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# Potential of ultraviolet germicidal irradiation for infection prevention and control of SARS-CoV-2 in South Africa

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## Abstract

The response to the challenges arising during the COVID-19 pandemic has seen the rapid implementation of innovative technological solutions which have been built on established knowledge and resources. This has been reflected in infection, prevention and control practices (IPC) to minimise the transmission of the disease. In this article, we review ultraviolet germicidal irradiation (UVGI) as such a technology. We illustrate the way it has traditionally been used in airborne and surface disinfection strategies, and how it has, more recently, been adapted. UVGI has been widely used as an environmental IPC measure against tuberculosis in South Africa, though challenges have been experienced in the implementation of the technology in public healthcare facilities. This has resulted in the development of a knowledge and infrastructure base. We posit that, given the established UVGI resources in South Africa, the technology may be a viable environmental IPC solution for the COVID-19 period and beyond.

Keywords: coronavirus; COVID-19; UVGI; airborne infection; surface decontamination

## Introduction

Coronavirus disease, more commonly referred to as COVID-19, is caused by the severe acute respiratory syndrome coronavirus, SARS-CoV-2, which is primarily transmitted through droplets generated by coughing and sneezing. It is also spread indirectly when a susceptible individual touches an object which may be contaminated by the virus (fomite transmission), or under special circumstances, by the airborne route, in enclosed spaces, prolonged exposure to respiratory droplets, or inadequate ventilation and air handling (World Health Organization, 2020a; Centers for Disease Control and Prevention, 2020). The World Health Organisation (WHO) classified COVID-19 as a pandemic on 11 March 2020. In response to this global pandemic, the scientific community has driven several parallel health research streams. These include, among others, the genomic and microbiological aspects of the virus; clinical presentation and treatment of the disease; vaccine development; epidemiology and disease control; and infection prevention and control (IPC) practices in domestic and clinical settings. IPC, by virtue of being a practical and evidence-based approach for protecting patients and health workers from being harmed by avoidable infections (World Health Organization, 2016), has received much attention. There are several IPC strategies for the control of infectious diseases, including environmental and engineering controls (World Health Organization, 2020b). Capitalising on established resources and knowledge for the prevention and control of COVID-19 would save financial resources and time (Morawska, et al., 2020). This would demand revisiting the measures that have been implemented for infectious

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diseases and considering how they might be appropriated and deployed to address the challenges posed by COVID-19.

In this review article we consider an already well understood and established technology – ultraviolet germicidal irradiation (UVGI) – as a potential solution in IPC practices to minimise the risk of transmission of COVID-19. UVGI is a recognised environmental control measure used to minimise the risk of transmission of airborne diseases, such as tuberculosis (World Health Organization, 2009), and is recommended globally by health agencies to kill infectious microorganisms as it is considered to be "cost efficient, accessible and installation friendly" (Mamahlodi, 2019). UVGI refers to the use of ultraviolet radiation, which presents in the shortwave UV-C range (100 to 280nm) (International Commission on Illumination, 2003) to kill or inactivate microorganisms, such as bacteria, viruses and fungal spores. UVGI has been used to target different microorganisms across different mediums in sanitation and disinfection practices, including airborne disinfection, surface decontamination and water purification. There is limited knowledge on the feasibility of UVGI in preventing and controlling the spread of coronavirus through surface and airborne transmission.

This study reviews the feasibility of UVGI in preventing and controlling the spread of coronavirus. We first present an overview of the scientific evidence for UVGI in sanitation and disinfection. We present the ways in which UVGI is generated and the susceptibility to UVGI of microorganisms, which are the targets of these interventions. Second, we explore the potential that UVGI may have in disinfection and sanitisation strategies to minimise risk of transmission. We also review the way in which UVGI has been implemented in the South African healthcare context. Our discussion draws on the potential and feasibility of UVGI as an IPC measure for SARS-CoV-2 management.

