EO sterilant might eliminate this contaminant. No REL or PEL is listed for HEA,[37] which is listed as a possible carcinogen and possible mutagen.[38] The same mass spectrum was observed for an authentic preparation of HEA, which formed in ~90% apparent purity by warming a neat mixture of ethylene glycol and acetic acid for a minute.

The ease of formation observed for HEA is consistent with postulating its formation from EO by scavenging of acetate residues from constituents of the elastomer. We did not quantify either contaminant and the vapor pressure of each at 25°C is higher than 1 torr (1300 ppm), so both warrant additional study to measure the amount of each generated during EO treatment and to ascertain the potential exposure before EO is considered for disinfecting respirators.

SUMMARY AND LIMITATIONS OF THE STUDY

The data from this study demonstrate that 6 of the 7 readily available decontamination technologies evaluated do not deposit significant quantities of toxic residues on the FFRs. The suspected presence of HEA after EO treatment will require quantitative evaluation of exposure risk before EO could be recommended for this application. However, several additional factors were noted that will influence the acceptability of several of these methods. All FFRs treated with bleach retained a bleach odor following the off-gassing period. Although the amount is below action levels, the odor is unpleasant and might cause adverse health effects in users with certain asthmatic conditions. Also, bleach corroded the metal parts on the FFRs (staples, nosepieces, etc.) and discolored others. DMDO and mixed oxidants also oxidized the metal parts and left distinct odors on the FFRs.

FFRs treated with DMDO accumulated visible white residues that were tentatively assigned as Oxone because DMDO is known to decay rapidly. A standard synthetic procedure[39] using DMDO as the oxidant recommends no extraordinary protective measures. However, specific information about the toxicity of DMDO is desirable and lacking.

Little or none of the gaseous sterilizers (EO and VHP) remained on the FFRs following decontamination and off-gassing. However, EO treatment of FFRs produced detectable residues of HEA, a hazardous byproduct, possibly formed by a reaction of EO with rubber parts of the respirator. Detection was only qualitative, so quantitative studies are needed to clarify these observations. In addition, protracted off-gassing follows EO treatment, which limits throughput.

Throughput posed a more serious problem for the VHP technology during our testing with the VHP sterilizer—the sterilization cycle aborted whenever more than six FFRs were loaded in the chamber during the 1-hr sterilization cycle. Cellulosic materials absorb peroxide,[22] but the masks appear not to contain cellulose—the main components reported

in such FFRs are polyesters and polyolefins, with smaller amounts of acrylates and urethanes. We found no data indicating that polyester absorbs peroxide, so why the FFRs caused the VHP cycle to abort is unclear.

This study is an initial survey of potential toxicity of FFRs introduced by several available decontamination technologies. The results suggest that most or all of the methods evaluated do not introduce major health risks, but this is only one of several performance criteria that must be met before any combination of decontamination technology and respirators can be recommended for reuse. **These results are not to be interpreted as endorsing any method for decontaminating FFRs**.

Before even limited recommendations can be issued by the cognizant regulatory offices, extensive data are needed that describe the effect of candidate decontaminants on filtration efficiency, fit, and the ability of each method to inactivate the influenza virus *in situ*. These studies are in progress and will be reported in the near future. Additional work is also needed to extend the information base to other models of FFRs—hundreds exist and a representative sample must be tested before conclusions can be drawn about compatibility with specific decontamination technologies. However, the usefulness of these data extend beyond just FFR reuse during an influenza pandemic but also has utility to those interested in designing a new class of FFR. There is a lot of attention surrounding the development of an FFR that can be decontaminated and reused multiple times. The data from this study point out design features that should be avoided if such a device were developed.

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