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Conceptualizing a novel Hybrid Decontamination System (HDS) based on UV/H₂O₂ treatment for the enhanced decontamination and reuse of N95 FFRs

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ABSTRACT

The ongoing Pandemic of COVID-19 caused by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) has severely stressed the worldwide healthcare system and has created dangerous shortages of personal protective equipment (PPE) including N95 filtering facepiece respirators (FFRs). Even though suppliers struggled to meet global demand for N95 masks at an unprecedented level, a shortage of FFR appears as a significant factor in the transmission of the disease to frontline workers. CDC, USA has mentioned that FFR decontamination and reuse may be necessary during times of shortage to ensure guaranteed availability. Hence present stressed condition faced by the healthcare sector seeks for an affordable decontamination strategy that can be replicated easily broadening the utility of FFR decontamination across a range of healthcare settings. After reviewing available literature on the various disinfection techniques that may be used for the decontamination of FFRs, a first of its kind, portable Hybrid Decontamination System/procedure has been conceptualized and designed. This system combines the disinfecting properties of both vaporous hydrogen peroxide (VHP) and ultra-violet C irradiation (UV C) to ensure maximum decontamination of N95 respirators. The instrument will be equipped with a hydrogen peroxide chamber and UV light source. Sterilization of the FFRs will be done through treatment with VHP followed by UV light treatment. The proposed system will allow the user to completely sanitize the FFRs in a time-efficient manner.

Introduction

The spread of Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) across the globe has led to an increase in the demand for filtering facepiece respirators (FFRs). Filtering facepieces are air-purifying particulate respirators working at negative pressure (ECRI, 2020). The usage of FFRs offers a non-pharmacological way of averting or slowing the spread of infectious diseases. FFRs are tightly fitted devices worn by healthcare professionals, infected persons, or the general public to lessen the spread of pathogens contained in aerosolized body fluids of the potentially infected persons, to other individuals. FFRs effectively filter out 95% solid and liquid aerosols (NPPTL-CDC, 2020).

National Institute for Occupational Safety and Health (NIOSH), USA approved filtering facepiece respirator for use during the ongoing COVID-19 pandemic. A NIOSH-approved N95 respirator creates a seal against the user’s face, eliminating the intrusion of contaminants along the edges. The filter has been listed in NIOSH Certified Equipment List (CEL) indicating its capacity to defend against at least 95% of airborne contaminants (CDC, 2020a, 2020b; Bergman et al., 2010). The mask must be double strapped and clearly labeled with both a letter designation (N, R, P) indicating the capacity of the mask’s filtering efficiency (in percentage) in presence of oil (NPPTL-CDC, 2020). It is recommended to use N when zero oil is existing in the air; R, when oil is present but only for one slot or 8 h of uninterrupted or intermittent use and P when oil is present but manufacturer’s time use restrictions to be followed if reuse to be done respectively (Table 1). The filter consists of thousands of synthetic wool fibers combined with a melt-blown extrusion process treated to sustain an electrostatic charge (i.e., an electret). In addition

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to providing a mechanical shield against aerosols; N95 filters filter out charged particles including microbes, though it provides little protection against gases, oils, or vapors (ECRI, 2020).

The current COVID19 pandemic triggered by SARS-CoV-2 has severely strained the global healthcare environment and generated a scarcity of personal protective equipment (PPE) worldwide. Though the FFRs such as N95 have been designed for single-use, the worldwide increase in demand has caused shortages in their supply (Nogee and Tomassoni, 2020; Wu et al., 2020). As it was expected in evolving respiratory pandemics, demand for N95 FFR has far surpassed their manufacturing capacity (Rodriguez-Martinez et al., 2020). Health care workers have no alternative in many countries but have to use low-level PPE and breathing devices (CDC 2020c; OSHA (Occupational Safety and Health Administration), 2020). A shortage of PPE is a significant factor in the transmission of the disease to frontline workers participating in the diagnosis, testing, and treatment of infected persons (Chughtai et al., 2020). The U.S. Centers for Disease Control and Prevention does not recommend N95 FFP respirators for general public use, stating that they should be reserved for healthcare workers (Srinivasan and Peh, 2020). When global demand for N95 masks grew by 2020 at an unprecedented level due to the pandemic, suppliers struggled to raise production to satisfy the demand. It has been reported that N95 masks which had a market valuation of over US$ 802 million in 2019, by 2027, this value is expected to rise more than double to approximately US$ 1.90 billion (Garside, 2020).