## Generating UVGI

Traditionally, UVGI has been generated using mercury vapour lamps enclosed in UV transmitting glass tubes (Reed, 2010). Lamps may either be low pressure, or medium pressure. Low pressure mercury lamps have monochromatic emission at approximately 253.7nm, while medium pressure mercury lamps have polychromatic emission over a broader spectrum of wavelengths, ranging between 185 to 600nm (Bolton & Cotton, 2011, p. 57). The use of mercury vapour lamps can present challenges emanating from the warm-up time required for design output, their relatively short lifespan leading to frequent lamp replacement, and regulation on the disposal of mercury lamps due to mercury being a toxin. To address the shortfalls, more recently, UV-C light emitting diodes (LED) have been developed. UV-C LEDs have the ability to vary their output intensity, may be installed in small spaces, require no warm-up time, require little maintenance, potentially have a long life, and allow for wavelength selection to target specific microorganisms; UV LEDs however have characteristically low wattages and several LED lamps are required to generate an output similar to that of a single low-pressure mercury lamp (Nunayon, et al., 2020). UV LEDs have had limited technological application due to low radiant efficiency and their relative high cost; the shorter the wavelength, the lower the radiant energy and the higher the cost (Matafonova & Batoev, 2018).

In humans, UV-C may be absorbed by the outer layer of the eyes and skin, and short-term overexposure may be harmful, resulting in photokeratitis and keratoconjunctivitis (NIOSH, 2009). The maximum recommended exposure to UV at 254nm is 6 $mJ/cm^2$ over an 8-hour period (NIOSH, 1972) .

## Microorganism susceptibility to UVGI

When UV-C light penetrates a microorganism, it damages bonds in its nucleic acids resulting in an inability of the microorganism to successfully replicate. The effectiveness of the UVGI system is dependent on the sensitivity of the microorganism to UVGI and the dose of UVGI received by the microorganism. The dose is dependent on the UV irradiance and the exposure time of the microorganism to the UV irradiance (Mills, et al., 2018, p. e51).

Characterising the susceptibility of viral aerosols to UVGI is a first step in determining the potential usefulness of UVGI for the prevention of indoor airborne transmission of viral infectious diseases (Walker & Ko, 2007). Walker & Ko were among the first to investigate the effect of UVGI on viral aerosols. They characterised the UV disinfection of a strain of bacteriophage MS2, respiratory adenovirus and coronavirus (which served as a

surrogate for the SARS coronavirus). They also compared UV susceptibility at 254 nm between viral aerosols and viruses suspended in liquid. During their experimental stage, they found the survival of the coronavirus to be very sensitive to the suspension medium and mechanical forces. Coronavirus is an envelope virus, which was more likely to be inactivated by mechanical stresses. Bacteriophage MS2 and adenovirus were found to be highly resistant to UVGI disinfection, with mean Z values of $3.8x10^4$ and $4.8x10^4$, respectively at a dose of 2608 $\mu Ws/cm^2$ and 50% relative humidity. The susceptibility of the coronavirus was substantially higher, with mean Z value of $37.7x10^4$, at a lower dose of 599 $\mu Ws/cm^2$ and 50% relative humidity. Walker & Ko concluded that UV disinfection rates vary widely among viral aerosols and viruses suspended in liquid.

SARS-CoV-2 is structurally akin to SARS-CoV-1 and Middle Eastern respiratory syndrome coronavirus (MERS-CoV), both of which are susceptible to UVGI (van Doremalen, et al., 2020; Bedell, et al., 2016). van Doremalen et al. (2020) investigated the aerosol and surface stability of SARS-CoV-2 and compared it to SARS-CoV-1, which is the most closely related human coronavirus (Wu, et al., 2020). Five environments were investigated (aerosol, plastic, stainless steel, copper and cardboard) under different experimental conditions for three hours. SARS-CoV-2 remained viable in aerosol form for the duration of the experiments, with a similar rate of decay to that of SARS-CoV-1. SARS-CoV-2 was also found to be more stable on plastic and stainless steel, than on copper and cardboard; viable viruses were found on plastic and stainless steel 72 hours after commencement of tests. Buonanno et al. (2020) investigated the effect of far-UVC (207 to 220 nm) on airborne human coronaviruses alpha HCoV-229E and beta HCoV-OC43. They hypothesised that since all coronaviruses are comparable in physical and genomic size, and since these sizes are a factor in radiation response (Sparrow, et al., 1967), both these viruses, and all human coronaviruses, would respond similarly to far-UVC light. They developed a single-wavelength 222nm far-UVC approach generated by filtered excimer lamps; the ability of far-UVC to penetrate microorganisms is limited compared to that of conventional UVGI at 254nm. The inactivation rate constant, , for the alpha HCoV-229E and beta HCoV-OC43 strains, was 4.1 and 5.9 $cm^2/mJ$, respectively at a dosage to kill 90% ($D_{90}$) of the exposed virus. (3-log reduction). In their study, Buonanno et al. estimated $D_{90}$ values of 0.56 and 0.39 $mJ/cm^2$, for the alpha and beta strains, respectively. This result was comparable to findings by Walker & Ko (2007), who reported a $D_{88}$ value of 0.599 $mJ/cm^2$ for a strain of aerosolised murine beta coronavirus, using conventional UVGI lamps. An advantage of far-UVC is that it does not cause harmful exposure to humans.

