Photodiagnosis and Photodynamic Therapy 31 (2020) 101943

Contents lists available at ScienceDirect

Photodiagnosis and Photodynamic Therapy

journal homepage: www.elsevier.com/locate/pdpdt

Review

Ultraviolet germicidal irradiation for filtering facepiece respirators disinfection to facilitate reuse during COVID-19 pandemic: A review

Hua Yang[a], Jiajia Hu[b], Ping Li[c,d], Chengliang Zhang[e,*]

[a] Department of Thoracic Internal Medicine, Hunan Cancer Hospital, Affiliated Cancer Hospital of Xiangya Medical School, Central South University, Changsha, China
[b] Department of Anesthesiology, Xiangya Hospital, Central South University, Changsha, China
[c] Department of Obstetrics, Xiangya Hospital, Central South University Changsha, China
[d] Hunan Engineering Research Center of Early Life Development and Disease Prevention, Changsha,China
[e] Department of Cardiovascular Surgery, Xiangya Hospital, Central South University, Changsha, China

ARTICLE INFO

Keywords:
Ultraviolet germicidal irradiation
Filtering facepiece respirators
COVID-19 pandemic
N95
Reuse
Decontamination

ABSTRACT

Background: To review the effect of ultraviolet germicidal irradiation (UVGI) as a disinfection method for filtering facepiece respirators (FFRs) to facilitate reuse during COVID-19 pandemic.
Methods: Systematic review of the research concerning UVGI for FFRs disinfection to facilitate reuse (also termed limited reuse) during respiratory infectious diseases where aerosol transmission is considered possible.
Results: UVGI is one possible method for respiratory disinfection to facilitate the reuse of dwindling supplies. Appropriate dose UVGI exposition could provide enough energy to effectively decontaminate respiratory viral agents and maintain respirator's integrity for reuse. There was not currently sufficient research evidence on the effect of UVGI to inactivate coronaviruses SARS-CoV-2, and the practical application of UVGI is still unclear. .
Conclusion: Appropriate dose UVGI exposition could provide enough energy to effectively decontaminate respiratory viral agents and maintain respirator's integrity for reuse. Further evidence concerning UVGI as a decontamination technique specifically for SARS-CoV-2 isneeded.

1. Introduction

The Coronavirus pandemic (COVID-19) highlighted by the severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) has been global, with the death of over 535,000 as of July 6, 2020.. COVID-19 is contagious, and the main transmission routes are droplet, contact, and even airborne modalities [1]. COVID-19 is currently spreading explosively without effective clinical treatment, and extensive measures to reduce interpersonal transmission have been performed to control theoutbreak. Respiratory protection with the use of a mask respirator has been selected to prevent novel coronavirus transmission [2], as a public health intervention to intercept the transmission link and prevent spread [3].

The N95 filtering facepiece respirators (FFRs) typically made of meltblown polypropylene fabric, are capable of blocking more than 95 % of 0.3 μm airborne particles, and are a widely used effective respiratory protection device to reduce exposure [4]. The N95 FFR has been widely used successfully in previous severe acute respiratory syndrome(SARS), Middle Eastern respiratory syndrome (MERS), pandemic influenza, and other emerging infectious respiratory diseases [5–7]. National Institute for Occupational Safety and Health (NIOSH) recommended the use of FFR is at least NIOSH-approved N95 FFR during the influenza pandemic. The N95 FFR was also recommended for protecting medical workers by the Centers for Disease Control and Prevention (CDC) during the 2009 H1N1 pandemic [7]. The researchers reported that medical masks or N95 FFRs can effectively limit the virus spread and reduce the infection risk [8, 9].

The used N95 FFRs and medical masks may be contaminated by pathogens, which can be healthy infectious sources transferring to the users and cause pathogen infection. N95 FFRs and medical masks are intended for single-use and disposable design [10]. However, the global shortage of FFRs is another crisis [11]. Worldwide shortage supplement of FFRs has occurred because manufacturing production is unable to meet the dramatically growing demand while FFR stockpiles have been depleted, the shortage of raw materials and production capacity [12].

