UVC disinfection robot

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Abstract

The aim of the present work is to contribute in the fight against the spread of Covid-19, a novel human coronavirus, in hospitals, public transport, airlines, and any enclosed areas. In this study, we have adopted the physical disinfection method by using UVC light as agent. The UVC devices are studied and classified according their disinfectant units, complementary devices, combined disinfection agents, mobilities, and order types. Our finding shows that a mobile robot is the most efficient device to inactivate microorganisms, so we have developed a robot called i-Robot UVC. The robot is equipped with eight UVC lamps around a central column and two lamps on the top. The column is fixed on a mobile base where several sensors are integrated to measure temperature and humidity on the one hand, and on the other, to detect motion plus position and to avoid obstacles. The robot can estimate automatically the disinfection time while monitored by Wi-Fi connection from a phone or a tablet. I-Robot UVC disinfects rooms and equipment with ultraviolet light, and shuts down when humans are around to keep them safe. The robot can kill 99,999% bacteria and various through UVC lamps led. The innovative robot UVC was patented under the number TN2020/0063.

Keywords Covid-19 · Disinfection · Hospitals · UVC · Robot

Introduction

The SARS-CoV-2 responsible for the disease known as Covid-19 is a virus that is mostly transmitted through aerosols. The pandemic has recently emerged from China with a total of 83.021 confirmed cases of pneumonia around the world (as of June 2, 2020) (www.worldometers.info/coronavirus/). To reduce the pandemic spread of the virus, five measures have been adopted: (1) massive testing, (2) quarantine, (3) disinfection, (4) social distancing, and (5) sanitary measures. The disinfection

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techniques are of chemical and/or physical type (Otto et al. 2011). The effectiveness of a disinfection plan depends on the environmental factors such as temperature, relative humidity, organic load, pH, surface topography, water hardness, or the presence of other chemicals compounds (Otto et al. 2011; Mojarad et al. 2017; Darnella et al. 2004). In fact, the agents used in a chemical disinfection procedure are classified according their nature: (1) acids: acetic acid and citric acid; (2) alcohols: ethanol and isopropanol; (3) aldehydes: formaldehyde and gluteraldehyde; (4) alkalis: sodium or ammonium hydroxide, sodium carbonate, and calcium oxide; (5) biguanides: chlorhexidine; (6) halogens: chlorine or iodine compounds; (7) oxidizing agents; and (8) quaternary ammonium compounds. The chemical disinfection of microorganisms refers to the application of a chemical agent at known concentration C. The disinfection phenomenon is a kinetic process described mathematically for the first time by the well-known Chick-Watson model since 1908. The basic rate model of disinfection is described according to the following equation (Chick 1908):

$$\frac{dN}{dt} = -kN \tag{1}$$

where N is the number of microorganisms after time t and k is the observed disinfection rate constant. Several authors (Hom 1972; Lambert and Johnston 2000; Prokop and Humphrey 1970) have

refined the Chick-Watson model by taking account other parameters involved in the disinfection process. Disinfectant concentration and contact time are integral to disinfection kinetics and the practical application of the Ct concept (Ct being the disinfectant concentration multiplied by the contact time). The physical disinfection methods are UV light treatment (Guridi et al. 2019), gamma irradiation treatment (Silindir and Özer 2009), and heat treatment of virus (Sauerbrei and Wutzler 2009). In fact, since 2004, Darnell et al. have examined several methods to inactivate the coronavirus. In this study, the authors have reported that the coronavirus was inactivated by UVC (254 nm), or at a temperature higher than or equal to 65 °C, alkaline (pH > 12) or acidic (pH < 3) conditions, and formalin and glutaraldehyde treatments.

When UVC is used as a disinfection technique, Equation (1) takes the following form (Kamiko and Ohgaki 1989):

$$\frac{dN}{dt} = -ZIN \tag{2}$$

where I ($\mu W/cm^2$) and Z ($cm^2/\mu Ws$) are respectively the UV intensity and the microorganism susceptibility factor. The susceptibility parameters vary with environmental conditions, such as relative humidity (RH) (Ko et al. 2000; McDevitt et al. 2012). It is known that UVC effectiveness decreases with increasing RH (McDevitt et al. 2012). The UVC effectiveness for microorganisms is correlated also to room configuration, lamp placement, lamp age, air movement patterns, and by the mixing degree of room air. The dose relates, D ($\mu J/cm^2$), to the UV intensity according Equation (3):

$$D = It \tag{3}$$

where t (s) is the irradiation time.