Most microorganisms have developed repair mechanisms, which is counterproductive to the damage induced by UVGI. Repair mechanisms include photoreactivation, in which the induced damage is repaired using light energy, and excision repair, which is a dark repair process in which damaged nucleic acids are replaced (Sinha & Hader, 2002). None of the studies we reviewed, investigated photoreactivation and dark repair in the family of coronaviruses.

**Sanitation and disinfection strategies for different mediums and different organisms**

UVGI systems have been used in water purification, airborne disinfection and surface decontamination. Water disinfection by UVGI has been used for more than a century, and has been recommended as an alternative to chemical additives for water treatment (Li, et al., 2017). UV disinfection systems have been installed in water treatment plants and used in household water treatment applications (Brownell, et al., 2008). Recent studies have shown that UV-C LEDs are able to inactivate pathogens in water (Li, et al., 2017; Zou, et al., 2019). As SARS-CoV-2 is transmitted via droplet, contact and airborne routes, we focus on UVGI strategies that may be effective in addressing these transmission routes.

*Surface decontamination*

van Doremalen et al. (2020) showed that virulent SARS-CoV-2 remained (under experimental conditions) on certain surfaces for several days. Reid et al. (2020) investigated the use of UVGI disinfection pods on portable medical equipment (PME) in a healthcare facility. PME are used by multiple members of staff and multiple patients and are a potential source of disease transmission in healthcare facilities. Examples include computer workstations, vital signs monitoring devices and porter wheelchairs. The UV disinfection pod investigated was made from a lightweight and collapsible material, and it fully contained irradiation from a xenon-pulsed ultraviolet light. The study showed a significant reduction in pathogens from all PME in the investigation.

Allen (2020) investigated whether regular cleaning using either germicidal wipes or UVGI (Phonesoap - www.phonesoap.com) led to lower bacterial levels, compared to irregular cleaning, on electronic tablet devices commonly used in clinical and research applications. Some manufacturers of electronic tablets discourage the use of germicidal wipes, citing the degradation of the screen and moisture exposure, which may affect usability. UVGI presents an alternative in reducing pathogen loads on such devices. The Phonesoap exposed the tablet to an irradiance of 3274 $\mu W/cm^2$ from a mercury lamp source, for a period of 30s. Results of the study indicated a reduction in the burden of bacteria when regularly cleaning the tablet with germicidal wipes or the Phonesoap device versus irregular cleaning. There was, however, no significant difference in reduction of bacterial load between the use of germicidal wipes or the Phonesoap device.

