Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Investigation on the effectiveness of ventilation dilution on mitigating COVID-19 patients’ secondary airway damage due to exposure to disinfectants

Yifan Li\textsuperscript{a,b,1}, Yiran Lu\textsuperscript{a,b,1}, Ying Wang\textsuperscript{c,d,1}, Li Liu\textsuperscript{a,b,1}, Hao Zhou\textsuperscript{b,e}, Borong Lin\textsuperscript{a,b}, Zhiyong Peng\textsuperscript{d,f}, Yufeng Yuan\textsuperscript{d,g,*}

\textsuperscript{a} Department of Building Science, Tsinghua University, Beijing 100084, China
\textsuperscript{b} Laboratory of Eco-Planning & Green Building, Ministry of Education, Tsinghua University, Beijing 100084, China
\textsuperscript{c} Department of Infection Management, Zhongnan Hospital of Wuhan University, Wuhan, Hubei 430071, China
\textsuperscript{d} Department of Critical Care Medicine, Zhongnan Hospital of Wuhan University, Wuhan, Hubei 430071, China
\textsuperscript{e} Department of Hepatobiliary and Pancreatic Surgery, Zhongnan Hospital of Wuhan University, Wuhan, Hubei 430071, China
\textsuperscript{f} Institute for Urban Governance and Sustainable Development, Tsinghua University, Beijing 100084, China
\textsuperscript{g} Laboratory of Eco-Planning & Green Building, Ministry of Education, Tsinghua University, Beijing 100084, China

\textsuperscript{1} These three authors contributed equally to this work.

\textsuperscript{*} Corresponding author. Hubei Engineering Center for Infectious Disease Prevention, Control and Treatment, Wuhan, Hubei 430071, China.
\textit{E-mail address:} yuanyf1971@whu.edu.cn (Y. Yuan).

\textbf{ARTICLE INFO}

\textbf{Keywords:}
COVID-19
ICUs
Chlorine-containing disinfectants
Inhalation exposure

\textbf{ABSTRACT}

Chlorine-containing disinfectants are widely used in hospitals to prevent hospital-acquired severe acute respiratory syndrome coronavirus 2 infection. Meanwhile, ventilation is a simple but effective means to maintain clean air. It is essential to explore the exposure level and health effects of coronavirus disease 2019 patients’ inhalation exposure to by-products of chloride-containing disinfectants under frequent surface disinfection and understand the role of ventilation in mitigating subsequent airway damage.

We determined ventilation dilution performance and indoor air quality of two intensive care unit wards of the largest temporary hospital constructed in China, Leishenshan Hospital. The chloride inhalation exposure levels, and health risks indicated by interleukin-6 and D-dimer test results of 32 patients were analysed.

The mean ± standard deviation values of the outdoor air change rate in the two intensive care unit wards were 8.8 ± 1.5 h\textsuperscript{-1} (Intensive care unit 1) and 4.1 ± 1.4 h\textsuperscript{-1} (Intensive care unit 2). The median carbon dioxide and fine particulate matter concentrations were 480 ppm and 19 μg/m\textsuperscript{3} for intensive care unit 1, and 567 ppm and 21 μg/m\textsuperscript{3} for intensive care unit 2, all of which were around the average levels of those in permanent hospitals (579 ppm and 21 μg/m\textsuperscript{3}). Of these patients, the median (lower quartile, upper quartile) chloride exposure time and calculated dose were 26.66 (2.89, 57.21) h and 0.357 (0.008, 1.317) mg, respectively.

A statistically significant positive correlation was observed between interleukin-6 and D-dimer concentrations. To conclude, ventilation helped maintain ward air cleanliness and health risks were not observed.

\textbf{1. Background}

Coronavirus disease 2019 (COVID-19), caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), was declared a global pandemic on 11 March 2020. Until 4 March 2022, there have been over 438 million confirmed cases of COVID-19 and approximately 6 million deaths [1]. Due to occupational exposure, healthcare workers (HCWs) have been one of the groups at high risk of acquiring SARS-CoV-2 infection during the pandemic [3]. SARS-CoV-2 is mainly transmitted through respiratory droplets and contact routes [3]. Therefore, in hospitals, maintaining social distancing and using personal protective equipment (PPE) correctly are effective measures to minimise the risk of hospital-acquired SARS-CoV-2 infection [4,5]. In addition, disinfection measures and ventilation systems are crucial to further reduce the risk of the spread of SARS-CoV-2 [6].

In hospitals, the surfaces of function zones, medical equipment, patients’ items, and PPE are easily contaminated [7–10]. Such contamination is usually concentrated in the isolation wards and intensive care
The World Health Organization (WHO) recommends that inpatient rooms, especially the surfaces with high contact frequency, should be disinfected at least twice per day [17]. The National Health Commission of the People’s Republic of China also proposed to increase the disinfection frequency of the surfaces of environmental objects in areas with a high population density and ensure the safe use of disinfectants, the health risks to COVID-19 patients who face prolonged exposure to disinfectants during hospitalization has received little attention.

