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Reusability of filtering facepiece respirators after decontamination through drying and germicidal UV irradiation

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ABSTRACT

Introduction During pandemics, such as the SARS-CoV-2, filtering facepiece respirators plays an essential role in protecting healthcare personnel. The recycling of respirators is possible in case of critical shortage, but it raises the question of the effectiveness of decontamination as well as the performance of the reused respirators.

Method Disposable respirators were subjected to ultraviolet germicidal irradiation (UVGI) treatment at single or successive doses of 60 mJ/cm^2 after a short drying cycle (30 min, 70°C). The germicidal efficacy of this treatment was tested by spiking respirators with two staphylococcal bacteriophages (vB_HSa_2002 and P66 phages). The respirator performance was investigated by the following parameters: particle penetration (NaCl aerosol, 10–300 nm), scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR), differential scanning calorimetry and mechanical tensile tests.

Results No viable phage particles were recovered from any of the respirators after decontamination (log reduction in virus titre >3), and no reduction in chemical or physical properties (SEM, particle penetrations <5%–6%) were observed. Increasing the UVGI dose 10-fold led to chemical alterations of the respirator filtration media (FTIR) but did not affect the physical properties (particle penetration), which was unaltered even at 3000 mJ/cm^2 (50 cycles). When respirators had been used by healthcare workers and undergone decontamination, they had particle penetration significantly greater than never donned respirators.

Conclusion This decontamination procedure is an attractive method for respirators in case of shortages during a SARS pandemic. A successful implementation requires a careful design and particle penetration performance control tests over the successive reuse cycles.

Key questions

What is already known?

- N95 or FFP2 disposable respirators are the most common respiratory protection devices used in healthcare settings to prevent contamination from airborne aerosols.
- The decontamination and recycling of respirators is an alternative in case of shortage, provided that the procedure is balanced to allow sufficient disinfection with the least possible impairment of the properties of the respirators.

What are the new findings?

- Decontamination through drying and a UV irradiation of 60 mJ/cm^2 was sufficient to ensure decontamination (>3 log reduction in virus titre) without mechanical or filtration performance impairment of the respirator.
- Wearing the respirators causes a greater decrease in penetration efficiency than the disinfection cycle.

What do the new findings imply?

- In case of shortage, respirators can be recycled using drying and germicidal UV, which is relatively simple and inexpensive procedure.
- The integrity and penetration efficiency of the respirators during disinfection-recycling cycles must be monitored.

INTRODUCTION

The SARS-CoV-2 pandemic (COVID-19) that started at the end of 2019 led to a severe shortage of respirators such as the filtering facepiece respirators (FFRs) in Europe. This respirator shortage was caused by the tremendous need in protecting civilians and healthcare workers from airborne SARS-CoV-2. Infection control procedures call for disposable single-use FFR to avoid cross-contamination.

Respirators are rated according to percentage of penetration to aerosols, according to the labels FFP1-FFP2-FFP3 (EU Standard) and N95-N99-N100 (US standard).

The most common respiratory protection used in healthcare settings are disposable FFP2 and N95 respirators and are capable of capturing ≥94% and ≥95%, respectively, of aerosols in submicron range.[1 2] Contrastingly, surgical masks do not provide respiratory protection from small airborne particles due to their loose fit and low filtration capacity.[3 4] FFR are negative pressure air-purifying particulate respirators that differ from other respirators because the filtering media itself is the respirator. These disposable respirators are not recommended for reuse and should only be considered in a situation of critical shortage. One recommendation of respirator reuse during the COVID-19 pandemic is to provide one respirator per day for each healthcare worker who may be in direct contact with infected patients.[5] This recommendation is based on the persistence of SARS-CoV-2 up to 72 hours on different surfaces.[6] Decontamination of disposable FFR is the last resort. Appropriate methods need to be developed that inactivate viral particles, are harmless to the user and do not significantly compromise respirator filtering capacity.[7]