Another strategy for surface decontamination using UVGI is the use of whole-room devices. Bedell et al. (2016) report on the use of whole-room UVGI disinfection system – Surfacide (www.surfacide.com) – to inactivate strains of MERS coronavirus. Surfacide is an automated UV-C device which incorporates a laser system to measure the disinfection space and identify objects nearby; the system is then able to calculate the 360° rotation disinfection cycle time. Under controlled experimental conditions, Surfacide was able to disinfect the MERS coronavirus strains from surfaces to undetectable viral levels up to 30 minutes after exposure. Whole-room devices have also been used for terminal disinfection. Terminal disinfection refers to a final disinfection step taken once visible contamination has been cleaned; terminal disinfection does not replace the need to first clean surfaces. However, terminal disinfection would allow for surfaces that are visibly soiled and are most prone to contamination to undergo manual cleaning, and terminal disinfection would target all other surfaces (Lindsley, et al., 2017). The use of UVGI as a terminal disinfection method had been investigated in healthcare facilities (Andersen, et al., 2017) and ambulances (Lindsley, et al., 2017). As seen in the current COVID-19 pandemic, and highlighted by Lindsley et al., ambulances are used to transport contagious patients and become a site of transmission via contaminated surfaces; ambulances would therefore have to be decontaminated before they are returned to service. Lindsley et al. investigated the efficacy of a custom-built UVGI system for terminal disinfection in an ambulance patient compartment and examined the position and reflectivity of surfaces on the disinfection time. Their study focused on surfaces that are touched often and those not exposed to direct light. They found that the position of the UVGI fixture greatly affected disinfection time as surfaces that were further away from the UVGI source and those in shadowed areas received lower dosages of UV-C. The addition of reflective surfaces (reflective aluminium or UV-reflective paint) was found to greatly reduce the disinfection time. Exposure to UV-C may negatively impact surface materials and different materials are affected by UV-C in different ways. Metals and ceramics are least affected by UV-C; polymers are susceptible to degradation by UV-C (UVSolutions, 2019).

Respiratory protection is an important defence against disease transmission and is essential for frontline workers who are in contact or exposed to COVID-19 patients. Consequently, there has been an increased need and demand for personal protective equipment (PPE) such as N95 respirators. While these respirators are not designed for decontamination, several studies have focused on the use of UVGI as a potential simple and rapidly deployable technology for decontaminating respirators and masks to address their limited supply in the face of the COVID-19 pandemic (Boškoski, et al., 2020; Hamzavi, et al., 2020; Nogee & Tomassoni, 2020; Nogueira, 2020; Yang, et al., 2020; Ou, et al., 2020). Decontamination strategies should meet the requirement of removing pathogens, not being harmful to the wearer, and not compromising the integrity of any part of the N95 filtering facepiece respirators (FFR) (Institute of Medicine, 2006). The shortage of PPE was also considered prior to the current pandemic. Mills et al. (2018) investigated a UVGI decontamination and reuse strategy for the N95 FFR, as a potential solution in the case of a shortfall of PPE in the event of a pandemic. The aim was to decontaminate FFRs without affecting their performance. Mills et al. evaluated the efficiency of a UVGI decontamination strategy of intact N95 FFRs contaminated with both an influenza strain (H1N1) and a soiling agent (either artificial saliva or artificial sebum) to mimic real-world situations. The UVGI device was custom built and made of polished aluminium. Fifteen different N95 FFRs were tested and it was noted that variation in FFR design may influence the effectiveness of decontamination for reuse. Twelve of the fifteen N95 FFRs showed a significant reduction in viral viability under UVGI decontamination; the remaining three were of similar structure (cup-shaped, rough texture). The FFR straps posed a challenge for decontamination, with straps of only five of the FFRs showing a significant reduction in virus viability for both saliva and sebum conditions. This finding is important because proper doffing techniques for FFR requires handling of the straps, which could be a driver of fomite transfer. A further point to be highlighted here is the use of the term "significant reduction" when speaking of viral viability in FFR decontamination strategies. There are no guidelines for

decontamination levels, however, Mills et al. considered a ≥3 log reduction to be significant. The principle for sterilisation is >6-log reduction in microbial population, and is translated into the dosage, D99, where that would result in a 99% disinfection rate (Kowalski, 2009).

*Airborne disinfection*

IPC measures such as effective ventilation, enhanced by particle filtration and air disinfection, may be needed to reduce the risk of indoor airborne infection in healthcare facilities managing COVID-19 patients (Morawska, et al., 2020; Xiao & Torok, 2020). Airborne transmission of microorganisms can be reduced by employing a ventilation strategy (natural, mechanical, or negative pressure isolation) that dilutes and removes contaminated air from spaces and controls airflow patterns in rooms and buildings (Coker, et al., 2000). The efficacy of such a system is dependent on, among other factors, the rate at which the contaminated air is removed from the environment. As an example, the WHO specified in the interim IPC guidelines, a ventilation rate of 160l/s/person in a COVID-19 infective ward where a natural ventilation strategy is employed (World Health Organization, 2020b). Morawska et al. (2020) acknowledges that the capacity to increase ventilation rates may be limited by the original design and implementation of the ventilation strategy; employing local filtration and disinfection methods, such as UVGI, becomes beneficial.