Hence to satisfy the rocket high demand of N95 FFR, wearing an N95 respirator for extended hours or reusing a respirator several times are suggested practices to ease shortages. One of the proposed strategies for mitigating the massive demand for N95 FFRs is their reuse after appropriate decontamination that allows the inactivation of any potentially infectious material attached to the surfaces (Rodriguez-Martinez et al., 2020). While single-use N95e FFRs are not approved for routine decontamination as standard practice, CDC, USA has mentioned that FFR decontamination and reuse may be necessary during times of shortage to ensure guaranteed availability (CDC, 2020a). Food Drug Association (FDA) issued an Emergency Use Authorization (EUA) on March 28, 2020, for the Battelle Critical Care Decontamination System (CCDS) to decontaminate compatible N95 respirators during the COVID19 public health emergency. In light of this, strategies revolving around the extended use and reuse of FFRs have surfaced, based on a safe, easy, and accessible sterilization solution. Complete decontamination recycling strategy of respirators is based on the following four key aspects: inactivation of the intended organism, no damage on the respirator’s filtration; no change in the shape of the respirator; and safety of the individual wearing the respirator is not compromised. Therefore, it is imperative to devise efficient disinfection techniques which will retain the filtration performance and fit of the FFRs while at the same time inactivate all biological contaminants. The disinfection method must be time and cost-effective as well as easy to operate. The most promising results so far to treat FFRs were demonstrated by physical and chemical decontamination methods viz. ultraviolet germicidal irradiation, steam sterilization, ethylene oxide, and vapor hydrogen (Polkinghorne and Branley, 2020).

Table 1

| Respirator (FFRs) type | Filtration percentage of airborne particles (at least) at instant to oil retention | Source: NIOSH approved FFRs (NPPTL-CDC, 2020). |
|-----------------------|---------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------|
| N95                   | 95%                                                                              | No                                                                                                                                  |
| N99                   | 99%                                                                              | No                                                                                                                                  |
| N100                  | 99.97%                                                                           | No                                                                                                                                  |
| R95                   | 95%                                                                              | Somewhat                                                               |
| P95                   | 95%                                                                              | Strongly                                                               |
| P99                   | 99%                                                                              | Strongly                                                               |
| P100                  | 99.97%                                                                           | Strongly                                                               |

Fig. 1. The requirements for an ideal FFR decontamination strategy.

The need for abundant, complete, reliable respiratory defense is fostering research, as the current pandemic is anticipated to continue for months and the risk of potential airborne biological threats remains. The present condition faced by the healthcare sector related to the availability of quality FFRs and its reusability seeks for appropriate decontamination strategy that can be replicated easily broadening the utility of FFR decontamination across a range of healthcare settings. Based upon this background, the present paper discusses the advantages and limitations of the available disinfection technologies being practiced for FFR decontamination to identify appropriate disinfection measures with the most effective result as well as the least hazardous and environmental concern. Accordingly, a Hybrid Decontamination System (HDS) has been conceptualized based on vaporous hydrogen peroxide (VHP) and ultra-violet irradiation (UV C) to ensure the complete decontamination of FFRs and to prevent PPE shortages in the future while facing the spread of an infectious disease. It is expected that such decontamination strategies of HDS would be very much relevant to ease out the shortage of FER and may be implemented by health care facilities at the time of crisis.

Current disinfection techniques

Previous influenza outbreaks (SARS-CoV, MERS-CoV, H1N1, etc.) and the ongoing SARS-CoV-2 pandemic have caused researchers to focus on the decontamination and reuse of FFRs in emergencies. Various organizations have proposed the reuse of N95 FFRs after the respirator has been thoroughly decontaminated (CDC, 2020a, 2020c). However, improper decontaminated respirators may create more problem by exposing the person wearing it to the pathogens in the FFR (CDC, 2020a). In addition, for the FFR to be effective in blocking the transmission of pathogens, its filtration performance and fit must not be compromised during the decontamination procedure. In general, an ideal decontamination process should be easy to operate and should not cause any damage to the material, appearance and fitting aspects of the FFR. Further, ideal disinfection should disinfect a broad spectrum of biological agents from all parts of FFRs, should not leave any hazardous residue, should retain optimum filtration efficiency following treatment (Fig 1). Therefore, it is imperative to choose a disinfection technology that not only decontaminates the respirator but also does not damage its fit and filter-
tion performance. Various research groups have evaluated the FFR qual-
ity after decontamination with different disinfectants (Table 2). Many
of these approaches can be undertaken in existing available equipment
for FFR decontamination or may be repurposed to maintain necessary
product conditions.

Presently the suggested decontamination methods for FFRs are steam
sterilization by microwave and autoclave, chlorine-based products, 
ethylene oxide, UV germicidal irradiation, \( \text{H}_2\text{O}_2 \) gas plasma, vaporized 
\( \text{H}_2\text{O}_2 \), soapy water decontamination. As shown in Table 2, chemical 
sterilization using soap and water, alcohols, and bleach is not the ideal
strategy for FFR decontamination as they render the respirator non-
functional many times. Steam sterilization by autoclave or microwave
though are effective, and non-toxic (with no hazardous residual), but
may damage polymer fibers in the filter compromising its performance
(Su-Velez et al., 2020). Due to the strong viral inactivation efficiency
and no disinfection or oxidation product production, vaporized hy-
dergon peroxide (VHP) cum UV irradiation appears to be viable options
for successful decontamination. Fischer et al. (2020) showed that N95 res-
pirators can be decontaminated and reused up to 3 times by using
UV light and VHP and 1–2 times by using dry heat without compromising
its quality.

