Inactivation of airborne SARS-Co-V2 using NTP-UVGI hybrid process

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Abstract
Indoor environments such as healthcare centers are known as one of the key centers in the outbreak of viral infectious diseases. In the present study, the pathogenic agents’ treatment system (PATS) was designed by the combination of non-thermal plasma (NTP) with the ultraviolet germicidal irradiation (UVGI) processes. Then, the treatment efficiency of PATS was measured for the "SARS-Co-V2." The exhaled air of the confirmed case of "COVID-19" was considered as the viral source of "SARS-Co-V2" and directed to the upstream of PATS. The treatment process was done by passing directed air through two steps of treatment (NTP and UVGI). The treatment efficiency of PATS was measured by sampling at the sampling points (before and after the treatment process). According to the energy emission pattern (corona discharge, UV rays) in the designed system, during two steps, the high efficiency of treatment for the collected pathogens was achieved. Based on the real-time polymerase chain reaction (RT-PCR) results, the CT value was lower than 29 (CTs < 29), and after the treatment using PATS was upper than 40 (CTs > 40) confirming the highest removal efficiency of "SARS-Co-V2." Also, the treatment efficiency of each reactor in individual operation was at the optimum level. The findings suggested, the present PATS may eliminate the viral pathogens with hospital sources and also, be applicable in the other intensive care unit (ICU) wards with the same risk thus, significantly reducing the possible exposure risk of healthcare and sick companions, and preventing the outbreak of infectious diseases.

Keywords Airborne · Healthcare center · Non-thermal plasma · "SARS-Co-V2" · Treatment · UVGI

Introduction
Public indoor environments such as hospitals with unsuitable conditioner and ventilation systems, improper personal protective equipment (PPE), and wrong individual health (hand-washing, respiratory health) are the main reasons for the spread and outbreak of viral infectious diseases (Kozajda et al. 2019; Hadei et al. 2020; Grinshpun and Yermakov 2021; Shao et al. 2021; Yarahmadi et al. 2021). According to reports of the reasons for the outbreak of "COVID-19" in China, common indoor spaces with one or more infected persons is a main "SARS-Co-V2" infection risk (Qian et al. 2021); the primary source of "SARS-Co-V2" spread in the indoor environments was the secretions of patients’ respiratory tract. "SARS-Co-V2" is settled on the surfaces (1–2 m distance from carrier person) immediately after leaving the respiratory droplets (mainly upper than 5 microns). The viruses with less than 5 microns in diameter may put the healthcare personnel and other hospital visitors at high exposure risk. Recently published works have reported on the airborne possibility of "SARS-Co-V2" (Liu et al. 2020; Wiktorczyk-Kapischke et al. 2021; Yarahmadi et al. 2021).

In removing airborne particles carrying pathogens from the air, especially in closed and indoor environments, considering several methods is known and recommended: removal of viral particles from the air using air exchange, air ionization to increase filtration efficiency and particle precipitation, Air sterilization techniques, and harmless virus, thus reducing the rate of viral inactivation and the need to remove particles from the air. With this approach, UVGI technologies, cold plasma, reactive oxygen species (ROS), and filter coatings deactivate the virus through mechanisms such as the natural antiviral properties of the material or direct virus
damage. Chemical disinfectants and super-heated sterilization are also common ways to inactivate viral particles (Berry et al. 2022).

Commonly, the most acceptable directive air flow between spaces is to ensure a minimum flow difference of 75 CFM or a pressure difference of 0.01-in. water gage (“W.G”) (Dreiling 2008). The necessity for redesigning and presenting new treatment and control patterns is tangible to inhibit and reduce the pathogenic agents at the hospitals, especially in the ICU wards of the hospitals from the “COVID-19” patients.