Upper-room UVGI could be used in pandemic situations for air disinfection (McDevitt, et al., 2012). In upper-room UVGI, mercury vapour lamp luminaires are typically suspended from the ceiling or mounted on walls. These luminaires may have a shield at their base directing radiation upwards, or may have horizontal louvres directing rays horizontally outward, creating an intense UVGI zone in the upper part of the room and minimising radiation levels in the occupied part of the room. These systems are dependent on good air mixing to transport contaminated air from the occupied lower room to the irradiated upper-room. Air mixing can be improved with mixing fans in naturally ventilated systems, and the positioning of supply diffusers and exhaust grilles in mechanically ventilated systems (NIOSH, 2009).

Appropriately designed and properly maintained upper-room UVGI systems have shown to offer protection to healthcare workers in tuberculosis (TB) settings (NIOSH, 2009). McDevitt et al. (2012) characterised the susceptibility of influenza A to different doses of UV-C at different humidity levels. Their work formed the scientific basis for designing effective upper-room UVGI systems for the prevention of the transmission of the influenza virus via the airborne route. They found that influenza is effectively inactivated during exposure to UVGI and there is variation on the susceptibility of influenza to UV-C at different humidity levels, where a higher relative humidity corresponded to a decreased susceptibility. The effect of relative humidity on UV-C efficacy is microorganism dependent. Kowalski & Bahnfleth (2000, p. 4) discuss previous studies in which increased resistance to UV-C is experienced with a decrease in relative humidity.

Ethington et al. (2018) investigated whether using continuous upper-room UVGI to lower the bioburden in the air would positively affect the rate and types of hospital-acquired infections in an intensive care unit in a long-term acute care hospital, without any other change in cleaning regimens. The results showed a significant reduction in airborne bacterial load post-installation and a reduction in hospital infection rates for 12 months of UVGI use, compared to the preceding 12 month records. The drop in hospital infections was not associated with those typically subject to airborne transmission, and not all the reductions in hospital acquired infections were statistically significant, though an obvious downtrend was seen.

More recently, upper-room UVGI LED systems have been investigated. Nunayon et al. (2020) designed and compared the disinfection efficacy of a novel upper-room UVGI LED system to that of a conventional mercury vapour lamp upper-room UVGI system. Performance was quantified by log reduction and single-stage decay rates of aerosolised bacterial strains of Escherichia coli, Serratia marcescens and Staphylococcus epidermidis. They found that the decrease in microbial concentrations in the air of the upper-room UVGI LED against the upper-room mercury vapour lamp UVGI system varied widely based on the species of bacteria. A distinct feature of UVGI LED is that irradiation levels can be adjusted. Nunayon et al.'s study highlighted the promise of UVGI LED for future application in airborne disinfection.

UVGI should not be considered a primary environmental control measure. For TB IPC, upper-room UVGI serves as an adjunct to other environmental IPC measures such as ventilation, in settings occupied by unsuspected or undiagnosed individuals, or in areas where suspected and confirmed TB patients are located or

accommodated, such as negative-pressure isolation rooms, wards and locations where high-risk procedures are performed (NIOSH, 2009).

UVGI is also used in mechanically ventilated systems within the delivery or exhaust ducts, typically called in-duct UVGI, where UVGI lamps are used to either decontaminate the air entering the room, or the air leaving the room, which may be recirculated to other parts of a facility. Kowalski & Bahnfleth (2000) present a methodology for the design of a more effective UVGI airstream disinfection system.