ICU wards are responsible for treating COVID-19 patients with the most severe symptoms and protecting HCWs from hospital-acquired SARS-CoV-2 infection. Considering that indoor air in ICU wards is easily polluted by disinfectants, their volatilization by-products, and virus-laden aerosols emitted during AGPs [31,32], the outdoor air change rate (ACH) and the ventilation performance in ICU wards are important factors to consider for maintaining air cleanliness. In fact, COVID-19 patients with compromised immune systems and medical conditions in ICU wards require high indoor air quality (IAQ) to facilitate them recover [33]. Leading organisations and societies, including the WHO, American Centers for Disease Control and Prevention, European Society of Intensive Care Medicine, and Society of Critical Care Medicine, recommend an ACH of at least 12 h⁻¹ for COVID-19 wards [34]. Further, as listed in the Standard 170–2021 Ventilation of Health Care Facilities [35] jointly recommended by the American National Standards Institute; the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); and the American Society for Health Care Engineering, the minimum outdoor ACH and total ACH of an airborne infection isolation room (AIIR) are required to be 2 h⁻¹ and 12 h⁻¹, respectively. This standard also requires an indoor temperature in the range of 21–24 °C and a relative humidity (RH) no more than 60% in AIIRs.

Some studies have measured IAQ parameters, including temperature, RH, carbon dioxide (CO₂) and fine particulate matter (PM₂.₅) concentrations while air sampling in ICU wards admit COVID-19 patients [8,23,31,36–41] and have also reported the ventilation rates of these ICUs [8,23,31,40]. These studies have helped us to gain knowledge of the IAQ to which severely ill COVID-19 patients are exposed in ICU wards. However, these studies have mainly focused on exploring the possibility of airborne transmission of SARS-CoV-2, rather than elucidating the IAQ, or discussing by-products from the widespread use of disinfectants during COVID-19 pandemic. Notably, Gregorio et al. (2021) [31] measured the concentration of total volatile organic compounds (TVOCs) in COVID-19 ICUs, but did not further examine the chemical composition of the TVOCs to analyse their effects on patients. Thus, even though we understand the possible health risks posed by inhalation exposure to indoor pollutants, few studies have considered the impact on patients’ health. Because disinfectants are widely used during COVID-19 pandemic, it is essential to analyse the level and consequences of patients’ exposure to disinfectants in ICUs.

In this study, we evaluated COVID-19 patients’ inhalation exposure to by-products of a 1000 mg/L chlorine-containing disinfectant in ICU ward air and the corresponding health risks. To that end, we first determined the outdoor ventilation performance and IAQ characteristics; then estimated the COVID-19 patients’ disinfectant exposure times and doses; and finally, assessed longitudinal changes in the inflammatory parameters of patients admitted to ICU wards of the #1 infection department at Leishenshan (LSS) Hospital from February to April 2020. The findings of this study call for public attention to COVID-19 patients’ inhalation exposure to air pollutants, especially disinfectants used in hospital wards, as these pollutants pose health risks. Moreover, they highlight the role of ventilation in mitigating airway damage caused by such exposure.

Fig. 1. Outdoor air mechanical ventilation system and indoor environmental monitoring sites in the intensive care units of Leishenshan Hospital. AHU, air handling unit; PPE, personal protective equipment; ACH, designed outdoor air change rate. Intensive care unit (ICU) 1 and 2 in Leishenshan Hospital were mirror-symmetric in terms of spatial arrangement. The ICUs were under negative pressure control, and the pressure of each of the different spatial areas in the two ICUs are marked on the left side in the figure. Sites that underwent environmental monitoring are marked with numbers, and other areas are marked with capital letters. The cyan squares denote the air diffusers, and the yellow lines denote the tubes that connect the air diffusers to fresh AHUs. The grey squares denote the exhaust outlets, but the exhaust tubes are not depicted. The grey arrows show how the ICU wards are connected to the indoor clean area and to the outdoor environment. The AHUs extracted fresh air from the outdoor environment and diffused it into the wards. Patients could leave the ICU wards through patient buffer rooms to the outdoor environment. Healthcare workers were required to enter the ICU wards through buffer rooms and exit through PPE doffing rooms. Each ICU ward (ICU 1 and ICU 2, each with an area of 290 m² and a height of 2.6 m) had 14 patient beds with a nurses’ station and had at least two environmental monitoring devices, including devices set at the nurses’ stations (monitoring site No. 7 and 8) and by the patients’ bedside (monitoring site No. 13–15). As marked, the ACH values of ICUs 1 and 2 were 13 h⁻¹ and 15 h⁻¹ (Table S1), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
2. Methods

2.1. Study design, patient selection, and data collection

This was a retrospective, observational, single-centre case study conducted in the ICU wards (ICU 1 and ICU 2) of the #1 Infection Department of LSS Hospital, a COVID-19-dedicated temporary hospital in Wuhan, Hubei province, China. ICUs 1 and 2 were mirror-symmetric versions of each other in terms of spatial arrangement and were under negative pressure control through mechanical ventilation (Fig. 1). Each ICU ward (each with an area of 290 m² and a height of 2.6 m) had 14 patient beds with a nurses’ station. The mechanical ventilation system was designed to ensure an outdoor ACH of 13–15 h⁻¹ for both wards (Fig. 1, Table S1).

Fig. 2 presented our research framework, and in this study, we monitored the indoor environment of ICU wards to determine the IAQ and we analysed the patients’ inhalation exposure to by-products of a 1000 mg/L chlorine-containing disinfectant in the ICU wards, and the health risks posed by such exposure. For more details, please see the
method section in supplementary material.