As observed in Table 1, VHP, UV C, and microwave generated moist
heat treatments are suitable for decontamination of FFRs. 3M a multi-
national company headquartered in the USA, the manufacturer of the
popular 3M N95 FFRs, released a list of VHP, UV, and moist heat-related
decontamination technologies for FFR disinfection (3M Technical Bul-
letin, 2021). Currently, VHP systems from Steris, STERRAD, Sterilu-
cent, and Battelle have passed the filtration efficiency and fit evaluation
test after 10, 2, 10, and 3 cycles, respectively. A frequent application
of VHP is for terminal decontamination of hospital rooms, biosafety
cabinets, and medical equipment and materials that are intolerant to
heat or have diffusion-restricted space. This generally kills extremely
challenging pathogens, including bacterial spores and viruses. Several
studies have established that certain N95 respirators can be securely
decontaminated with appropriate use of Integrated Vapor-Phase Hy-
dergon Peroxide- VHP (Battelle, 2016, 2020; Bergman et al., 2010;
Viscusi et al., 2009). Xenex Lightstrike System, which is based on UV
disinfection, is relying on similar principal (Technical Bulletin, XENEX,
2021). A recent revision reported that ultraviolet germicidal irradiation
and vaporized hydrogen peroxide appear to have the potential for de-
contamination of FFR (Fischer et al., 2020). Based on this data, along
with the data in Table 2, we can identify that VHP cum UVC are potent
disinfection techniques that will not compromise the filtration efficiency
and fit of the FFR and applicable up to 10 cycles. However, Table 2 also
indicates that both the decontamination methods are associated with
some limitations. Hydrogen peroxide is toxic and the de-gassing time
is long (Schwartz et al., 2020). UV C irradiation may not be adequate
to produce the desired level of disinfection in the case of surfaces with
multiple curves due to shadow effects (Lindsey et al., 2015). Varied au-
thorizations for decontamination products changes with time and as per
the requirement of public health emergency, and availability of compa-
rable product; however, attempt to minimize the limitations, it is always
better to be prepared for any airborne pandemic in future. We hereby
present here a hybrid decontamination system (HDS) for the complete
decontamination and reuse of FFRs.

Proposed Hybrid Decontamination System (HDS)

Based on this background present work aims to develop a multi-
chambered treatment unit with provision for multiple disinfection bar-
riers appropriate for decontamination of N95 FFR for reuse. In present
times, the use of multiple disinfection barriers is receiving international
attention to ensure and maximize the efficiency of conventional disinfec-
tants. As a report on the removal of SARS-CoV-2 by current conventional
decontamination strategies is at the experimental stage, it is imperative
to take extra precaution by combining different compatible disinfection
strategies to ensure complete eradication of the viruses from any sur-
face (Venugopal et al., 2020). A system with multiple disinfection steps
might provide synergistic benefits, enhanced reliability, robustness, and
flexibility for decontamination.

 Adequate evidence is indicative that the novel coronavirus 2 is one of
the uncomplicated viruses to be deactivated. The genome of the SARS-
CoV-2 virus is phylogenetically very comparable to bat SARS-associated
coronaviruses (84% nucleotide similarity with bat-SL-CoVZC45 coron-
avirus), and the spike protein has a 78% nucleotide similarity with the
human SARS-CoV-1 virus (Chan et al., 2020). Therefore, SARS-CoV-2
is expected to be prone to environmental causes or disinfectants ap-
plied during previous SARS outbreaks (Wang et al., 2020). Maris (1990)
in their work on coronavirus stated that the existence of envelope in
coronaviruses render them vulnerable to microbicides as opposed to
non-enveloped. The recent analysis predicts that conventional disinfec-
tant procedures should be successful to kill or inactivate the virus
(Kataki et al., 2021). US EPA has released a list of 402 disinfectants
that can be used against the SARS CoV 2 pathogen (US EPA, 2020).

It has been shown that the combination of hydrogen peroxide and UV
irradiation leads to a powerful decontamination system and this
combination has been increasingly used for wastewater disinfection
(Baylis and Waite, 1979; Sun et al., 2016; Collivignarelli et al., 2018;
Galvis et al., 2018). Bounty et al. (2012) reported a 4 log reduction of
denavirus at a UV dose of about 200 mJ cm\(^{-2}\) and an addition of 10
mg \( 1^{-1} \) \( \text{H}_2\text{O}_2 \) to the process could help achieve 4 log inactivation at a
lower UV dose of 120 mJ cm\(^{-2}\). When used in conjunction, they create
an environment rich in reactive oxygen species (ROS) which are potent
in eliminating biological contaminants. In this regard, an automated,
hands-free, system has been conceptualized and designed for the com-
plete and thorough disinfection of N95 FFRs. This system relies on
the decontamination properties of VHP and UV C while reducing the restric-
tions faced when they are used individually (Fig. 2).

Hybrid Decontamination System-working details

As shown in Fig. 2, the decontamination system has been designed
to be compact and is divided into two chambers: vaporization chamber
and sterilization chamber. A circular rotating tray is equipped with a
rack that allows the FFRs to be held in place. The tray rotates while
sterilization is occurring to ensure that all FFRs are evenly exposed
to VHP and receive the same intensity of UV C irradiation. The proposed
decontamination process has been illustrated in Fig. 3.