**UVGI in South Africa**

UVGI is readily available in South Africa, but much of the focus and scientific literature is concerned with upper-room UVGI as an adjunct environmental control measure in reducing the airborne transmission of TB. An infection control audit of 10 primary healthcare facilities in the Western Cape revealed that there were no UVGI fixtures installed in those facilities (Mphaphlele, et al., 2012). Mphaphlele et al. (2015) presented a controlled trial of the effectiveness of upper-room UVGI disinfection with air mixing at the airborne infection research (AIR) facility, based at a referral TB hospital in eMalahleni, South Africa. The AIR facility is based on the design of the Riley facility, which exposes guinea pigs, in two chambers, to exhaust air from wards. One chamber serves as the control, and the other the intervention – upper-room UVGI. The study was able to achieve an estimated 80% protection with two well characterised UVGI fixtures and ceiling fans and forms the basis for new dosing guidelines, where the fixture UV output must be known and incorporated into the dosing formula in the design of upper-room UVGI strategies.

Two recent publications (Singh, et al., 2018; Mamahlodi, 2019) highlight the current status of upper-room UVGI in South Africa. Singh et al. (2018) investigated the efficacy of local (South African) UVGI device installations in public sector healthcare facilities, and determined the coverage of these installations. Airborne TB inactivation experiments were conducted in an ambient conditioned walk-in chamber. The test chamber was fitted, in turn, with UVGI devices from four South African suppliers. There are no standardised tests to assess the efficacy of UVGI devices and systems, but generally, the objective would be to reduce airborne transmission by 80%, as in Mphaphlele et al. (2015). An alternative metric for assessing the efficacy of UVGI systems is the UVGI inactivation rate, measured in equivalent air changes per hour (eACH) that a UVGI system would deliver, as used by Miller et al. (2002). The UVGI inactivation rate is calculated by establishing the rate of decay of an airborne pathogen with and without the UVGI system; the difference between the two is calculated to be UVGI inactivation rate.

UVGI devices investigated by Singh et al. (2018) included ceiling-mounted, wall-mounted and portable devices. The effectiveness of the tested UVGI devices ranged from 43.7 to 100%, with six of the 13 devices tested meeting 100% desirable effectiveness. Very few of the open and closed UVGI devices met occupational safety standards. In the same study, a self-administered questionnaire was sent to delegated authorities at 119 healthcare facilities. The questionnaire sought to elicit which UVGI devices, and how many, were installed in which facilities, as well as details on function and maintenance. A total of 15 089 devices were reported to have been installed in South African public healthcare facilities, although the information retrieved was considered poor. Two provinces (Mpumalanga and the Free State) did not supply any installation information. KwaZulu Natal reported that UVGI had been installed in two facilities, however, it had been discontinued due to complaints of skin irritation and conjunctivitis. Gauteng confirmed that 11 facilities had installed UVGI, but 52% of these devices were either not functional or not in use. The study found that UVGI device installation did not consider air mixing, room volume, occupancy and dosing, and routine maintenance. Additionally, there was no evidence of operational and maintenance manuals or training of personnel at the time of data collection (2014). Most devices had South African Bureau of Standards certification (SANS(IEC) 60-589-2-1), however, this certification is for general purpose luminaires, and not explicitly for UVGI to reduce airborne microorganisms. Many of the devices that performed well in the efficacy test were not widely installed in public healthcare facilities, as these were closed devices, rather than the preferred louvred devices. The devices with closely spaced louvres were less effective than the closed devices, possibly due to the reduction in UV output.

Singh et al. (2018) illustrate several barriers to effective implementation of UVGI systems, which support the moratorium on new installations of UVGI systems in South African public healthcare systems imposed by the National Health Council in June 2011. The onus of the dissolution of the moratorium lies with the National

Department of Health (NDoH), which must ensure that it provides supplementary technical specifications for upper room UVGI and reserve the right to witness any performance tests that may be needed (NDoH, 2020). In addition, NDoH can require a system designer to present for approval a final technical design report prior to system installation with a description of the design methodology, design assumptions and performance target, as well as a specified compliance certificate. Currently, there are no national standards on the design and implementation of UVGI systems in South Africa, but they are under development (Singh, et al., 2015; van Reenen, et al., 2019).