IQ parameters, including temperature, RH, CO₂ and PM₂.₅ concentrations, were measured using 15 distributed integrated environmental monitoring devices (IBEM, an intelligent indoor air quality monitoring and feedback system, which has been calibrated and validated) [42] at 5-min intervals from 4 March to 15 April 2020.

Patients hospitalised in the ICUs for more than 24 h between 13 February and 14 April 2020 and whose laboratory test results were available (N = 32) were included in the study (Fig. 3). We obtained the epidemiological and clinical characteristics of these 32 patients from their electronic medical records (EMRs), which were obtained from the authors who previously worked at LSS Hospital. The following information was extracted for each patient: age, sex, comorbidity, disease severity at admission, respiratory support treatment, and laboratory test results.

2.2. Outdoor ACH

To meet the urgent need to admit COVID-19 patients, LSS Hospital was constructed in merely 10 days. It is necessary to evaluate whether the actual outdoor ACH of ICU wards in such an emergency hospital meet the standard design and construction requirements.

The actual outdoor ACH can be calculated by the following equation (Equation (1)) describing the steady state after sufficient dilution [43, 44]:

\[ n = 10^6 \frac{G}{V(C_e - C_o)} \]  

where \( n \) is the actual outdoor ACH (h⁻¹), \( G \) is the indoor occupants’ total CO₂ generation rate (m³/h); \( V \) is the volume of the subject room (m³); \( C_e \) is the equilibrium indoor CO₂ concentration (ppm = 10⁻⁶ mol/mol); and \( C_o \) is the outdoor CO₂ concentration (ppm). The above equation is based on the assumption that the indoor air is well mixed, and requires the parameters involved to remain constant throughout each targeted dilution period.

The ICU wards had four 6-h shifts per day — two day shifts and two night shifts. Normally, compared with day shifts, the occupancy was more stable during night shifts. Therefore, we estimated the actual outdoor ACH of wards based on the CO₂ concentration data collected during the middle 2 h of each night shift. Specifically, the CO₂ concentration data points measured in the ICU wards during 22:00–23:55 and 04:00–05:55 were combined to represent the CO₂ concentrations for one night. In addition, we counted the number of occupants, including both patients and HCWs, in the ICU wards each night. The CO₂ concentration data for each night were included only if the nightly data covered at least 85% of the above-mentioned 4-h night shift periods, the nightly data points were within 10% of the mean difference, and the number of occupants was stable. For nights with the same number of occupants in each ICU ward, the data points were further merged and the relative difference between each data point and the corresponding mean value was found to be less than 13%. This was acceptable considering the slight differences in total CO₂ generation rate for groups of occupants with different sex compositions.

The \( G \) value was estimated based on the age, sex, and activity levels of the patients and HCWs (Tables S2–S4) [45, 46]. The mean CO₂ concentrations during the 4-h night shift periods with the same number of occupants in each ICU ward was taken as the \( C_e \) value. The minimum CO₂ concentrations measured by devices placed in ICU 1 and ICU 2 (except those placed at the nurses’ stations and by the patients’ bedsides) were averaged separately, and the averages were considered as the \( C_o \) values for the corresponding ICU wards (Table SS), because these included monitoring sites shared mechanical ventilation systems with the ICU wards and were not constantly occupied. The outdoor ACH for nights with the same number of occupants was first calculated, and then the mean values were taken as the actual outdoor ACHs for the corresponding ICU wards.

2.3. Characteristics of exposure to chlorine-containing disinfectants

2.3.1. Surface disinfection procedure in the ICU wards of LSS hospital

A disinfectant containing 1000 mg/L available chlorine was used twice per day to wipe the surfaces of objects in the ICU wards of LSS Hospital for routine surface disinfection and cleaning. Before disinfection, the disinfectant was prepared by dissolving two effervescent tablets, with trichloroisocyanuric acid (TCCA) as the main component and an available chlorine content of 40% ± 4% (w/w), in 1 L of water. During tablet dissolution, TCCA reacted with water to produce HClO and cyanuric acid (Fig. 4a), which further reacted to form hydrochloric acid and Cl₂ (Fig. 4b and c).

Such chlorine-containing disinfectant should be used immediately after it is prepared. In LSS Hospital, if the disinfection procedure in the ICUs was not completed using the prepared 1 L of disinfectant, the cleaner would prepare more disinfectant to complete the disinfection of all of the solid surfaces. The surface disinfection procedure lasted at least 2 h, and usually 2 L of disinfectant was required for complete surface disinfection.

Wang et al. (2022) [47] randomly sampled the surfaces of frequently contacted objects around three patients and the nurses’ station in ICU 1 of LSS Hospital from 12 March to 17 March 2020, and the three patients were tested positive for SARS-CoV-2 at 12 March 2020. Among these surfaces that were normally disinfected with a 1000 mg/L chlorine-containing disinfectant, 11.11% (2/18) were tested positive for SARS-CoV-2. Samples collected at the nurses’ station and a treatment vehicle were weakly positive (CT value = 37.56 and 39.00, respectively) but no hospital-acquired SARS-CoV-2 infection of HCWs was reported in the ICUs of LSS Hospital. It indicates that the above-mentioned surface disinfection measures are effective.