The D90 is the required UVC dose for 90% inactivation of a microorganism. The SARS-CoV-2 is of about 120 nm in diameter. Its inactivation dose corresponds to D90 = 6.11 $\mu J/cm^2$ (Jingwen et al. 2020). The virus is highly susceptible to UVC irradiation and its susceptibility is 3 times greater than the influenza (common cold) virus. The dose received by surface unity at given distance r (cm) from the sanitizer depends on the power, P (μW), of the emitted UVC lamp according to the following equation (Owens et al. 2005):

$$D = \frac{Pt}{2\pi Lr} \tag{4}$$

where L (cm) and t (s) are, respectively, the length of the lamp and the exposure time, so the exposure time can be estimated according Equation (5):

$$t = \frac{2\pi LrD}{P} \tag{5}$$

In order to express the relative number of living microorganisms that are inactivated, the log 10 reduction factor

is calculated according the following equation (Mazzola et al. 2003):

$$Log10reduction = \log\left(\frac{N_0}{N}\right) \tag{6}$$

where N_0 and N are respectively the number of microorganisms before and after exposure to UV light, so when the log 10 reduction takes the values 1, 2, 3, and 4, the percent reduced microorganisms is respectively 90%, 99%, 99.9%, and 99.99%.

The medical frameworks are on the front lines of the battle against coronavirus, so the hospitals must be disinfected efficiently and quickly. In this context, the UVC technique is recommended by the scientist community to win the war against the Covid-19 pandemic. In this work, we will firstly present and discuss the different devices using UVC disinfection. Then, we will expose a prototype disinfection robot developed by Tunisian engineers.

UVC devices

The devices using the UVC technique can be classified as follows: (1) disinfection unit, (2) complementary devices, (3) combined disinfection agents, (4) mobility devices, and (5) order type.

In fact, all devices are manufactured to ensure maximum efficiency and ease of use. The different types of devices will be discussed in the next sections.

Disinfection unit

Only artificial light sources, the so-called disinfection units, generate radiant energy within the UVC-band. Two main types were distinguished: the lamps and the UVC-LEDs. The lamps are of gas discharge type: mercury, xenon, and xenon-mercury (in small amount).

The UVC-LEDs are semiconductors consisting of stable structure doped in precious metals (Harris et al. 2012; Nyangaresi et al. 2018).The power supply of the sources can be continuous or pulsed, so the light emitted by the sources, the lifetime, and the spectrum emission depends on the nature of source and the power supply type. The conventional UVC lamps, of medium or low pressure, remain the most common disinfection unit source. However, these lamps present inherent disadvantages such as the use of mercury, the low mechanical stability, and ozone production. They are related at 30 W power and their peak emission was at 254 nm; their lifetime is about 8000 hours. The technology using high-intensity pulsed xenon lamps is a polychromatic source that produces short-time flashes (Otaki et al. 2003). The lamps are used to generate broad spectrum 200–300 nm high intensity UV light. The

UVC-LEDs are also emerging UVC light source as an alternative to conventional lamps. The advantage of UVC-LEDs is their compact size and energy saving, which is four to nine times more efficient than the UVC lamps in water treatment. However, their use is still limited as a result of their high cost (Harris et al. 2012; Nyangaresi et al. 2018). Several studies were reported in order to compare the efficiency of the different disinfection units. In fact, McDonald et al. (2000) have compared the decontamination of surfaces and the inactivation of microbe by using conventional lamps and pulsed light sources. They found that pulsed UV light is more effective than conventional lamps. Stibich et al. (2011) have compared the conventional lamps and pulsed xenon systems for the reduction of the healthcare-associated pathogens in hospital rooms. They have shown that pulsed xenon and mercury lamps have the same effectiveness at relatively short exposure time, about 10 min. Song et al. (2020) have used continuous and pulsed xenon UV to inactivate microorganisms in ambulances. They have reported that the device does not need to use chemical agents and reduce 90% of E. coli, Staphylococcus albus, and environmental pathogens in 30 min. Although the disinfection unit has evolved in the direction of using more compact systems and mercury free, UVC mercury lamps remain the most used thanks to their low cost.