Currently, a possible strategy for N95 FFRs or medical masks shortage is to reuse them with proper decontamination process. The decontamination methods should not deteriorate the respirator filtering power or release any toxic substance. The damage of medical masks or N95 FFRs blocking structure caused by improper decontamination

* Corresponding author at: Department of Cardiovascular Surgery, Xiangya Hospital, Central South University, 87 Xiangya Road, Changsha, Hunan 410008, China.
E-mail address: zhangchengliang@csu.edu.cn (C. Zhang).

https://doi.org/10.1016/j.pdpdt.2020.101943
Received 6 July 2020; Received in revised form 29 July 2020; Accepted 31 July 2020
Available online 04 August 2020
1572-1000/

methods can bring an unacceptable infection disaster. The CDC reported that autoclave, dry heat, isopropyl alcohol, soap and water cause significant respirators filter degradation, significantly increase particle penetration, and decrease FFR filtering power [13]. To eliminate the potential infection risk, N95 FFRs and medical masks should be completely decontaminated before reuse. Numerous decontaminate measures have been recommended for N95 FFRs and medical masks reuse, but specific instruments or materials were required [14]. Ultraviolet germicidal irradiation (UVGI) is a disinfection method that inactivates microorganisms by damaging DNA and preventing microorganism replication by ultraviolet C (UV-C) radiation within the 254 nm electromagnetic short wave [15,16]. The research confirmed that UV-C can inactivate coronaviruses including severe acute respiratory syndrome coronavirus (SARS-CoV), Middle East respiratory syndrome coronavirus (MERS-CoV) [17], influenza [18,19]. UVGI is one possible effective decontamination method for respiratory disinfection to facilitate the reuse of decreased supplies.

2. Materials and methods

Systematic review the research concerning UVGI for FFRs disinfection to facilitate reuse during respiratory infectious diseases where aerosol transmission is considered possible. The research concerning UVGI for FFRs disinfection are summarized

Extensive pieces of laboratory research concerning UVGI for FFRs disinfection to facilitate the reuse of dwindling supplies (Table 1).

In 2009 research, FFRs fitted with a 40-W UV-C light (intensity $0.18-0.20\ mW\cdot cm^{-2}$, dose 176–181 $mJ\cdot cm^{-2}$, duration 15 min), and result indicated that UVGI may be the most promising decontamination measurement for the advantages of effective agent elimination and FFR integrity maintenance, without significant alter the filter penetration, airflow resistance, and physical appearance [20]. Meanwhile, this research team found that UVGI did not influence the wearing experience of FFR users including fit, odor, comfort, and donning difficulty [21].

Another research that FFRs contaminated with the H1N1 influenza virus were fitted with 80-W UV-C (intensity 1.6–2.2 $mW\cdot cm^{-2}$, dose $18\ kJ\ m^{-2}$, duration 15 min) in a 120 cm × 25 cm box. Meanwhile, microwave-generated steam (MGS), warm moist heat (WMH) were performed for comparison. Results confirmed all these three decontamination technologies provided 4-log reduction of the viable H1N1 virus, and the H1N1 influenza virus was reduced to below the limit of detection levels in 93 % FFRs [22]. However, this study did not evaluate the respirator filtering power, and structural integrity. The dose of UV-C was higher than that examined in the following trial.

In 2012, Lore et al. [19] performed an examination with 15-W UV-C (intensity 1.6–2.2 $mW\cdot cm^{-2}$, dose $18\ kJ\ m^{-2}$, duration 15 min) in a 126 cm × 15.2 cm × 10.8 cm lamp. Comparing to MGS and WMH, UVGI was demonstrated to be the most effective method in quantitatively reducing Influenza FA RNA on FFRs. Meanwhile, results indicated that UVGI in this dose did not significantly degrade the filter penetration at 300-nm particle size.

Another research was performed in 2015 [23]. In a 91 cm × 31 cm × 64 cm high chamber, The FFRs were fitted with two 15-W UV-C light at 0, 120, 240, 470, and 950 $J\cdot cm^{-2}$ on each side. The result showed the FFR filtration performance and flow resistance do not decrease at doses up to 950 $J\cdot cm^{-2}$. However, the result suggested that the breaking strength of FFR decreased after a dose of 2360 UVGI exposure, and the disinfection cycles should be limited.

N95 FFRs contaminated with the H1N1 influenza virus accepted a UV-C light (dose 1 $J\cdot cm^{-2}$, duration 1 min). Results showed that all FFRs treated with UVGI were cut out and the H1N1 influenza virus was extracted. The influenza viability was significantly reduced (≥ 3 logs) on the N95 FFRs' surfaces [18]. Research performed by Liao et al. [24] in 2020 examined the FFRs decontamination methods including heat under various humilities, steam, alcohol, diluted chlorine-based solution, and UVGI, and found that UVGI (254 nm, 8 W) does not change the filtration properties within reasonable disinfection cycles [18].