Plasma is a completely or partially ionized gas, including various particles such as electrons, ions, radicals, atoms, and molecules. It has been known as the fourth state of matter (Subrahmanyam 2009; Yarahmadi et al. 2010a, b; Brandenburg et al. 2011; Ikaunieks et al. 2011; Pârvulescu et al. 2012; Bisht et al. 2014; Schmidt et al. 2015; Yarahmadi et al. 2015). In air pollution control using NTP-based technologies, Yarahmadi et al. (2010a, b) used a DBD reactor to the removal of NOx from the gas stream (Yarahmadi et al. 2010a, b). Babaie et al. (2016) applied the cold plasma technique to purify diesel engine particulate matter (Babaie et al. 2016). Yarahmadi and Soleimani-Alyar (2020) designed an NTP-catalyst hybrid process to remove CO from mobile sources (Yarahmadi and Soleimani-Alyar 2020), and Abedi et al. (2014) and Sultana et al. (2015) studied the combined plasma-catalyst process for treatment of VOCs (Abedi et al. 2014; Sultana et al. 2015). The ability of NTP in viral disinfection was shown primarily by a China researcher in 2015 (Verma 2020). Other researchers have investigated this ability and then reported the antiviral effect of non-thermal plasma technology (Hati et al. 2012; Liang et al. 2012; Pradeep and Chulkkyoon 2016; Guo et al. 2018; Su et al. 2018; Bunz et al. 2020; Xia et al. 2020). Since the use of NTP to inactivate more than 99% of viral airborne particles has shown significant positive effects (Wu et al. 2015; Xia et al. 2019; Verma 2020). Also, the use of ultraviolet rays in the wavelength of UVC poses the potential to disturb the reproduction ability of pathogenic masses and inactivate pathogens via absorption of the ray by proteins, viral DNA, and RNA (Wang et al. 2019; Xia et al. 2019; Bhardwaj et al. 2021). But, disinfection based on ultraviolet technology (UVGI) is also difficult to be done in the air because it demands a dose of UV consisting of a combination of radioactive fluxes and exposure times. (Xia et al. 2019).

Considering the two factors of aerosol transmission and aerosol pathogenicity with the potential to transfer disease from airborne pathogens such as viruses is critical in choosing the proper pathogenic airborne treatment technology. The UV ray only addresses the pathogenicity of aerosol, and the particle filtration only addresses the aerosol transmission. Regarding filtration and UV ray, NTP technology addresses both the transmission (by charge-driven filtration) and pathogenicity (by reaction with reactive plasma species) of airborne pathogens (Xia et al. 2019). The possibility of combining NTP methods with the other treatment techniques is known as the main advantage of NTP technology, which leads to improving NTP performance and efficiency (Whitehead 2010; Karuppiah et al. 2014; Jo et al. 2016; Yarahmadi and Soleimani-Alyar 2020). In the present study, this feature of NTP was used to remove pathogenic agents by focusing on “SARS-Co-V2.” Accordingly, the main strategy of the present study was showing applicability and high efficiency of the new model of the system made to treat and destroy “SARS-Co-V2” with hospital sources, especially in “COVID-19” hospital units. The present study was done in Pars Plasma Bonyan (Knowledge-Based Company) at the Incubation and Innovation Center of Iran University of Medical Science from 2020 to 2021.

Materials and methods

The PATS consisted of two parts; (1) collection of respiratory aerosols (from the respiratory region of the "COVID-19" patients) using exhaust system, and (2) treatment and removal of the collected aerosols.

Collection of respiratory droplets and airborne particles using local exhaust system

This part consists of the bilateral slot hood connected to the exhaust hood and placed in the isolated chamber unit (Fig. 1) that has the role of two protective layers to prevent the spread of respiratory pathogenic agents to the healthcare environment. The exhaust hood was connected to a flexible duct integrated with the treatment part. The capture and collection process of possible pathogenic agents (particles containing "SARS-Co-V2") was done at a given distance from the patient’s breathing zone and bed area and then directed to the inlet of the treatment system for destruction and treatment.

The "COVID-19" patient bed

In the present study, the exhaled air of a confirmed case of "COVID-19" on an ICU bed was used as a source of "SARS-Co-V2" virus-carrying particles (Fig. 1b). In other words, the isolated chamber unit was placed on the ICU bed and also connected to the PATS by a flexible duct.
The pathogenic agents' treatment system

In this section, treatment was done during two steps; (1) corona discharge process and (2) photochemical after firing certain energy bands, respectively. For this purpose, the NTP reactor (dielectric barrier discharge) and ultraviolet (UV) reactor were combined as series (Fig. 2).

In the plasma section, nine Pyrex DBD reactors with an internal diameter of 4.5 cm (cylinder thickness 0.2 cm) and a useful length of 70 cm equipped with a stainless steel central electrode with a diameter of 0.14 cm were used to generate corona discharge (Fig. 2a).