2.3.2. Exposure variables

The scenario of patients’ exposure to by-products of 1000 mg/L chlorine-containing disinfectant is shown in Fig. 5. The air inhaled by the patients in ICUs may be from two sources: (i) air from the ICU ward and (ii) air from the ventilator. After surface disinfection, chlorides may remain in the ICU ward air for some time. As each ventilator was equipped with a filter to purify the air, we assumed that it could also block chlorides. That is, we assumed that the patients in the ICU wards were exposed to chlorides through inhalation only when they directly inhaled ICU ward air. The chlorides from the disinfectant may have then adversely affected the patients’ health.

Based on the EMRs, we estimated the duration of patients’ exposure to chlorides using Equation (2):

\[ t_{ex} = \sum_{i=1}^{N_k} f_{t_{i}} \]  

where \( t_{ex} \) is the duration of patient \( k \)’s inhalation exposure to chlorides (h); \( t_{i} \) is the duration of inhalation exposure to chlorides by patient \( k \)
during period \(i\) (h) (Equation 3); and \(N_k\) is the number of periods during which patient \(k\) received various types of respiratory treatments or breathed spontaneously, according to the EMRs.

In the disinfection process,

\[
t_p_{ik} = \begin{cases} t_{k-bi} & \text{Spontaneous breathing without standard oxygen therapy} \\ 0 & \text{On respiratory support and } Q_b \leq Q_{k-r,i} \text{ or on extracorporeal membrane oxygenation} \\ t_{k-r,i} & \text{On respiratory support. } Q_b > Q_{k-r,i}. \end{cases}
\] (3-1)

where \(t_{k-bi}\) is the duration of patient \(k\) breathing ICU ward air spontaneously during period \(i\) (h); \(Q_b\) is the minute ventilation (L/min), with each patient assumed to have a normal respiratory flow of 6 L/min [48]; \(Q_{k-r,i}\) is the respiratory support flow of patient \(k\) during period \(i\) (L/min); see Table 1 for the values; \(t_{k-r,i}\) is the duration of respiratory support treatment for patient \(k\) when \(Q_{k-r,i}\) is less than \(Q_b\) during period \(i\) (h).

Otherwise, \(t_p_{ik} = 0\) (3-2)

If \(Q_{k-r,i}\) is less than \(Q_b\), it implies that the respiratory support flow can cover a patient’s minute ventilation, and the patient will not inhale air from the ICU ward. Otherwise, the patient may face inhalation exposure to chlorides.

The estimated cumulative inhaled mass of available chlorine (i.e. exposure doses of chlorides) was calculated using Equation (4),

\[
M_{p_k} = 0.001 \sum_{i=1}^{N_k} t_{p_{ik}} \times Q_{p_{ik}} \times \tau_{p_{ik}}, \quad (i = 1, 2, 3, ..., N_i; \ k = 1, 2, 3, ..., 32)
\] (4)

where \(M_{p_k}\) is the cumulative mass of available chlorine inhaled by patient \(k\) during hospitalisation (mg); \(Q_{p_{ik}}\) is the actual inspiratory flow of chlorides for patient \(k\) during period \(i\) (L/min), using Equation (5); and \(\tau_{p_{ik}}\) is the time-averaged theoretical mass concentration of chlorides in the ICU ward air during period \(i\) (mg/m³), using Equation (6). The calculation of \(M_{p_k}\) was reduced to the above equation based on the following assumptions: (1) during disinfection, all of the available chlorine in the disinfectant was converted into HClO and \(\text{Cl}_2\); (2) the partial pressure of water vapour on the surface of the disinfectant...
solution was not saturated, and all of the above-mentioned generated chlorides gradually volatilised into the ICU ward air as the disinfection worker wiped the surfaces; (3) the chlorides were evenly distributed in the ward air due to the designed high ACH (Fig. 1); (4) no photolysis reaction occurred in the ward, and no reaction with organics occurred on the solid surfaces; and (5) the chlorides were removed only by ventilation.

\[
Q_{t_i} = \begin{cases} 
0 & Q_b - Q_{k-t} < Q_{k-t} \\
Q_b - Q_{k-t} & Q_b - Q_{k-t} > 0 
\end{cases}
\]  

(5)

\[
\tau_{t_i} = \begin{cases} 
0, & \text{during periods without chlorides in ICU ward air} \\
60n_{c_1}/(n_1 \times V 	imes t_{c_{1,d}}), & \text{during periods with chlorides in ICU ward air} 
\end{cases}
\]  

(6)

where \(m_{c_1}\) is the mass of available chlorine produced in a single surface disinfection process (mg), i.e. 2000 mg in our study; \(n_i\) is the actual outdoor air change rate during period \(i\), h\(^{-1}\); \(V\) is the volume of the subject room, 754 m\(^3\); \(t_{c_{1,d}}\) is the chlorine removal time, min, using Equation (7); and \(d\) is the number of days since the ICUs of LSS Hospital began receiving patients, starting from 13 February and ending on 14 April. Therefore, the values of \(d\) ranged from 1 to 62.

\[
\frac{dv}{dt} = n_iVc_{\text{int}} + q - n_iVc(t)
\]  

(7-1)

where \(c\) is the indoor chlorine concentration, ppm; \(c_{\text{int}}\) is the chlorine concentration in outdoor air, 0 ppm; \(t\) is time, min; \(q\) is chlorine generation rate, which equals \(2.1 \times 10^{-7} \text{ m}^3/\text{h}\) when \(0 < t \leq 120\) and equals 0 when \(t > 120\).