Several methods have been evaluated for their efficiency in decontaminating FFR such as autoclaving, steam generated by heat or microwaves, ethylene oxide, vaporised hydrogen peroxide and bleach. Moreover, a >4 log reductions in viable viral particles has been obtained after decontamination of H1N1 influenza-contaminated and H5N1 avian influenza-contaminated FFR via ultraviolet germicidal irradiation (UVGI) with a dose of 1440–1800 mJ/cm^2.[8 9] A similar log reduction has been observed with a dose of 1800 mJ/cm^2 on the MS2 coliphage,[10] but a 3-log reduction was already achieved with a 30 mJ/cm^2 UVGI dose.[11]

Advantages of UVGI systems are the setup flexibility, short treatment time, facility of dosage and the absence of residual disinfecting agent after treatment. The UVGI treatment is less aggressive than other disinfection methods used in the hospital sector (eg, autoclaving or bleach), thus limiting damage to disposable respirators.[12] Nevertheless, UVGI treatment is one of the germicidal procedures frequently used in the hospital and biological field. Other 'softer' disinfection methods, such as drying at medium temperature (typically between 70°C and 90°C), have been suggested to deactivate the SARS-CoV-2.[13–15] Arguably, drying and storing the respirators for a few days could be sufficient to deactivate the coronavirus, which cannot survive indefinitely outside the human body. However, the disadvantage of the latter methods when used alone is they do not necessarily eliminate other pathogens that may be present. Moreover, a recent review highlighted UVGI as one of the most promising decontamination methods for N95 FFRs.[16]

The effects of UVGI on respirator appearance, airflow resistance (breathability), particle filtration efficiency (penetration rate) and in one instance fit, have been studied in detail for multiple decontamination cycles. No significant effects were found for UVGI doses of 176–181 mJ/cm^2 after a 30 min irradiance (15 min each side)[17] as well as for UVGI doses of 1620 mJ/cm^2 (each side) in particular for particle penetration and airflow resistance of different models of FFR.[18] Only at extreme UVGI doses (120 000 to 950 000 mJ/cm^2) a slight effect on strength, particle penetration (1.25% increase) and airflow resistance (below 5%) of the material was observed.[19] However, no study has yet demonstrated simultaneously that a treatment was efficient in decontaminating FFRs while maintaining its physical integrity over multiple decontamination cycles.

By using a protocol similar to a reference protocol developed at the University of Nebraska, USA,[20] our aim was to test a decontamination procedure involving drying and germicidal UV ensuring germicidal efficacy while being low enough to avoid a physical or chemical alteration of the filter medium and allowing multiple recycling treatments.

METHODS

The full description of the methods and the experimental setting used is in the online supplemental material. Our method is based on a procedure developed by the University of Nebraska.[20] Briefly, the decontamination procedure consisted of subjecting disposable FFP2 respirators (3M 6923 and 1862, 3M, Germany) to a drying cycle (oven temperature at 70°C for 30 min) and subsequently exposing them to germicidal treatment with UVC. The respirators were suspended in a rotating circulating rack and irradiated for 4 min at an irradiance of 0.25 mW/cm^2 corresponding to a dose of 60 mJ/cm^2 (UVC, 254 nm). The respirators were irradiated homogeneously by multidirectional irradiance set-up by the distribution of several UVC light sources (n=10) and the presence of reflective walls in the chamber.

The effectiveness of the decontamination procedure was tested using two *Staphylococcus aureus*' bacteriophages (vB_HSa_2002 and P66 phages), belonging to the family of double-stranded DNA viruses. A count of viable phage particles on contaminated respirators subjected to germicidal treatment was compared with controls (spiked respirators that were not treated). The effect on the integrity of the respirators after successive decontamination cycles was assessed by increasing the UV doses from 60 mJ up to 3000 mJ/cm^2 (corresponding to 50 cycles). Physical and chemical alterations were investigated through scanning electron microscopy (SEM), Fourier-transform infrared spectroscopy (FTIR) and a fine particle penetration test (NaCl aerosol, 10–300 nm range). Respirators were also visually inspected after the decontamination procedure for possible mechanical damage (deformation, seal integrity and strings). Tests were conducted on both unused and used respirators, the latter being collected from frontline units from the Center for Primary Care and Public Health (Unisanté).

RESULTS

Decontamination procedure efficiency and phage release from FFR

No viable phage particles were recovered from any of the FFR extract solutions (12 masks and n=2 per mask) obtained from decontaminated FFR (table 1).