\( \text{H}_2\text{O}_2 \) treatment

Once, the FFRs have been placed on the circular rotating rack, they
enter into the sterilization chamber. This is followed by the release of
VHP from the vaporization chamber (Fig. 3). VHP enters the steriliza-
tion chamber till a concentration of 480 ppm is reached. For detection
of \( \text{H}_2\text{O}_2 \) level inside the chamber, a \( \text{H}_2\text{O}_2 \) sensor is placed inside the
sterilization chamber.

A study conducted by Schwartz et al. (2020) demonstrates the use of
VHP (480+ ppm) to decontaminate N95 FFRs. In another recent study,
Grossman et al. (2020) suggest a concentration of 700 ppm for disinfec-
tion. As our proposed system is equipped with two disinfection technolo-
gies, we suggest the use of 480 ppm for the disinfection of N95 FFRs.
The VHP treatment will consist of two main steps:

a. **Gassing Phase**: Hydrogen peroxide vapors will be created in a con-
tainer by heating the liquid \( \text{H}_2\text{O}_2 \) solution (35%). \( \text{H}_2\text{O}_2 \) has a low
vapor pressure of 5 mm Hg at 30°C, therefore, a temperature range
of 50-60°C should be adequate for \( \text{H}_2\text{O}_2 \) to vaporize. Vaporous \( \text{H}_2\text{O}_2 \)
will then diffuse throughout the sterilization chamber and the \( \text{H}_2\text{O}_2 \)
vapors container. The vapors will create a biocidal environment that
initiates the deactivation of microorganisms by chemical interac-
tions at multiple biologically important reaction sites. Assuming that
the rate of release of \( \text{H}_2\text{O}_2 \) vapors will be 2 g min\(^{-1}\) for a volume of
| S.No | Disinfection technique                  | Mode of action                                                                 | Advantages                                                                                                      | Disadvantages                                                                                                      | FFR quality check after disinfection                                      | Reference                                      |
|------|----------------------------------------|-------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------|-----------------------------------------------|
| 1    | Vaporous Hydrogen Peroxide (VHP)       | Produces hydroxyl radicals which can destroy proteins, nucleic acids and lipid membranes | • Fast germicide  
• Effective against a large set of microorganisms  | Degassing (removal of H₂O₂ vapors) is time consuming.  
• Efficiency of filtration is retained after 10 cycles and the FFR fit is not affected up to 20 cycles  |  | Battelle (2016), Viscusi et al. (2009), Schwartz et al. (2020), Torres et al. (2020)  |
| 2    | H₂O₂ Gas Plasma                        |                                                                                |                                                                                                                  | · Filtration performance of the FFR is compromised after 3 cycles                                               |  | Bergman et al. (2010)  |
| 3    | UV C                                   | Destroys nucleic acids by creating photo-dimers                                | Ineffective for sterilization of tools with multiple curves due to shadow effects.  
• Requires enclosed devices to protect users from exposure.  
• Requires careful consideration of FFR model, material type, and design  |  |  | Bergman et al. (2010), Viscusi et al. (2009), Bergman et al. (2010), Torres et al. (2020), Lowe et al. (2020), Fisher et al. (2011), Lore et al. (2012), Viscusi et al. (2011), Mills et al. (2018)  |
| 4    | Steam sterilization (microwave generated) | High temperature  
denatures proteins and enzymes.  
Steam sterilization (autoclave)                                                                 | • Inactivates pathogen at wavelengths between 240 - 280 nm.  
• Significant reductions (≥3 log) in influenza viability under different soiling conditions of FFR  
• Leaves no toxic residue  
• Non toxic and inexpensive  
• Used for sterilization of equipments which are heat and moisture resistant  
• Can fully penetrate to porous FFR surface  | · Inactivates virus  
• Little effect on FFR fit  
• High powered microwaves may degrade the filter material  | · No change in filtration efficiency for up to 3 cycles  
· Little effect on FFR fit  
· High powered microwaves may degrade the filter material  | Bergman et al. (2010), Fisher et al. (2011), Lore et al. (2012), Viscusi et al. (2011)  |
| 5    | Ethylene oxide (EtO) gas                | Leads to alkylation which causes structural changes in proteins and nucleic acids | • Can be used to disinfect equipment which are sensitive to heat and moisture.  
• Inactivates all types of microorganisms  
• Generally does not affect physical appearance, fitting and filter performance  | Potential carcinogen EtO is not recommended as it is highly reactive, diffusible toxic gas and needs a long aeration time to be completely removed. Presence of residual gas  |  | Viscusi et al. (2009), Salter et al. (2010)  |
| 6    | Chlorine and chlorine related compounds | Mechanism of action not fully understood  
• Antimicrobial action against a vast array of microbes.  
• High biocidal efficacy  |  | Unpleasant odor of bleach remains after disinfection.  
Chlorine off-gassing may also be observed.  | · Does not affect filtration performance for up to 3 cycles.  
· 2-hydroxyethyl acetate residue was formed as a byproduct  | Bergman et al. (2010), Viscusi et al. (2009), Lin et al. (2017), Salter et al. (2010)  |
| 7    | Alcohol                                 | Denaturation of proteins                                                      | Not recommended for disinfection of medical apparatus.  |  |  | Lin et al. (2017)  |
b. Gassing Dwell: This is the time allowed for \( \text{H}_2\text{O}_2 \) vapors to penetrate and decontaminate all layers/ parts of the FFR. During this time, \( \text{H}_2\text{O}_2 \) vapors will be released at a low rate to maintain the minimum concentration of 480 ppm. Current practices involving decontamination through \( \text{H}_2\text{O}_2 \) vapors allow the FFRs to be in contact with \( \text{H}_2\text{O}_2 \) for 20 min after the gassing phase (Schwartz et al., 2020; Battelle, 2016). This will allow enough time for the \( \text{H}_2\text{O}_2 \) to interact with the microorganisms and to completely inactivate it. A lesser time may allow the \( \text{H}_2\text{O}_2 \) to damage, but may not be able to com-
with nitric oxide (NO) \textit{(in vivo)} to form the peroxynitrite ion which can lead to lipid peroxidation, protein oxidation and inactivation of microbial enzymes (Hogg et al., 2017, Trujillo et al., 2010). Studies have suggested that the VHP displays a better ability to degrade protein structure (Fichet et al., 2007). The primary virucidal mechanism of \( \text{H}_2\text{O}_2 \) is excessive disruption to viral nucleic acids, lipids, and other cell components by OH-radicals for which virus do not bear any repair mechanism (McDonnell, 2009). UV C mainly inactivates the microorganism by disrupting nucleic acids. This occurs because UV C light causes pyrimidine-type molecules (in RNA and DNA) to dimerize which causes distortions in nucleic acid molecules, ultimately leading to cell/virus death (Chang et al., 1985). UV C irradiation will also convert the remaining \( \text{H}_2\text{O}_2 \) into radical species, further leading to the elimination of viable microorganisms. The detailed schematic representation on FFR treatment is presented in Fig. 4.