Substitute \(c(0) = 0\) into Equations (7-1), and get Equations (7-2); when the indoor/peak concentration ratio is lower than 1% and indoor concentration is less than 1 ppb, we get the duration of chlorine existing in ICU ward air, namely \(t_{c_{1,d}}\), as shown in Fig. S5.

\[
c = \begin{cases} 
\frac{q}{n_iV}(1 - e^{-v_0}), & 0 < t \leq 120 \\
(c(120)e^{-v_0}, & t > 120 
\end{cases}
\]  

(7-2)

2.3.3. Health risk assessment of chloride inhalation

The inflammatory reaction caused by chloride inhalation is indicated by changes in inflammatory marker concentrations [50–53]. We chose the serum interleukin (IL)-6 concentration, which is commonly tested in COVID-19 patients, including those in our study, to represent the health risk of chloride inhalation exposure, namely, plasma D-dimer concentration [55]. If a patient’s serum IL-6 concentration remained high when their D-dimer level decreased, it suggested that the use of chlorine-containing disinfectant had affected the patient’s health. For the 32 ICU patients included in our study, regular measurements of serum IL-6 and plasma D-dimer concentrations were available, and we collected all paired laboratory test results for these two biomarkers throughout the patients’ stay in the ICU wards. That is, if a patient’s IL-6 and D-dimer concentrations were tested on the same day, these test results were considered a pair. We used Spearman’s correlation coefficient to assess the association between paired IL-6 and D-dimer concentrations. Statistical analyses were performed using SPSS Version 23.0 (IBM Corp, Armonk, NY, USA). Two-tailed \(p\)-values < 0.05 were considered to indicate statistical significance.

3. Results

3.1. Characteristics of the participants

The mean (standard deviation) age of the 32 patients included in our study was 69.5 (11.8) years. Of these 32 patients, 9 (28.1%) were female and 23 (71.9%) were male; 16 (50.0%) had hypertension; and 7 (21.8%) had respiratory failure, diabetes, or coronary heart disease (Table 2).

During hospitalisation, all of the 32 patients received respiratory support treatment. Specifically, 19 patients (59.38%) received standard oxygen therapy, 12 (37.50%) received high-flow nasal cannula oxygen therapy (HFNC), 14 (43.75%) received non-invasive ventilation (NIV), 22 (68.75%) received invasive ventilation (IV), and 3 (9.38%) received extracorporeal membrane oxygenation (ECMO, Fig. 6).

Table 1

| Recorded parameters in the medical records | Recorded respiratory flow | The tidal volume × the respiratory rate | Mechanical ventilation |
|-------------------------------------------|----------------------------|-----------------------------------------|------------------------|
| Missing medical records                  | COVID-19 diagnosis and treatment guideline [49] | Refer to the parameter settings in the same breathing mode | |

Table 2

| Items | Age* (years) | Sex* | Comorbidities† | Disease severity status* |
|-------|--------------|------|----------------|-------------------------|
|       |              | Female | Male | Hypertension | Respiratory failure | Diabetes | Coronary heart disease | General | Severe | Critical |
| Patients‡ (n = 32) | 69.5 (11.8) | 9 (28.1%) | 23 (71.9%) | 16 (50.0%) | 7 (21.8%) | 7 (21.8%) | 4 (12.5%) | 19 (59.4%) | 9 (28.1%) |

* From February to April 2020, 2011 Coronavirus disease 2019 patients were admitted to Leishenshan (LSS) Hospital. Patients who were hospitalised in the two intensive care units of the #1 Infection Department of LSS Hospital for more than 24 h and had available laboratory test results were included in our study.

† Age is expressed as the mean (standard deviation). Sex, comorbidities, and disease severity status are expressed as the number of people (percentage). We obtained these data from the medical records.
Fig. 6. Patients' length of stay in the intensive care units and the type and duration of respiratory support received. HFNC, high-flow nasal cannula oxygen therapy; NIV, non-invasive ventilation; IV, invasive ventilation (including tracheotomy and tracheal intubation); ECMO, extracorporeal membrane oxygenation; ID, identification; ICU, intensive care unit. The grey bar indicates spontaneous breathing, not relying on standard oxygen therapy. The light blue, dark blue, yellow, pink, and red bars indicate standard oxygen therapy, NIV, IV, and ECMO, respectively. Chronological order is considered in this figure. We obtained data on the type and duration of respiratory support from the electronic medical records (EMRs). The patient ID numbers are based on the case numbers of the patients’ EMRs. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Actual outdoor air change rate and relevant parameters of the intensive care unit wards of Leishenshan Hospital.