We can see that appropriate dose UVGI exposition could provide enough energy to effectively decontaminate respiratory viral agent and maintenance respirator's integrity for reuse. However, the research performed by Lindsley et al. [23] showed the structural integrity of the FFRs had a noticeable decrease at a dose of 2360 $J\cdot cm^{-2}$. The filter penetration and resistance, the strength of the FFR materials were dramatically affected by high UVGI dose [23]. Meanwhile, the research evaluated the disinfection cycle of UVGI (8 W UV-C light) on meltblown samples and found the FFRs data were in agreement with the NIOSH standard at 10 cycles, while decreased to 93 % at 20 cycles [24]. Meanwhile, UVGI treatments at high dosage can lead to improper fitting. So, the upper limit of the UVGI dosage and disinfection cycle would be considered.

The efficacy of UVGI disinfection for FFRs high relates to the UV penetration depth. The polypropylene can absorb the energy of UV, so it is difficult to conclude the effect of UVGI on viral particles that smaller than a wavelength. Furthermore, UVGI requires FFRs to lay on the same distance without stacked. Another disadvantage of UVGI is that UV-C significantly impacts the mechanical strength of FFRs with higher doses over 1000 $J\cdot cm^{-2}$ or more disinfection cycles [23].

Mills et al. [18] emphasized that the intensity of UV-C, FFR model, fit, material type, and design require careful consideration in the UVGI implementation. Meanwhile, Lindsley et al. suggested that the disinfection cycle number should match the FFR model and the UVGI dose required to inactivate the pathogen without filtration properties damage [23]. There was no sufficient data concerning the effect of UVGI on the elastic of PPRs. But several studies tested the breaking strength of FFR, and found a dose of over 2360 J/cm2 reduced the breaking strength of the straps by 20–51 %. The break down rate of elastic under UV-C still unclear basing on current data. Research showed that the filter penetration, flow resistance, breaking strength fit, odor detection, comfort, and donning difficulty and appearance. The break down rate of elastic should be tested in the future.

So, we should keep in mind that N95FFR reuse is referred to as "limited reuse" [10]. Improper use of UV germicidal lamps had the potential consequences of phototoxicity [25]. Meanwhile, the technical and device design, staff training will be essential to the successful practical application of UVGI. decontamination must account for actual clinical practice, regulations, and financial considerations. so that UVGI may mitigate potential FFR shortages in a pandemic[26]

Unfortunately, there was no reported research concerning the effect of UVGI in inactivating coronaviruses SARS-CoV-2. Limited reuse of FFRs has been recommended and widely used during previous respiratory pathogen pandemics [27,28]. Experts call for the proposed study to investigate the effect of UVGI on N95 FFR decontamination during the COVID-19 pandemic for FFR reuse [29]. Meanwhile, the effect of UVGI on the elastic of FFRs and medical masks, and the sources of UV-C are important issues to evaluate in the future.

In conclusion, appropriate dose UVGI exposition could provide enough energy to effectively decontaminate respiratory viral agent and maintenance respirator's integrity for reuse. There is not sufficient evidence to assess the effect of UVGI for FFRs decontamination of SARS-CoV-2. Further evidence concerning UVGI as a decontamination technique for SARS-CoV-2 is needed.

Funding statement

This work was supported by the Natural Science Foundation of Hunan Province [2019JJ50950 to Chengliang Zhang], and the Youth Science Foundation of Xiangya Hospital [2019Q14 to Chengliang Zhang]

Acknowledgements

We thank all the investigators completing the original studies where

Table 1
Researches of ultraviolet germicidal irradiation for filtering facepiece respirators disinfection.