Complementary devices

In addition to the disinfection unit, UVC–pulsed (continuous) lamps (UVC-LEDs), complementary devices, such as reflective walls and humidifiers, were used to enhance disinfection effectiveness. In this context, several authors (Rutala et al. 2013; Krishnamoorthy and Tande 2014; Sung et al. 2011; Woo et al. 2012) have studied the effect of complementary devices to reduce the disinfection time therefore increasing the effectiveness of UVC lamps. In fact, Rutala et al. (2013) have shown that combining UVC lamps with reflective walls reduce the time necessary to decontaminate a room already contaminated with methicillin-resistant Staphylococcus aureus, from 25 min 13 s to 5 min 3 s and Clostridium difficile spores, from 43 min 42 s to 9 min 24 s. Krishnamoorthy and Tande (2014) have shown that employing reflective paint increases from 20 to 10%, depending on the distance source-surface, the radiative fluxes on certain surfaces. The experimental results are in agreement with these obtained by mathematical modeling. It has been demonstrated that using humidifiers equally enhances disinfection effectiveness. In fact, Woo et al. (2012) have associated UVC lamps with humidifier using deionized water, beef extract, and artificial salvia, which generates different humidity levels (30%, 60%, and 90%), in order to examine the relative humidity effect on the disinfection effectiveness of MS2 bacteriophage. A 5.8 logs reduction factor was seen for deionized water at relative humidity of 30% after applying an UVC lamp (1 mW/cm^2) for 30 min.

McDevitt et al. (2012) have studied the susceptibility of influenza virus to UVC and have reported that it increases with decreasing relative humidity. Complementary devices such as humidifiers and reflective walls are shown to increase the inactivation effectiveness of several microorganisms.

Combined disinfection agents

Combined disinfectant agents, physical and chemical agents, are being used as emergent technologies in hospitals. The chemical agents include hydrogen peroxide vapor systems and gaseous ozone with mobile UVC lamps. In fact, Anderson et al. (2017, 2018) have reported that the addition of UVC disinfection treatment to standard protocol, with chemical agents, had a direct positive effect on the Clostridium difficile and vancomycin-resistant contamination. Haddad et al. (2017) have reported that combining portable xenon–pulsed ultraviolet germicidal light device and standard manual cleaning of surfaces decreases the bacterial load by 70%. Boyce (2016) has recommended the use of newer disinfectants and no-touch decontamination technologies to improve disinfection of surfaces in healthcare. Combined disinfection agents, especially hydrogen peroxide vapor and UVC, allow more effective disinfection.

Mobility devices

Mahida et al. (2013) have evaluated the Tru-D mobile and automated UVC room decontamination device. They have shown that the device eradicates all the microorganisms with a mean log10 reduction between three and four when used at 22 μJ/cm^2. This includes a mean of microorganisms percent reduced between 99.9 and 99.99%. The robot was placed in a center position, the device is simple to use and does not require monitoring during decontamination. It operates without the need to deactivate room ventilation or smoke detectors. Tru-D is quicker compared to hydrogen peroxide. Recently, Cadnum et al. (2017) have compared the efficacy of a standard UVC room disinfection device operated in one location and mobile robotics operating in stationary or mobile position. The robot navigates around the patient room to minimize the distance between the device and shadowing. The finding of the authors is that the robotic device operating in a stationary position was as effective as the standard device against organisms in close proximity to the device but significantly less effective at greater distances. However, the UVC robot device programmed to automatically navigate the room is effective in reducing contamination at sites throughout the room. A disinfectant robot is a recent technology used to deactivate microorganisms, but requires a mastery of a set of technologies ranging from robotics, electronics, mechanics, and programming.