| Ward  | Patients (persons) | Healthcare workers (persons) | CO₂ generation rate [G (m³/h)] | Mean CO₂ concentration [C_e (ppm)] | Actual outdoor ACH [n (h⁻¹)] | Mean ± SD (h⁻¹) |
|-------|--------------------|------------------------------|---------------------------------|-----------------------------------|-------------------------------|-----------------|
| ICU 1 | 7                  | 7                            | 0.2331                          | 464                               | 7.2                           | 8.8 ± 1.5       |
|       | 8                  | 7                            | 0.2460                          | 460                               | 8.4                           |                 |
|       | 9                  | 8                            | 0.2813                          | 460                               | 9.6                           |                 |
|       | 11                 | 9                            | 0.3245                          | 476                               | 7.8                           |                 |
|       | 12                 | 9                            | 0.3379                          | 462                               | 10.9                          |                 |
| ICU 2 | 5                  | 6                            | 0.1819                          | 555                               | 2.6                           | 4.1 ± 1.4       |
|       | 6                  | 6                            | 0.1933                          | 564                               | 2.5                           |                 |
|       | 8                  | 7                            | 0.2425                          | 564                               | 3.2                           |                 |
|       | 9                  | 8                            | 0.2753                          | 544                               | 4.5                           |                 |
|       | 11                 | 9                            | 0.3316                          | 552                               | 4.9                           |                 |
|       | 12                 | 9                            | 0.3445                          | 555                               | 5.0                           |                 |
|       | 13                 | 10                           | 0.3807                          | 546                               | 6.1                           |                 |

Abbreviations: CO₂, carbon dioxide; SD, standard deviation; ICU, intensive care unit; ACH, air change rate.

The actual outdoor ACH was calculated using the following equation describing the steady state after sufficient dilution: $n = \frac{10^6 G}{V(C_e - C_o)}$, where $n$ is the actual outdoor ACH (h⁻¹), $G$ is the indoor occupants’ total CO₂ generation rate (m³/h), $V$ is the volume of the subject room (m³), $C_e$ is the equilibrium indoor CO₂ concentration (ppm = $10^{-6}$ mol/mol), and $C_o$ is the outdoor CO₂ concentration (ppm). The volume of each ward was 754 m³, and the $C_o$ was 421 ppm and 463 ppm for ICU 1 and ICU 2, respectively.
Building and Environment 228 (2023) 109787

Y. Li et al.

8

Fig. 7. Temperature and relative humidity in intensive care unit wards admitting coronavirus disease 2019 patients. ICU, intensive care unit; ASHRAE, American Society of Heating, Refrigerating and Air-Conditioning Engineers; AIIR, airborne infection isolation room. Except for this study, the temperature and relative humidity (RH) data points depicted were collected from ICU wards admitting coronavirus disease 2019 (COVID-19) patients in permanent hospitals worldwide (Table S6) [8,23,31,36–41]. The average temperature and RH in these permanent ICU wards were 25.1 °C and 38.1%, respectively, by the blue dash-dot line and the pink dash-double dot line, respectively. Most of the included studies presented the temperature and RH data as the mean ± standard deviation and thus, our results are also presented in this format. The air moisture (g/kg dry air), or absolute humidity, was calculated and is labelled next to each corresponding data point. The average absolute humidity in the permanent ICU wards was 7.53 g/kg dry air, as represented by the grey dashed line. The grey area represents the general requirements of indoor air quality (IAQ) listed in Table 7.1 of the ASHRAE standard [35]. Specifically, according to the standard, in an AIIR, the temperature should be in the range of 21–24 °C and the RH should be <60%. Masoumbeigi et al. (2020) [39] measured the IAQ in two ward areas of ICU 2 and four isolation rooms of ICU 3 in a military referral hospital in Iran and obtained the same result; therefore, only one data point is depicted here. Ghaffari et al. (2021) [37] presented four groups of IAQ data collected from the same ICU ward, and thus, the data were averaged before inclusion in this figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Ventilation and IAQ

The mean ± standard deviation values of the actual outdoor ACH of ICU 1 and ICU 2 wards at LSS Hospital were estimated to be 8.8 ± 1.5 h⁻¹ and 4.1 ± 1.4 h⁻¹, respectively (Table 3), which was much lower than the 13–15 h⁻¹ targeted by the ventilation system, but met the ASHRAE standard requirement of 2 h⁻¹ [35].

Temperature and RH are indicators of thermal comfort, and CO₂ and PM_{2.5} concentrations are indicators of air cleanliness. In ICU 1 ward, the median (lower quartile, upper quartile) temperature, RH, CO₂ concentration, and PM_{2.5} concentration from 4 March to 5 April 2020 were 21.8 (20.7, 22.5) °C, 44.7 (39.4, 55.0) %, 480 (462, 500) ppm, and 19 (13, 27) µg/m³, respectively. The corresponding median (lower quartile, upper quartile) values in ICU 2 ward from 4 March to 12 April 2020 were 19.3 (18.1, 21.1) °C, 47.9 (42.8, 52.6) %, 567 (550, 587) ppm, and 21 (13, 27) µg/m³, respectively. The ASHRAE standard stipulates that, in an AIIR, the temperature should be in the range of 21–24 °C and the RH should be ≤60%, but it does not set a limit for CO₂ or PM_{2.5} concentrations [35]. ICU 1 and ICU 2 wards met the temperature and RH requirements for only 58.80% and 21.93% of the environmental monitoring period, respectively. These low rates were predicted to be mainly due to the low indoor temperature (Fig. 5).