\( \text{H}_2\text{O}_2 \) is a safer, healthier oxidizing option typically available at a concentration of 35% which is effective against a range of bacteria, fungi, yeasts, viruses, and spores. Exposure of \( \text{H}_2\text{O}_2 \) vapor (20 \( \mu \)l) to a coronavirus surrogate TGEV on stainless steel for 2–3 h was observed to result in roughly a drop of 5 log10 (TCID 50 ml–1) as per the study reported by Goyal et al. (2014). Various studies have suggested that VHP (dry or wet) is effective in decontaminating FFR (Bergman et al., 2010; Battelle, 2016, 2020; Viscusi et al., 2009; Schwartz et al., 2020; Torres et al., 2020). Duke University Hospitals are currently using VHP at a concentration of 300-750ppm to decontaminate FFRs (Schwartz et al., 2020). In addition, the U.S. Food and Drug Administration issued an emergency use authorization (EUA) to Advanced Sterilization Products (ASP) for the STERRAD Sterilization Cycles (STERRAD 100S Cycle, STERRAD NX Standard Cycle, or STERRAD 100NX Express Cycle), which uses VHP gas plasma sterilization (Battelle, 2020).

The sterilization effects of UV C light have also been extensively studied. It has been shown that UV C light was successful in inactivating the SARS-CoV (Duan et al., 2003; Darnell et al., 2004). Duan et al. (2003) (45) found that 60 min of UV irradiance is enough to kill viral infectivity at undetectable amounts using a SARS coronavirus strain CoV-P9. Susceptibility of mouse coronavirus, hepatitis virus, Kilham rat virus, and canine parvovirus towards UV irradiation was shown by Sakinit et al. (1998). A UV exposure, particularly UV-C, (254 nm, 4016 \( \mu \)W cm\(^{-2} \)) as shown by Darnell et al. (2004), is effective in a 400-fold decrease in infectious virus at 1 min of exposure, which subsequently became fully inactivated after 15 min of exposure. Due to the similarity between the structure of SARS-CoV and SARS-CoV-2 (Zhou et al., 2020), it can be assumed that the latter will also be highly susceptible to UV light (Kowalski et al., 2020). Additionally, a report published in Nebraska Medicine outlined the decontamination process of N 95 FFRs via UVGI. Currently, the University of Nebraska Medical Center uses UVGI to sterilize N95 FFRs in 15 min (Low et al., 2020).

Moreover, upon application of UV C, the residual \( \text{H}_2\text{O}_2 \) will be converted to hydroxyl radicals which will further inactivate the microorganism. The dual action of hydroxyl radicals and UV C will ensure that all biological contaminants are eradicated. Thus, the sterilization process will become more efficient. Owing to the large amount of evidence supporting the individual sterilization properties of \( \text{H}_2\text{O}_2 \) vapors and UV C light, we can safely say that the proposed system will also be effective in the decontamination of FFRs and will provide maximum sanitization.