UVGI innovation to address COVID-19 has started taking place in South Africa, for example in the form of a UV-C sanitiser to disinfect air, surfaces, whole rooms and face masks (University of Cape Town, 2020). The potential application lies beyond healthcare settings, and includes large areas such as lecture theatres. The design incorporates wall and ceiling mounted units in combination with occupancy-detection sensors. When the room is vacant, the units are triggered to irradiate the space for a designated period and is automatically deactivated. Many South African suppliers have UVGI air and surface disinfection units on offer, including applications for ambulances (www.technilamp.co.za; www.ulilog.co.za; www.thelamphouse.co.za; www.ozoneair.co.za ) and some South African suppliers have explicitly suggested UVGI for COVID-19 responses on their webpages (www.thelamphouse.co.za; www.ozoneair.co.za ).

## Discussion

We have shown how available technology, in the form of UVGI devices, has been used as an environmental IPC measure to reduce infectious disease transmission. Recent scientific literature has shown SARS-CoV-2 to be susceptible to UVGI; UVGI is therefore posited to be a promising technology for COVID-19 and beyond. This pandemic has resulted in innovation to overcome some of the decontamination and disinfection challenges associated with the coronavirus. The shortage of PPE in the form of respirators and facemasks is an example. While manufacturers had to ramp up production and new manufacturers started to supply these forms of PPE, the shortage was also addressed through exploring reuse of respirators and facemasks. UVGI has proved to be beneficial here, with studies showing its effectiveness. In a similar way, the disinfection of PMEs and ambulances using UVGI could also be investigated, and evidence made available for best practice in these areas.

The implementation of UVGI in South Africa, specifically upper-room UVGI to minimise the airborne transmission of TB, has faced many challenges; it may therefore not be an attractive solution towards future IPC practices. Although the disinfection potential of UVGI has been proven, it is dependent to a large extent upon the application of appropriate procedures for monitoring, validation and maintenance to avoid creating a false sense of safety for health care workers, patients and visitors. The operating and maintenance costs of upper-room UVGI are considerably lower than for mechanical ventilation, but intermittent and costly electricity can be a challenge (Nardell et al., 2013). With South Africa experiencing power outages, the effective use of UVGI can be adversely affected unless contingency measures are put in place. While upper room UVGI, often combined with natural or mechanical ventilation, has been described as a cost-effective method for providing effective airborne disinfection (Mamahlodi, 2019), this is yet to be verified no investment cases for UVGI in South Africa have been published. Due to resource constraints, it is not feasible to install upper-room UVGI throughout health facilities in South Africa. Singh & Matuka (2015) recommend that the use of UVGI in healthcare facilities be prioritised based on risk assessment; the technology should complement rather than replace a ventilation strategy.

South Africa has a pool of UVGI actors who have been developing knowledge in this area, including testing capability for irradiance and microbial susceptibility. These include actors from national science councils and universities. The country has the advantage of being able to capitalise on its existing knowledge base and experienced personnel to facilitate training on UVGI. South Africa does possess some infrastructural resources in UVGI technology, even though these may be limited to airborne applications, with some UVGI suppliers having developed luminaires of acceptable standard for minimising the risk of airborne infection.

The poor implementation of UVGI as an environmental control measure to minimise the risk of TB transmission in South Africa should not undermine its potential in the response to COVID-19. As SARS-CoV-2 has been shown to be transmitted via the airborne route, the technology may be employed, with relevant standards and guidance. South African UVGI guidelines do not address surface disinfection and fomite transmission. There

is an opportunity here to expand what has already been learnt and extend it into a new set of evidence-based practice guidelines for South Africa. This may serve as preparation for pathogens of the future which are spread by these routes. Thus, the lessons that have been gained in the development and subsequent application of UVGI in different settings provide a pool of knowledge to direct further research on how the technology can be appropriated to address contemporary and emerging challenges such as COVID-19. UVGI on its own may not be the solution to infection prevention and control but it can complement other strategies to make them more effective. Further empirical research would be a useful contribution in providing deeper insights into the potential and feasibility of UVGI for infection prevention and control of SARS-CoV-2.

## Author contributions

Both authors contributed to the conceptualisation of the study. Each author wrote designated parts of the review. Both authors contributed to the synthesis of the final manuscript.

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