Year	First author	Pathogens	FFRs	Decontamination treatments	Laboratory conditions	UVGI methods	Research items
2009	Viscusi	None	Three N95 FFR models, three surgical N95 respirator models, Three models of P100 FFRs	UVGI, EtO, VHP, microwave, bleach	T 21 ± 2°C, RH 50 ± 10 %	FFRs fitted with a 40-W UV-C light (average UV intensity range from **0.18 to 0.20 mW•cm^{-2}**). 15 min exposure to outer and inner side, **176–181 mJ• cm^{-2}** exposure to each side of FFRs.	Filter aerosol penetration, filter airflow resistance.
2011	Viscusi	None	3 M 1870, 3 M 1860s	UVGI, MGS, and MH	T 21 ± 2°C, RH 50 ± 10 %	FFRs fitted with a 40-W UV-C light (UV intensity **1.8 mW•cm^{-2}**). exposure 30 min (15 min each FFR side).	FFRs in fit, odor detection, comfort, and donning difficulty
2011	Heimbuch	Influenza A	Three N95 FFR models (3 M 8210, 3 M 8000, Moldex 2200) and three surgical N95 respirator models (PFR95−270, 3 M 1870, 3 M 1860)	MGS, WMH, and UVGI	T 22 ± 2°C, RH 75 ± 5%	120 cm × 25 cm box, 80-W UV-C, **1.6 − 2.2 mW•cm^{-2}**, an average dose of **18 kJ m^{-2}**, 15 min	Concentration of viable virus
2012	Lore	Influenza A/ H5N1	3 M models 1860s and 1870 108 FFRs	UVGI, MGS, and MH	T 22 ± 2°C, RH > 60 %	**1.6–2.2** mW˙cm^{-2}, 15 min at a total UV-C dose of **18 kJ m-^{2}**.	Virus concentrations, virus extraction efficiency, virus culture quantification
2015	Lindsley	None	3 M 1860, 3 M 9120, GE 1730, 3 M KC 46,727	UVGI	T 27 ± 1.7°C, RH 25 ± 6.5 %	The FFRs were exposed to 15-W, **dose of** 0, 120, 240, 470, or 950 J•cm^{-2} of UV-C on each side. To expose the respirator straps, eight FFRs were exposed to 0, 590, 1180, or 2360 J•cm^{-2} to the FFRs.	Filter penetration, and flow resistance
2018	Mills	H1N1 influenza	Fifteen NIOSH-approved N95 FFR	UVGI	T 21 ± 2°C, RH 48 ± 6%	a UV dose of **1 J•**cm^{-2} in approximately 1 min	Viable virus recovered from each sampled location
2020	Liao	None	3 M 8210, 4C Air, ESound, Onnuriplan	heat under various humidities, steam, alcohol, diluted chlorine-based solution, UVGI	Not mentioned	UV-C with an intensity of 8 W, Samples were irradiated for 30 min and left to stand under ambient conditions for 10 min per cycle	degradation efficiency, meltblown fabrics resistence

EtO: ethylene oxide; VHP: vaporized hydrogen peroxide; UVGI: ultraviolet germicidal irradiation; MGS: microwave-generated steam; WMH: warm moist heat; UV-C: UVC: ultraviolet C; UV: ultraviolet; FFR: filtering facepiece respirator; NIOSH: National Institute for Occupational Safety and Health; T: temperature; RH, relative humidity.

we got our data. And we especially appreciate to all health care workers for their efforts to the control of COVID-19.