**Advantages of proposed HDS over single system methods of decontamination**

Simply using UV C to decontaminate respirators will not be effective as the FFRs have layers and the UV C may not be able to completely decontaminate all layers. The Centers for Disease Control and Prevention has suggested that UV C irradiation may not inactivate all biological

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*Fig. 4. Detailed mechanism for decontamination strategies (Step 1 VHP treatment and Step 2 UV-C treatment).*

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The efficiency of sterilization via treatment with \( \text{H}_2\text{O}_2 \) vapors and \( \text{UV} \) C irradiation individually is well recorded in the literature. Fig. 4 displays the mechanism of action of \( \text{H}_2\text{O}_2 \) and \( \text{UV C} \) light against microorganisms. \( \text{H}_2\text{O}_2 \) decomposes into reactive oxygen species (hydroxyl radicals, OH and superoxide ions, \( \text{O}_2^{-} \)) which attack important biomolecules that create cellular/viral structure and function (Linley et al., 2012). Moreover, the superoxide ion may combine

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contaminants on an FFR due to shadow effects produced by the multiple layers of the FFR’s construction (Lindsay et al., 2015). Therefore, solely relying on UV C treatment may not offer maximum decontamination.

The use of VHP also has some disadvantages. In systems involving decontamination through VHP, after treatment with H₂O₂ gas, the chamber has to be filled with fresh air to decompose all residual H₂O₂ into H₂O and O₂. This process is called de-gassing and it is a very time-consuming. The chamber is usually safe to enter only after 4 h, which makes the overall VHP based decontamination process not a very efficient one (Schwartz et al., 2020). Thus, in the proposed dual system, using UV C light following VHP treatment will achieve two purposes viz. i. inactivation of all remaining biologic contaminants and ii. conversion of residual H₂O₂(g) into water and oxygen and reduce the overall time of decontamination. Being sensitive, H₂O₂ breaks down to produce radical species in presence of light. In absence of any other chemicals, these radicals recombine to form stable products, in this case, water and oxygen (https://www.rsc.org/Education/Teachers/Resources/Contemporary/ student/pop_peroxide.html). Short wavelength UV light catalyzes the process that reduces overall de-gassing time. This will allow the user to observe maximum sanitization while the process remains time efficient.

Effectiveness of FFRTs post sterilization

Reports have shown that the sterilization technology equipped with vaporous H₂O₂ and UVCGI will not impair the FFR filtration performance and fit of the FFR (Table 2). When used individually, UV-C rays as high as 950 J cm⁻² efficiently sterilize the FFRTs without damaging its filtration performance and fitting to the user (Lindsay et al., 2015; Liao et al., 2020). This system utilizes a UV dose of 300 mJ cm⁻² which is well below the dose required to alter the filtration performance of the respirator. Treatment using vaporous H₂O₂ alone does not damage the function of FFR up to 20 cycles. Therefore, we are aiming at least 10 cycles of complete decontamination of FFRTs using the proposed device.

There will be no chemical residue post sterilization as fresh air will be circulated which will convert all remaining H₂O₂ into water and oxygen. The FFRTs will be removed only when the H₂O₂ concentration is below detectable levels. It should, however, be noted that the proposed system has only been conceptualized and designed. Therefore, the FFR function should be checked after each sterilization cycle. The standard protocol for determining the efficiency level for N95 FFRTs is provided by National Institute for Occupational Safety and Health (NIOSH) and the same procedure may be used to check the FFR filtration performance after sterilization (NIOSH, 2019) (NIOSH, 2020). The fit of the FFR must also be evaluated before the FFR is reused. A recent study on the aspect of the reusability and decontamination methods of N95 masks has been reviewed by Peters et al. (Peters et al., 2021). However, appropriate preparation on the technology development and related application is seems to be necessary, even for the future.

Conclusion

The lack of PPE is a major factor in the transmission of the pandemic COVID19 among the frontline staff engaged in testing, treating, and handling infectious people. One of the suggested solutions to minimize mass demand for N95 FFRTs is to reuse them after sufficient decontamination, enabling any contagious surface to be inactivated along with not compromising FFR quality. While FFRTs N95s are unapproved for routine decontamination as a normal practice, CDC, USA reported that FFR decontamination and reuse could be needed during scarcity to provide assured supply. Among the various suitable method suggested for FFR decontamination vaporous hydrogen peroxide (VHP) and UV C irradiation are effective methods for the decontamination of FFRTs with no immediate health and environmental concern. It has been shown that these two methods do not hamper the filtration efficiency and the FFR fit for up to 10 cycles with VHP and 3 cycles with UV. However, there are limitations associated with both disinfection techniques when used individually. Therefore, we have conceptualized and proposed a Hybrid Decontamination System (HDS) which combines the advantages of both methods and minimizes the limitations. The proposed decontamination technique is time efficient and will ensure maximum decontamination of FFRTs.