The diameter to length ratio (D/L) of equally 1/10 and also, Reynolds number of 4500 were the criteria for dimensionless factor in designing of the non-thermal plasma reactor.

The second system following the NTP reactor was the UVGI reactor, considering of lethal intensity affected by linear and spatial distances of effective spaces passing the current. The design and physical geometry of the UVGI reactor consisted of 9 UVC lamps (Fig. 2b) with a voltage of 83 V. Examples of geometric models and arrangements of lamps as well as light emission systems in the intended space were simulated using computational fluid dynamics (CFD).

The considered residence time was about 1 s. The applied voltage and current were 12 kV and 25 mA, respectively.

Exhaust fan

To compensate for the drop caused by the movement of air-fluid from inside the closed hood to the system exhaust (stack), an exhaust fan (Blade Back Ward) was used with 2 horsepower and 2800 rpm with 600 ACFM airflows. The static and dynamic pressure of the exhaust fan was − 4 in. H2O and 0.5 in. H2O, respectively.

To achieve the optimum and real performance of PATS, the design pattern of the two reactors was based on dimensionlessness of mechanical, aerodynamic, and hydraulic factors (Passalí et al. 2017; van Walsem et al. 2018).

The overview of the whole collection and treatment system is shown in Fig. 3.

The 2D/3D modeling by CFD

In the present study, main factors including energy, flow, and particle momentum were determined, which are necessary elements in the design modeling of a control device before manufacture. Then, the computational fluid dynamics (CFD) was applied to 2D and 3D modeling of geometric designs and arrangements of NTP reactor, UVGI reactor using ANSYS R19.0 software, and as well as to simulate the static pressure and light emission in the intended space of reactors.
Sampling and sample analysis

The collection and treatment of breath droplets and other airborne particles around the breathing zone of the "COVID-19" carrier was done to survey the PATS performance at the real conditions (confirmed case of "COVID-19" at ICU ward of the hospital). In other words, the exhaled air of the confirmed case of "COVID-19" was collected by the enclosed face hood (i.e., bilateral slot hood placed in the isolated chamber unit at the upstream of the system) under the ASHRAE 62-1989 (IAQ) standards, and then passed through two steps of treatment (NTP and UVGI) (ASHRAE 1990). The details of process is shown in Fig. 4.

The system performance for the destruction of "SARS-Co-V2" was measured using a practical sampling procedure for bioaerosols through the impingement method (Brosseau et al. 1994; McDermott 2004; Girlando 2014; Lindsley et al. 2017; Faridi et al. 2020; Yarahmadi et al. 2021).

The sampling set of air carrying "SARS-Co-V2" was consisted of a calibrated vacuumed pump with a flow rate...
of 2.5 LPM and a midget impinge (The impinger commercial name was Midget Impinger with Fritted Nozzle, 30 ml, Glass, USA) containing 10 ml of HBSS2 solution used for sampling before and after the PATS (Brosseau et al. 1994; McDermott 2004; SAFC Biosciences 2006; Girlando 2014; Yarahmadi et al. 2021). During sampling time, the central air conditioner system of the sampling yard was turned off.

Sampling time was equivalent to 20 min (accounted for the total sample volume of 50 L) at ambient temperature (23.5 °C) and pressure (0.88 bar), with 31 relative humidity (% RH). After sampling, the openings of midget mpinge were caped and immediately sent to the laboratory. For RT-PCR3 test, the samples were concentrated and sent to the reference laboratory of the Iran University of Medical Science for the "SARS-Co-V2" analysis. The viral RNA was extracted from 500 µl of the aerosol specimens using a QIAamp DSP Virus kit (QIAGEN GmbH, Hilden, Germany), according to the manufacturer’s protocols, and then the quantity and quality of the isolated RNAs were assessed using a NanoDrop™ (Thermo Scientific, Wilmington, USA) spectrophotometer.

Detection of the encoding region of the covid-19 virus envelope €, and also the RNA-dependent RNA polymerase (RdRp) genes were performed using specific primers and probes by real-time polymerase chain reaction (RT-PCR) method, with the Rotor-Gene Q (QIAGEN, Germany) instrument as described previously in detail. It is noteworthy that appropriate positive and negative controls were included in each assay (Corman et al. 2020).

**Results and discussion**

**Design pattern of local exhaust system**

The simulated results of the distribution of path line airborne aerosols and velocity streamline from the patient’s breathing zone inside the exhaust hood and the isolated hood Using CFD is shown in Fig. 5.