Order type

Manual disinfection devices are often suboptimal; recently, several mobile and automated room disinfection devices are tested. In fact, Bentancor and Vidal (2018) have presented a remotely programmed device using an Android mobile and an infrared detection security. In fact, the device turns off the lamps when a motion is detected. The robot communicates with the board using Bluetooth devices, thanks to a mobile application, it can be operated from a wide range of Android mobile devices (tablet, cell phone, etc.). The authors have reported the device is effective to eliminate high bacterial inocula and a wide range of microorganisms. The robot does not require use of chemical agents.

I-Robot UVC technology

Since the discovery of germicidal effects of UVC, research has focused on enhancing the disinfection effectiveness. Recent developments in technology have led to create different types of UVC sources, but UVC germicidal lamps remain the most frequently used due to their relatively low cost. Complementary devices such as humidifiers and wall reflectors decrease disinfection time when used with UVC. Combining disinfectant chemical agents with UVC is an emergent technology but has the disadvantage of damaging hospital material. In the world war against Coronavirus pandemic, robots join medical staff on the front line, especially UVC robot disinfectors. Thanks to the robot's mobility disinfection, time is reduced for an impressive effectiveness

without using any complementary devices or chemical agents. Considering the previous studies, a team of Tunisian researchers and engineers has designed and produced a robot disinfector called i-Robot UVC (Fig. 1).

In fact, i-Robot UVC can be controlled manually or run automatically; the robot is designed especially for all areas of hospital and any enclosed space to inactivate microorganisms. The construction of the robot involved: (1) the structural building, (2) the electronic assembling, and (3) the programming of the microcontroller and the mobile application. The structure was made by attaching to a central column two horizontal crows to immobilize eight UVC lamps. Two other lamps are mounted on top of the robot; the system of lamps can cover the space around the device. The central column was placed on a mobile base equipped by a pulse air modulation to avoid excessive lamps warming up. Multiple sensors were integrated on the mobile base to measure temperature and rate humidity. The power supply of the device is done with a direct voltage of 24 V which supplies energy to the UVC lamps and supplies the Arduino board and the rest of the electronic circuit. The required disinfectant time is estimated according to software by considering the dimension of space, the temperature, and the humidity rate. To measure distance, detect and avoid obstacles, i-Robot UVC is equipped by ultrasound sensor. Infrared sensors permit to detect motion, so the robot operates when people are not around and turns off the UVC lamps otherwise. Thanks to LiDAR sensor, the robot scans the environment and creates a digital map; this permits to optimize intervention. An operator equipped by protective suit controls the robot operation from a dashboard thanks to integrated cameras.

Fig. 1 The UVC disinfection Robot

UVC LAMPS

THE CENTRAL COLUMN

PULSE AIR MODULATION
To avoid excessive lamps warnin-up

THE MOBILE BASE
Equipped by sensors to measure temperature and humidity

ULTRASOUND & INFRARED SENSORS
To measure, detect distance and avoid obstacles and detect motion

Conclusions

A contribution of Tunisian research and engineering to the world war against Covid-19 pandemic has been presented in this report. The study of different disinfectant systems led us to identify our choice on the development of a mobile disinfection robot. The i-Robot UVC is an autonomous device and can be controlled manually. It can also work in a fully automated mode. The lamps integrated into the robot and its mobility can deactivate coronavirus and microorganisms in a record time. Based on artificial intelligence, integrated sensors, and cameras, the device is of high security. I-Robot UVC shuts down when humans are around to protect them from the harmful effects of UVC.

Authors' contributions Moez Guettari collected and analyzed data. He contributed to the study conception and design of the robot and co-wrote the manuscript. Ines Gharbi has collected and analyzed data. She also contributed to the study conception and design of the robot and co-wrote the manuscript. Samir Hamza contributed to the study conception and design of the robot, conceived the robot, and co-wrote the manuscript.

Funding This work is funded by the Ministry of Higher Education and Scientific Research.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

Ethical approval Not applicable.

Consent to participate The authors have consent to participate.

Consent to publish The authors have consent to publish.

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