It is anticipated that in absence of appropriate manufacturer recommendations about FFR decontamination, facilities dealing with COVID19 cases may consider adopting and developing such strategies to minimize the shortage of N95s. Though it is expected that the proposed strategy would effectively decontaminate without impacting the respirator functionality and effectiveness; however, it is emphasized that the proposed system must be tested as per NIOSH standard protocol for the efficacy of the FFRTs post sterilization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethics approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Consent for publication

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References

ECRI. 2020. Safety of extended use and reuse of N95 respirators. ECRI Clin. Evid. Assess. March 2020, 1-26. Available at: https://www.e Lover.com/data/assets/pdf_file/0006/997863/COVID-ECRI-N95-Respirators-2020-03.pdf.

NPPTL-CDC. 2020. NIOSH-Approved Particulate Filtering Facepiece Respirators, April 9, 2020. Available at: https://www.cdc.gov/niosh/nptl/topics/respirators/disp_part/default.html.

CDC. Decontamination and reuse of filtering facepiece respirators. 2020a. Available at: https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe-strategy/decontamination-reuse-respirators.html, [Accessed 27 September 2020].

CDC. N95: myth v/S facts. 2020b. Available at: https://www.cdc.gov/niosh/nptl/pdfs/ infoographic-n-95-508.pdf.

Bergman, M.S., Viccari, D.J., Heimbuch, B.K., Wander, J.D., Sambol, A.R., Shaffer, R.E., 2010. Evaluation of multiple (3-Cycle) decontamination processing for filtering facepiece respirators. J. Eng. Fibers and Fabr. 5, 33–41. doi:10.1177/15589295100500405.

Nogier, D., Tomassoni, A., 2020. Covid 19 and the N95 respirator shortage: closing the gap. Infect. Control Hosp. Epidemiol. doi:10.1017/ice.2020.12418, PMCID: PMC7205548.

Wu, H., Huang, J., Zhang, C.J.P., He, Z., Ming, W.K., 2020. Facemask shortage and the novel coronavirus disease (COVID-19) outbreak: reflections on public health measures. ElcminicalMedicine 21, 100329. doi:10.1016/j.clinmed.2020.100329.

Rodriguez-Martinez, C.E., Sossa-Briceno, M.P., Cortés-Luna, J.A., 2020. Decontamination and reuse of N95 filtering facepiece respirators: a systematic review of the literature. Am. J. Infect. Control 48 (12), 1520–1532. doi:10.1016/j.ajic.2020.07.004.
of the processes and removal of resistance gene. J. Environ. Chem. Eng. 8 (1), 1026-1034.
Bounty, S., Rodriguez, R.A., Linden, K.G., 2012. Inactivation of adenovirus using liquid H2O2/HCl oxidation. Water Res. 46 (13), 6273-6278. doi: 10.1016/j.watres.2012.08.036.

Grossman, J., Pierce, A., Mody, J., Gagne, J., Sykorá, C., Sayood, S., Cook, S., Shomer, N., Liang, S.Y., Eckhouse, S., 2020. Institution of a novel process for N95 respirator disinfection with vaporized hydrogen peroxide in the setting of the COVID-19 pandemic at a large academic medical center. J. Am. Coll. Surg. 231 (2), 279-280. doi: 10.1016/j.jamcollsurg.2020.04.029.

Tseng, C.C., Li, C.S., 2007. Inactivation of viruses on surfaces by ultraviolet germicidal irradiation. J. Occup. Environ. Med. 49 (4), 400-405. doi: 10.1528/joem.2007-0129.

Linley, E., Denyer, S.P., McDonnell, G., Simons, C., Maillard, J.Y., 2012. Use of hydrogen peroxide as a biocide: new consideration of its mechanisms of biocidal action. J. Antimicrob. Chemother. 67 (7), 1589-1596. doi: 10.1093/jac/dks129.

Hogg, R., Tenlenka, J., Kauppinen, V., 2017. Detection of nitric oxide and peroxynitrite in biological systems: a state-of-the-art review. Nitric Oxide 23-44. doi: 10.1016/j.nitro.2019.04.0273.10000-3.

Trujillo, M., Alvarez, B., Souza, J.M., Romero, N., Latorr, R., 2010. Mechanisms and biological consequences of peroxynitrite-dependent protein oxidation and nitration. Nitric Oxide 61-102. doi: 10.1016/j.nitro.2011.06.016.3.

Ficht, G., Antloge, K., Comoy, E., Deslys, J.P., McDonnell, G., 2007. Prior inactivation using a new gaseous hydrogen peroxide sterilisation process. J. Hosp. Infect. 67 (3), 278-286. doi: 10.1016/j.jhiny.2007.08.020.

Torres, A.E., Lyons, A.B., Narla, S., Kohli, I., Parks-Miller, A., Ozog, D., Hamzavi, I.H., Lim, W.H., 2020. Ultraviolet-C and other methods of decontamination of filtering facepiece N95 respirators during the COVID-19 pandemic. Photochem. Photobiol. Sci. 19, 746-751. doi: 10.1038/s41571-020-0331z.