References

[1] A.A. Chughtai, H. Seale, M.S. Islam, et al., Policies on the use of respiratory protection for hospital health workers to protect from coronavirus disease (COVID-19), Int. J. Nurs. Stud. 105 (2020) 103567.
[2] A. Azap, F.S. Erdinc, Medical mask or N95 respirator: when and how to use? Turk. J. Med. Sci. (2020).
[3] C.C. Leung, T.H. Lam, K.K. Cheng, Mass masking in the COVID-19 epidemic: people need guidance, Lancet 395 (10228) (2020) 945.
[4] NIOSH Guide to the Selection and Use of Particulate Respirators, National Institute for Occupational Safety and Health, 2017 Available at: https://www.cdc.gov/niosh/docs/96-101/default.html.
[5] Pandemic Influenza Preparedness and Response Guidance for Health Care Workers and Health Care Employers, Occupational Safety and Health Administration, 2009 Available at: https://www.osha.gov/Publications/OSHA_pandemic_health.pdf.
[6] Interim Domestic Guidance on the Use of Respirators to Prevent Transmission of SARS, Centers for Disease Control and Prevention, 2020 Available at: https://www.cdc.gov/sars/clinical/respirators.pdf.
[7] M.E. Gosch, R.E. Shaffer, A.E. Eagan, et al., B95: a new respirator for health care personnel, Am. J. Infect. Control 41 (12) (2013) 1224–1230.
[8] Z.G. Zhou, D.S. Yue, C.L. Mu, et al., Mask is the possible key for self-isolation in COVID-19 pandemic, J. Med. Virol. (2020).
[9] Q.X. Ma, H. Shan, H.L. Zhang, et al., Potential utilities of mask-wearing and instant hand hygiene for fighting SARS-CoV-2, J. Med. Virol. (2020).
[10] Recommended Guidance for Extended Use and Limited Reuse of N95 Filtering Facepiece Respirators in Healthcare Settings, Centers for Disease Control and Prevention, 2017 Available at: https://www.cdc.gov/niosh/topics/hcwcontrols/recommendedguidanceextuse.htm.
[11] M.W. Wang, M.Y. Zhou, G.H. Ji, et al., Mask crisis during the COVID-19 outbreak, Eur. Rev. Med. Pharmacol. Sci. 24 (6) (2020) 3397–3399.
[12] M.L. Ranney, V. Griffeth, A.K. Jha, Critical supply shortages - the need for ventilators and personal protective equipment during the Covid-19 pandemic, N. Engl. J. Med. (2020).
[13] Coronavirus Disease 2019 (COVID-19), Centers for Disease Control and Prevention, 2019 Available at: https://www.cdc.gov/coronavirus/2019-ncov/hcp/ppe-strategy/decontamination-reuse-respirators.html.
[14] B. van Straten, P. de Man, J. van den Dobbelsteen, et al., Sterilization of disposable face masks by means of standardized dry and steam sterilization processes; an alternative in the fight against mask shortages due to COVID-19, J. Hosp. Infect. (2020).
[15] E.M. Allen, M.F. Mctague, C.P. Bay, et al., The effectiveness of germicidal wipes and ultraviolet irradiation in reducing bacterial loads on electronic tablet devices used to obtain patient information in orthopaedic clinics evaluation of tablet cleaning methods, J. Hosp. Infect. (2020).
[16] Ultraviolet-based biophotonic technologies for control and prevention of COVID-19, SARS and related disorders[J].
[17] K. Bedell, A.H. Buchaklian, S. Perlman, Efficacy of an automated multiple emitter whole-room Ultraviolet-C disinfection system against coronaviruses MHV and MERS-CoV, Infect. Control Hosp. Epidemiol. 37 (5) (2016) 598–599.
[18] D. Mills, D.A. Harnish, C. Lawrence, et al., Ultraviolet germicidal irradiation of influenza-contaminated N95 filtering facepiece respirators, Am. J. Infect. Control 46 (7) (2018) e49–e55.
[19] M.B. Lore, B.K. Heimbuch, T.L. Brown, et al., Effectiveness of three decontamination treatments against influenza virus applied to filtering facepiece respirators, Ann. Occup. Hyg. 56 (1) (2012) 92–101.
[20] D.J. Viscusi, M.S. Bergman, B.C. Eimer, et al., Evaluation of five decontamination methods for filtering facepiece respirators, Ann. Occup. Hyg. 53 (8) (2009) 815–827.
[21] D.J. Viscusi, M.S. Bergman, D.A. Novak, et al., Impact of three biological decontamination methods on filtering facepiece respirator fit, odor, comfort, and donning ease, J. Occup. Environ. Hyg. 8 (7) (2011) 426–436.
[22] B.K. Heimbuch, W.H. Wallace, K. Kinney, et al., A pandemic influenza preparedness study: use of energetic methods to decontaminate filtering facepiece respirators contaminated with H1N1 aerosols and droplets, Am. J. Infect. Control 39 (1) (2011) e1–e9.
[23] W.G. Lindsley, S.J. Martin, R.E. Thewlis, et al., Effects of ultraviolet germicidal irradiation (UVGI) on N95 respirator filtration performance and structural integrity, J. Occup. Environ. Hyg. 12 (8) (2015) 509–517.
[24] L. Liao, W. Xiao, M. Zhao, et al., Can N95 respirators Be reused after disinfection? How many times? ACS Nano (2020).
[25] K. Leung, T. Ko, Improper use of germicidal range ultraviolet lamp for household disinfection leading to phototoxicity in COVID-19 suspects, Cornea (2020).
[26] C. Nemeth, D. Laufersweiler, E. Polander, et al., Preparing for an influenza pandemic: hospital acceptance study of filtering facepiece respirator decontamination using ultraviolet germicidal irradiation, J. Patient Saf. (2020).
[27] S. Beckman, B. Materna, S. Goldmacher, et al., Evaluation of respiratory protection programs and practices in California hospitals during the 2009-2010 H1N1 influenza pandemic, Am. J. Infect. Control 41 (11) (2013) 1024–1031.
[28] L. Hines, E. Rees, N. Pavelchak, Respiratory protection policies and practices among the health care workforce exposed to influenza in New York State: evaluating emergency preparedness for the next pandemic, Am. J. Infect. Control 42 (3) (2014) 240–245.
[29] D. Nogee, A. Tomassoni, Concise communication: Covid-19 and the N95 respirator shortage: closing the gap, Infect. Control Hosp. Epidemiol. (2020) 1–4.