Table 1 Viable *Staphylococcus aureus* phage particles measured on FFR before and after the decontamination process

		vB_HSa_2002		p66	
		Phage titre (PFU/mL)	Total amount of PFU/FFR	Phage titre (PFU/mL)	Total amount of PFU/FFR
UVGI treated (n=12)	Mean	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	SD	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Untreated (n=8)	mean	1.00E+05	2.00E+05	1.33E+04	2.66E+04
	SD	6.50E+04	1.16E+05	1.15E+04	2.02E+04

FFR, filtering facepiece respirators; PFU, plaque-forming units; UVGI, ultraviolet germicidal irradiation.

Similar fractions (approximately 1/2000, ie, $2\times10^5\pm1.16\text{x}10^5$ plaque-forming unit (PFU) and $2.66\times10^4\pm2.02\text{x}10^4$ PFU for phage vB_HSa_2002 and P66, respectively) of the total amounts of phage particles applied (ie, 4×10^8 PFU and 4×10^7 PFU for phage vB_HSa_2002 and P66, respectively) were released from untreated masks within the FFR extract solutions after 1 hour shaking (table 1). It should be noted that the brief heat-drying phase alone has a germicidal effect. No viable phage particles were recovered after preliminary heat-drying tests carried out on a reduced number of respirators (n=4) with the vB_HSa_2002 phage (see online supplemental material).

Respirator integrity with increasing UVGI doses

While some structural changes were perceptible, the overall integrity and performance of the respirator was only moderately affected by UVGI dose. Penetration rates for fine particles (10–300 nm) were on average slightly higher in UVGI-treated compared with non-treated respirators (figure 1A). There was no clear trend between structural changes and UVGI doses. Particle penetration rates remained below 2% at UVGI doses up to 1200 and 3000 mJ/cm^2, corresponding to 20 and 50 treatment cycles. Note that penetration rates for respirators that have been worn once by healthcare professionals were