Sau, D.M., Zhao, X.S., Wen, R.F., Huang, J.J., Pi, G.H., Zhang, X.S., Han, J., Bi, S.L., Ruan, L., Dong, X.P., 2003. SARS Research Team. Stability of SARS coronavirus in human respiratory and environmental samples. J. Med. Virology. 71 (2), 178-185. doi: 10.1002/jmv.10515.

Xing, F., Wang, J., Wang, C., Wang, L., Shi, Y., Hu, Y., 2020. Conventional and rapid disinfection methods of filtering facepieces against COVID-19. Food Chem. 319, 127190. doi: 10.1016/j.foodchem.2020.127190.

Zhang, P., Xiong, J., Guo, Q., Sun, G., Liu, H., Gao, X., Yan, J., Wang, L., Su, L., 2020. Effect of hydrogen peroxide treatment on the filtration performance and structural integrity of N95 respirators. J. Occup. Environ. Health. 12 (8), 509-517. doi: 10.15954/10.15186/joeh.2015.10185.

Venugopal, A., Ganesan, H., Raja, S.S.S., Govindasamy, M., Arunasalam, M., Natarajan, A., Shanmugasundaram, P., Ramasamy, K., Velligiri, B., 2020. Novel wastewater surveillance strategy for early detection of COVID-19 outbreaks. Curr. Opin. Environ. Sci. 17, 8-13. doi: 10.1016/j.cospect.2020.05.003.

Chen, J.F.W., Yuan, S.K., Koh, K.H., To, K.K.W., Chu, H., Yang, J., Xing, F., Liu, J., Yip, C.C.Y., Poon, R.W.S., Toi, H.W., 2020. A familial cluster of pneumonia associated with the 2019 novel coronavirus indicating person-to-person transmission: a study of a family cluster. Lancet 395 (10232), 514-523. doi: 10.1016/S0140-6736(20)30154-9.

Wang, J., Shan, J., Ye, D., Yan, X., Zhang, Y., Li, W., Xing, J., Zhang, L., Pan, L., 2020. Disinfection technology of hospital waste and wastewater: suggestions for disinfection strategy during coronavirus disease 2019 (COVID-19) pandemic in China. Environ. Pollut., 114665. doi: 10.1016/j.envpol.2020.114665.

Maris, P., 1990. Virucidal effect of eight disinfectants against pneumovirus, coronavirus and parovirus. Ann. Rec. Vet. 21 (4), 275-279.

Kataki, S., Chatterjee, S., Vairale, M., Sharma, S., Dwivedi, S.K., 2021. Concerns and strategies for wastewater treatment during COVID-19 pandemic to stop plausible transmission. Resour. Conserv. Recycl. 164, 105156. doi: 10.1016/j.resconrec.2021.105156.

US EPA. List N: disinfectants for use against SARS-CoV-2. 2020. Available at: https://www.epa.gov/pesticide-registration/list-n-disinfectants-use-against-sars-cov-2.

Batley, C.E., Laitner, J.M., 2017. The combined effects of hydrogen peroxide and ultraviolet irradiation on bacterial spores. J. Appl. Bacteriol. 47, 263-269. doi: 10.1111/1365-2672.19800753.x.

Sun, P., Tyree, C., Huang, C.H., 2016. Inactivation of Escherichia coli, bacteriophage MS2, and adeno virus type 2 by H2O2/O3/UV photolysis in the optimization of H2O2/UV peroxynitrite advanced disinfection. Environ. Sci. Technol. 50 (8), 4448-4458. doi: 10.1021/acs.est.5b03609.

Colli vignarelli, M.C., Abba, A., Benigna, I., Sorlini, S., Torretta, V., 2018. Overview of the main disinfection processes for wastewater and drinking water treatment plants. Food Addit. Contam. Part A 35 (2), 277-314. doi: 10.1080/19440049.2017.1376683.

Galvis, E.A.S., Osipina, I.S., Jiménez, J.N., Fino, N.J., Palma, R.A.T., 2018. Elimination of carbapenem resistant Klesibacilla pneumoniae in water by UV-C, UV-C/ peracetic acid and UV-C/H2O2. Evaluation of response to antibiotic resistance, residual effect
Lin, T.H., Chen, C.C., Huang, S.H., Kuo, C.W., Lai, C.Y., Lin, W.Y., 2017. Filter quality of electret masks in filtering 14.6-594 nm aerosol particles: effects of five decontamination methods. PloS one 12 (10), e0186217. doi:10.1371/journal.pone.0186217.
Salter, W.B., Kinney, K., Wallace, W.H., Lumley, A.E., Heimbuch, B.K., Wander, J.D., 2010. Analysis of residual chemicals on filtering facepiece respirators after decontamination. J. Occup. Environ. Hyg. 7 (8), 437–445. doi:10.1080/15459624.2010.484794.
NIOSH, 2019. Determination of particulate filter efficiency level for N95 series filters against solid particulates for non-powdered air purifying respirators standard test procedure (STP). NIOSH STP, Dec 2019 (Procedure no. TEB-APR-STP-0059, Revision: 3.2), 19. https://www.cdc.gov/niosh/npptl/stps/pdfs/TEB-APR-STP-0059-508.pdf