Compared with the IAQ parameters measured in the ICU wards of permanent hospitals worldwide [8,23,31,36–41], the temperature was lower, the RH was higher, and the CO₂ and the PM_{2.5} concentrations were similar in the two ICU wards of LSS Hospital (Figs. 7 and 8, Table S6). This indicates that the ventilation system providing an outdoor ACH of 4.1 h⁻¹ to 8.8 h⁻¹ maintained the indoor air cleanliness of the ICU wards of LSS Hospital to a level found in other well-designed and well-constructed ICU wards.

3.3. Exposure to chlorides

Fig. 9 shows the patients’ level of chloride inhalation in the ICU wards of LSS Hospital. The median (lower quartile, upper quartile) chloride inhalation exposure time and calculated chloride inhalation dose of the patients were 26.66 (2.89, 57.21) h and 0.357 (0.008, 1.317) mg, respectively. The chloride exposure time and dose were both 0 for six patients (Patient ID numbers 1, 4, 6, 8, 10, and 32).

3.4. Health risk assessment

We first explored the association between the concentrations of the inflammatory marker, IL-6, and the COVID-19 severity indicator, D-dimer. The findings revealed a moderately positive correlation between these two variables ($r = 0.48$; $p < 0.01$; Fig. 10), which suggests that changes in these biomarkers were not affected by chloride inhalation exposure in the ICU wards of LSS Hospital.
involved to remain constant throughout each targeted dilution period. However, on one hand, the distribution of environmental monitoring devices set in ICU wards might not be sufficient to tell whether the indoor air is well mixed and requires the parameters estimated. Therefore, assuming that the indoor air is well mixed and requires the parameters used an equation describing the steady state reached after sufficient dilution (Equation (1)). As mentioned, such equation is based on the assumption that the outdoor airflow rate and the indoor air was well mixed or not; on the other hand, the values of G, Cce, and Cc were determined to be constant for each dilution period but they actually fluctuated. These may have introduced uncertainty. Additionally, instrument errors during the measurements cannot be ruled out. First, the G value was not directly measured in the ICU wards of LSS Hospital, but was estimated based on patients’ EMRs and the results of other studies. The age and sex distributions of HCWs each night were set to the same as those provided by Yu et al. (2020) [46] for the HCWs in LSS Hospital, although these may have been different for the ICUs. We referenced the individual CO2 generation rates measured by Yang et al. (2020) [45] in healthy people of different ages and sexes, although these rates may be different in COVID-19 patients, even at the same activity level of ‘lying, quiet’. In addition, factors such as wearing PPE, mental stress, and physical fatigue may increase CO2 generation by the HCWs in the ICU wards of LSS Hospital to a level greater than the amount generated by healthy subjects under the experimental conditions used by Yang et al. (2020) [45].

4. Discussion

4.1. Ventilation

The outdoor ACH of the ICU wards in LSS Hospital was estimated using an equation describing the steady state reached after sufficient dilution (Equation (1)). As mentioned, such equation is based on the assumption that the indoor air is well mixed and requires the parameters involved to remain constant throughout each targeted dilution period. However, on one hand, the distribution of environmental monitoring devices set in ICU wards might not be sufficient to tell whether the indoor air was well mixed or not; on the other hand, the values of G, Cce, and Cc were determined to be constant for each dilution period but they actually fluctuated. These may have introduced uncertainty. Additionally, instrument errors during the measurements cannot be ruled out. First, the G value was not directly measured in the ICU wards of LSS Hospital, but was estimated based on patients’ EMRs and the results of other studies. The age and sex distributions of HCWs each night were set to the same as those provided by Yu et al. (2020) [46] for the HCWs in LSS Hospital, although these may have been different for the ICUs. We referenced the individual CO2 generation rates measured by Yang et al. (2020) [45] in healthy people of different ages and sexes, although these rates may be different in COVID-19 patients, even at the same activity level of ‘lying, quiet’. In addition, factors such as wearing PPE, mental stress, and physical fatigue may increase CO2 generation by the HCWs in the ICU wards of LSS Hospital to a level greater than the amount generated by healthy subjects under the experimental conditions used by Yang et al. (2020) [45].

Second, the instrument errors introduced by the environmental monitoring device may be too great to ignore. Theoretically, assuming that the outdoor airflow rate and the Cc value are stable, Cc will increase with an increasing number of occupants. However, the CO2 concentrations measured were measured in the ICU wards at night did not conform to this trend (Fig. S2). The outdoor airflow rates were designed to be 10,139 m3/h and 11,020 m3/h for ICU 1 ward and ICU 2 ward, respectively. Under these airflow rates, the maximum additional CO2 concentrations contributed by the occupants were 33 ppm and 35 ppm, respectively, when the number of occupants in ICU 1 ward and ICU 2 ward reached the maximum numbers listed in Table 3. However, the CO2 sensors in our environmental monitoring devices only had an accuracy of ±40 ppm (±3% of the actual value), which means that the unavoidable instrument error may have masked the fluctuation in CO2 concentrations caused by the occupants, such that the CO2 concentrations did not consistently increase with an increase in the number of occupants in the wards.