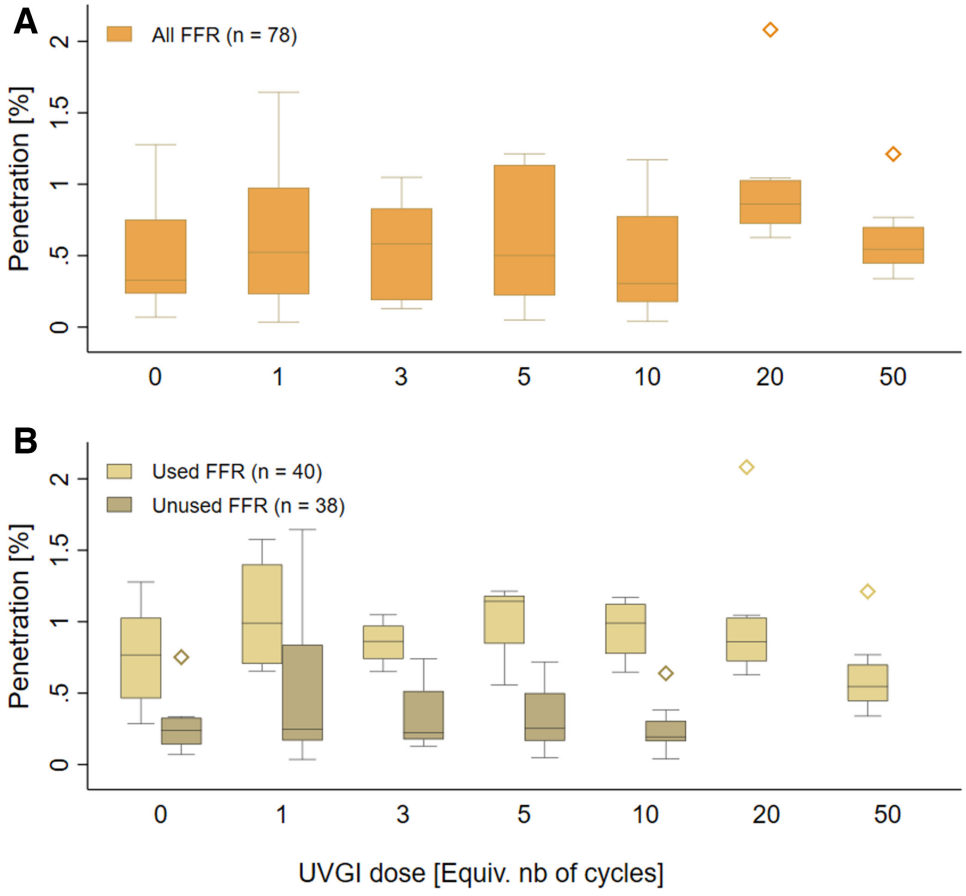

Figure 1 Penetration of fine particles (10–300 nm) through the FFR filter media in % as a function of the UVGI treatment duration (in equivalent number of cycles): (A) all respirators together and (B) separating unused respirators and respirators used once. FFR, filtering facepiece respirator; UVGI, ultraviolet germicidal irradiation.

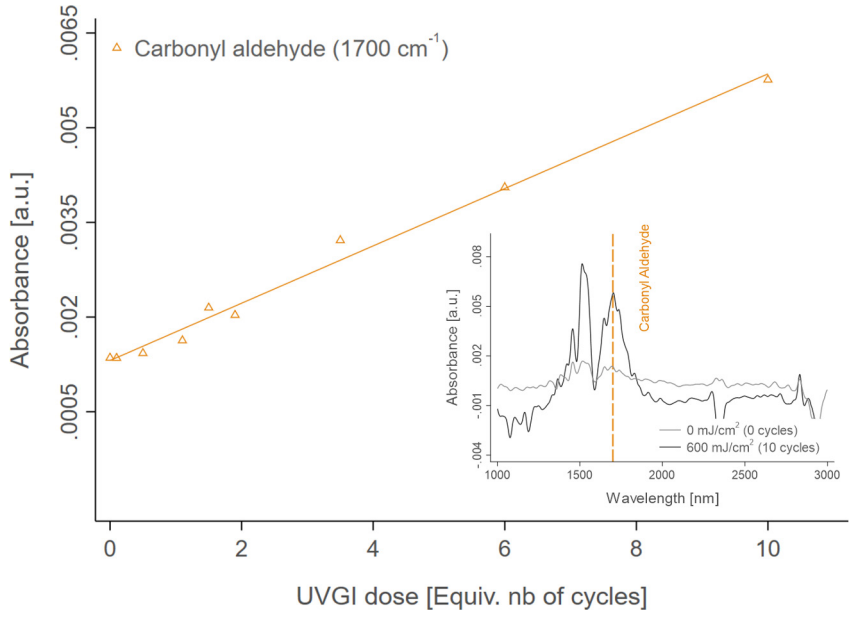

Figure 2 Structural change in the FFR filtering media observed by Fourier-transform infrared spectroscopy as a function of the number of UVGI treatment cycles. In thumbnail, examples of IR absorbance spectrum of the media after 0 and 10 cycles. UVGI, ultraviolet germicidal irradiation.

significantly higher (mean penetration 0.9%) compared with unused respirators (mean penetration 0.3%) (analysis of variance, p<0.001) (figure 1B).

An increase of the germicidal UV dose up to 10 cycles (600 mJ/cm^2) did not lead to any visible damage (with the naked eye or by electron microscopy) (see online supplemental material). The stiffness and strain to failure was also not significantly altered, and the crystallinity and melting enthalpy of the respirator material remained identical (see online supplemental material). Structural alterations of the filter media surface were observed with increasing UV dose as increases in aromatic C–C bonds (1520 1/cm) and carbonyl functions (1700 1/cm)[21 22] in the FTIR chromatograms corresponding to the oxidation of polypropylene (figure 2). This change in respirator surface properties could affect particle–surface interception mechanisms, such as direct interception and interception due to Brownian motion.