**Design pattern of the treatment system**

Using CFD, the simulation results of the distribution pattern of static pressure inside the NTP reactor and the ultraviolet radiation intensity in the UVGI reactor are shown in Fig. 6.

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2 Hank’s balanced salt solution.

3 Real-time polymerase chain reaction.

4 Standard temperature and pressure.
Fig. 5 Simulation of particle diffusion lines (a) and velocity streamlines (b) in the isolated chamber unit, and from the isolated chamber unit to exhaust hood (c)

Fig. 6 The simulation of static pressure pattern in NTP process (a) and the absorbed radiation dose in UVGI reactor (b)
a negative pressure in the controlled chamber (i.e., isolated chamber unit) toward the slots of the exhaust hood was minimized the risk of respiratory-mucosal exposure of the healthcare staff. The created negative pressure was equal to 15 Pa according to the standard of the American Air Conditioning Association.

The 2D and 3D designs of two types of reactors; NTP and UVGI were shown the energy distribution and effective treatment way in both the two geometries of NTP and UVGI before the manufacturing (Fig. 6a, b).

The same energy distribution in the spaces of reactors (Fig. 6a, b) confirms the calculation, geometry, and design accuracy following the research goals.

Comparison of capture velocity to acceptable values was shown by distance from the hood suction point in the isolated chamber unit (Fig. 7). The comparison of the acceptable rate of capturing of particles and possible emitted gases confirmed the relative performance in the patient's breathing zone after sneezing and coughing.

Based on the results from Table 1, the performance indicators of bilateral slot hood include air change per hour, differential pressure (in-out the Plexiglas shield) were defined in terms of geometric and aerodynamic features of the hood in the distances higher than 10 cm above bed surface. The comparison of acceptable standard limits was optimum and higher than the standard level in the physical-aerodynamic

### Table 1: Aerodynamic function test results

| Measurement criteria                                      | Standard method          | Standard levels | Field measurement |
|-----------------------------------------------------------|--------------------------|-----------------|-------------------|
| Air change per hour                                      | Calculation method-ASHRAE| 10              | 40                |
| Differential pressure (Pa)                                | Calculation method-ASHRAE| 15              | 30                |
| The minimum velocity at the ducts connected to the slot hood | ACGIH                  | 2500            | 3000              |
| Average slot(adjustable) velocity                         | ACGIH                    | 1000            | 1200              |

*Air velocity measurement at 4 in. above bed surface*
parameters such as capture velocity, differential pressure, and minimum velocity in duct.

The destroy/inactivation of the ability of PATS in three modes of operation (NTP alone, UVGI alone, NTP combined with the UVGI) was provided by considering the physical energy of UV and NTP as well as the precious calculation and design of NTP-UVGI reactors. Also, the maximum efficiency of PATS was confirmed employing negative test results of RT-PCR at the outlet point of reactors.

Based on the results, the treatment efficiency of individual reactors was high (Tables 2). Since two reactors are in series the plasma reactor operates at a high-risk concentration of virus, thus the second reactor (UVGI) in series builds on the conversion in the first reactor.

To improve biosafety indicators, two matching mechanisms of plasma and UVGI were used in series. In this method, the output of the first reactor becomes the input of the second reactor. Consequently, the input load to the final reactor for inactivation will be very light and low risk.

In other words, the emission of UVGI and reactive oxygen and nitrogen species (RONS) has potent antimicrobial effects. UVGI can harm the nucleic acids directly (Filipić et al. 2020; Bono et al. 2021), but reactive oxygen species (ROS) and reactive nitrogen species (RNS) induced by NTP discharges can oxidize nucleic acids, proteins, and lipids (Guo et al. 2018; Liao et al. 2018; Filipić et al. 2020). Based on the given results from Table 2, NTP discharge can significantly alter the structure or inactivate the "SARS-CoV-2" by creating a strong electromagnetic field with the active medium of electrons, ions, radicals, and reactive species of nitrogen and oxygen, photons, and UV, especially reactive species of nitrogen and oxygen that inactivate the proteins and nucleic acid of viruses. In other words, cold plasma (the radicals and electrons from NTP discharges) with appropriate intensity can alter proteins on the surfaces of the viral pathogens. Plasma oxidation of viruses disables the mechanism by which they enter cells (Verma 2020).