A generation in reactive oxygen species (ROS) was measured during the UVGI cycle in the exposure chamber air. Ambient hydrogen peroxide (H_2O_2) levels were determined with photonic-based detection and increased from 35±31 (background) to 200±52 nmol/L_{air}. Interestingly, the consumption of ozone (O_3) was observed concomitantly, and O_3 concentration fell from 33 ppb for background to 17 ppb after germicidal UV treatment. According to the existing literature on advanced oxidation processes, UV irradiance at 254 nm triggers the photocatalytic dismutation of O_3 into hydroxyl radicals (HO·) that, in turn, can form more stable airborne H_2O_2 molecules.[23]

DISCUSSION

Two phages were used as model systems to test the efficacy of our decontamination procedure (drying cycle+UVGI) on viral particles infectivity. Indeed, despite these phages being non-enveloped harmless virus models, it has been shown previously that the enveloped (H1N1 and HSV1) and the non-enveloped viruses (eg, DNA murine minute virus)—which are generally more resistant than enveloped viruses—were fully inactivated by a combination of heat and exposure to 17 mJ/cm^2 UVC.[24] Therefore, a procedure fully inactivating non-enveloped DNA phages would be very likely efficient in inactivating SARS-CoV-2. Our setting allowed recovery in solution of fractions of the applied viable viral particles well above the detection limit of our drop tests assay (ie, 2×10^2 PFU/mL). Our results demonstrated that after a single decontamination cycle, no viable phage particles were recovered from any of the 24 phage-contaminated FFR tested. The developed decontamination procedure successfully inactivated the phage particles and represents therefore a valuable strategy to decontaminate FFR contaminated with SARS-CoV-2. However, it is difficult to precisely quantify its germicidal efficacy due to the detection limit of the method, which is due in particular to the biological material loss during extraction from the respirator in this experiment.

The germicidal efficiency observed for the overall decontamination process is due to both UVGI and heat-drying treatments. As already shown in our preliminary tests and in previous studies,[14] heat treatment alone has a germicidal effect. However, the UVGI treatment alone is also an effective decontamination method in general and has the advantage of having a broad germicidal action spectrum. Nevertheless, a drying process is required to

achieve optimal and reproducible UVGI treatment in the depth of the material. By combining the two methods, we propose additional safety by overcoming some of the limitations of each treatment alone and bring convincing arguments for healthcare facilities, which are familiar UVGI treatment.

A drying of 70°C during 30 min and a UV dose of 60 mJ/cm^2 per recycling cycle ensured a germicidal effect without damaging the mechanical and protective properties of the respirator as have been previously published. Although chemical structure changes are measurable on the surface of the filter media at doses below 120 mJ/cm^2 (two cycles), respirator performance assessed as particle penetration across the filtering media was only moderately affected by UVGI treatment. Even after 10 cycles, fine particle penetration remained below the 5%–6% thresholds expected for FFP2 or N95 type FFRs.

Our results also show that the wear and tear caused by the use of the respirator affects the penetration performance more than the decontamination procedure itself. This is probably due to the condensation of the user's exhaled breath in the respirator, as high humidity levels have been previously associated with a deterioration of the electrostatic charge of the filtering media.[25] Tests for multiple reuse cycles were not conducted in this study since recycled respirators can only be used in case of effective shortage, which we did not encounter. These results suggest that respirator performance tests after recycling are necessary. It could be that the number of decontamination cycles are not the limiting factor but rather the number of times the respirator is used.

UVGI treatment and thermal drying are easy to install and relatively inexpensive. Consequently, the decontamination procedure is an interesting alternative in a situation where there is a shortage of disposable respirators. However, the implementation of the decontamination procedure requires some precautions that could limit its germicidal effectiveness such as shading due to the geometry of the respirator and the rapid attenuation of radiation in the filtering media. By using of multidirectional UV sources, controlling the effective radiation dose during treatment, and pretreating the respirator with heat (70°C), these undesirable effects are avoided. ROS and ozone measurements suggested the presence of H_2O_2 concomitantly with the UV treatment. H_2O_2 is a gaseous reactive species and can act as a biocidal agent in the depth of the filtering medium giving the UVGI treatment an additional desired effect.

Only one FFP2 respirator brand was used in this study. Similar findings are expected with other FFP2 respirators undergoing UVGI treatment because the filter media are typically polypropylene. There are, however, some caution needed in extrapolating these results to other FFP2 respirator brands, in particular during periods of respiratory supply shortage. Respirators that have not undergone testing and can be of lower quality will then likely appear on the market. For this reason, recycling should be limited to respirators with particularly low penetration rates, typically around 1%. This gives a larger margin of safety with respect to the minimum requirements of the FFP2 and N95 standards.

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