UVGI reactor with a special arrangement and design to provide the absorbed radiation dose of energy (Bhardwaj et al. 2021) deactivated viruses in exhaled air, resulting in the highest effectiveness in the destruction of particles containing "SARS-CoV-2." (Table 2). Pathogenic inactivation using UVGI technology is due to the denaturation of enzymes, proteins, and membranes as well as disruption of cellular metabolic activities (Wang et al. 2019).

Maximum degradation efficiency of two reactors was resulting from the interactions of the active plasma medium which is rich in energetic radicals, ions, and electrons with UV waves, and finally, a chemical vessel (unit) which in addition to the possible residues of the virus can adsorb and remove the byproducts of plasma (such as ozone, NOx) and UV reactors that are the main reason for the success of this "clean technology." In other words, the self-purification of the system occurs following the degradation and removal of contaminants during the two integrated stages of NTP-UV (Table 2).

Based on the findings and results of the present study, NTP reactors can be effective against respiratory viral pathogens such as COVID-19 especially in closed and crowded spaces (Verma 2020). According to the results (Table 2), the treatment efficiency was high, and the complete removal of "SARS-CoV-2" was achieved in a different mode of PATS operation. It means that, if there was any fault in the system operation, causing offline one of the reactors, the system may have the continuous operation with the other one reactor.

The findings suggested, the present PATS may capture the viral pathogens with hospital sources and then treat captured pathogens and thereby, significantly reduce the possible exposure risk of healthcare and sick companions as well as, people from hospital vicinity. Thus, the designed system may

| Operation mode of PATS | Pathogenic agent | The result of RT-PCR a, b, c, d, e |
|------------------------|-----------------|----------------------------------|
| Plasma reactor         | SARS-CoV-2      | Positive b                       |
| UVGI reactor           | SARS-CoV-2      | Positive b                       |
| Plasma combined with UVGI reactors | SARS-CoV-2 | Positive b                       |

a The description of RT-PCR in terms of CT for the collected samples before and after the PATS: b CTs < 29 are strong positive reactions indicative of abundant target nucleic acid in the sample c CTs of 30–37 are positive reactions indicative of moderate amounts of target nucleic acid d CTs of 38–40 are weak reactions indicative of minimal amounts of target nucleic acid which could represent an infection state or environmental contamination or primer dimer formation e CTs > 40 are undetectable result
be applicable in the other ICU wards with the same risk and even indoors such as offices and residential complexes.

This system showed a very effective efficiency in protecting the medical staff and other people who are exposed to airborne respiratory droplets from the respiratory area of COVID-19 patients. If the other designed systems were applied to screen asymptomatic patients, visitors, and other staff at the entrance of the hospitals, the outbreak of COVID-19 disease be reduced in hospital settings and thus in the community appeared.

One of the main limitations of the present study was the lack of quantitative analysis of SARS-Co-V2 before and after the PATS. There was no possibility of reporting the number of virions in the exhaled air and the numbers following the combined exposure to non-thermal plasma and UV. Unfortunately, there were limitations in the analyzing technologies for the counting number of viruses. Thus, the reference laboratory was able to analyze just the presence of viruses and reported it as CT values.

Conclusion

In most healthcare settings, air exchange is not sufficient to control airborne particles contaminated with pathogenic agents. Thus it is found to be necessary to create pressure differences to prevent the spread of pollutants inside the spaces of health centers as well as to separate clean spaces from other less clean spaces. To prevent the viral spread in the healthcare centers as well as to protect healthcare personnel and other hospital visitors, a device was designed and made by which the exhaled air of the infected patient is immediately exhausted through the nose and mouth (enclosed face hood) under ASHRAE 62-1989 (IAQ) and ACGIH standards. Special slot hood with geometric and aerodynamic considerations of the local exhaust system reduces the risk of viral spread in the actual operating conditions of the ICU wards. Then, the exhausted air (containing the viruses) is purified in two steps. After the bioaerosols are destroyed and inactivated, the air passed through a disinfection vessel to remove any residues of byproduct or waste. Then, the purified air is evacuated out of the hospital (stack or other out space).

Also, this system is based on the mechanism of confinement and isolation of the source of the patient’s respiratory droplets which are collected and prevented from spreading to the area around the hospital, reducing the exposure risk for other people, including healthcare personnel, patients suspected of COVID 19, and visitors, etc.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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