Third, the outdoor CO2 concentrations were not measured outside, but were estimated from the lowest CO2 concentrations measured in ICU spaces, including patient buffer rooms, bronchoscopy rooms, treatment rooms, and PPE doffing rooms (Fig. 1). Unlike the ICU wards, these spaces were not always occupied, and the most commonly used rooms were the PPE doffing rooms, which were regularly occupied every 6 h. In addition, the outdoor ACHs in these spaces were designed to be sufficiently high to ensure good dilution performance (Table S1). Therefore, we assumed that the CO2 concentrations in these spaces could be quickly diluted to the outdoor level, and the minimum concentrations could be averaged and taken as the Cc value. Considering that the outdoor air...
inlets of the fresh air handling units of the mechanical ventilation systems in the two ICUs were adjacent to each other, the CO₂ concentrations in the outdoor air delivered to spaces in the two ICUs should be approximately the same. However, according to our estimates, the Cₒ value differed by 42 ppm between ICU 1 and ICU 2. The Cₑ value estimated to be higher in ICU 2 than ICU 1, and the CO₂ concentration was also approximately 90 ppm higher in ICU 2 than in ICU 1 with the same number of occupants. This may be the result of natural fluctuation in outdoor CO₂ concentrations, the exhaust gas from the incinerator on the north side of the LSS Hospital complex, instrument errors, or the airflow field around the air inlets of the fresh air handling units of the mechanical ventilation systems in the ICUs.

There were also other factors that difference the calculated outdoor ACH in the ICUs from the designed. For instance, the outdoor airflow rate may have decreased with an increase in the resistance of the HEPA filters installed in the ventilation ducts [56,57].

In conclusion, we estimated the actual outdoor ACHs in ICU 1 ward and ICU 2 ward of LSS Hospital to be 8.8 ± 1.5 h⁻¹ and 4.1 ± 1.4 h⁻¹, respectively. Although the data we referenced, instrument errors, and other potential factors may have contributed to uncertainty in the results, the estimated actual outdoor ACHs met the ASHRAE standard requirement of 2 h⁻¹ [35].

4.2. IAQ

Compared with the data collected in the ICUs of permanent hospitals [8,23,31,36–41], in the ICU wards of LSS Hospital, the temperature was lower, the RH was higher (Fig. 7, Table S6), and the absolute humidity was similar to or less than the average level (7.53 g/kg dry air). The RH was relatively high because of the low temperature. In addition, the relatively low temperature in the ICU wards of LSS Hospital may be due to differences in latitude, season, and building envelope compared with other studies. The latitude of LSS Hospital is 30.43 N, which is approximately the same as the latitude of the previously studied hospitals in Iran [36–39,41], but is substantially higher than the latitude of other hospitals studied in Southeast China [23], Singapore [8], Brazil [31], and Bangladesh [40]. Wuhan was in early spring when our measurements were taken from 4 March to 12 April 2020, with an average outdoor temperature of 13.9 ± 5.2 °C. Furthermore, as a temporary hospital, LSS Hospital constituted a group of prefabricated buildings constructed with containers settled on steel frames, which added the convection heat loss from the floors to the outdoor air. Therefore, the thermal insulation performance is expected to be worse than that of permanent hospitals.

As a natural tracer gas of human exhalation, the indoor CO₂ concentration reflects ventilation performance. Some previous studies have measured the CO₂ concentration in ICU wards of permanent hospitals [23,31,36,38,40,41], but not all of these studies have provided the corresponding outdoor airflow rate or the outdoor ACH, the number of occupants, or the area of the wards (Fig. 8, Table S6). However, the outdoor airflow rate per person may be estimated based on the following assumptions: (1) the outdoor CO₂ concentration is same globally, (2) the mean personal CO₂ generation rate was same for the occupants in the wards during measurement, and (3) CO₂ concentrations were measured when the number of occupants in each ward was fixed. The mean or median value of the indoor CO₂ concentration may then be taken as the Cₑ, and the outdoor airflow per person may be considered to decrease with an increase in the Cₑ. Thus, the dilution performance of the
The reader is referred to the Web version of this article.

The Spearman’s correlation between the concentrations of interleukin-6 and D-dimer in intensive care unit patients at Leishenshan Hospital during their hospitalisation. The grey dots indicate the interleukin-6 (IL-6) and D-dimer laboratory test results obtained on the same day. We used Spearman’s correlation coefficients to assess the association between the concentrations of the inflammatory marker, IL-6, and the coronavirus disease 2019 severity indicator, D-dimer. A moderately positive correlation was detected ($\rho = 0.48; p < 0.01$). The red and blue dashed lines indicate the normal ranges of IL-6 (0–7.0 pg/mL) and D-dimer (0–0.55 mg/L) concentrations. The red and blue histograms represent the distribution of patients’ laboratory test results for D-dimer and IL-6, respectively. The x-axis and y-axis are divided into 14 and 11 intervals with interval sizes of 1 mg/L and 500 pg/mL, respectively. The number of data points in each interval is marked at the top of the corresponding bar. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

occupants’ exhalation may have been greater in the ICU wards of LSS Hospital than in those of some permanent hospitals.

The PM$_{2.5}$ concentration reflects the cleanliness of the air and the level of lower respiratory tract exposure to some extent. Although most of the ICU patients were under respiratory support, some patients were breathing ICU ward air spontaneously when being weaned from the ventilators intermittently. Considering that PM$_{2.5}$ may carry pathogens, including SARS-CoV-2 and those carrying antibiotic-resistance genes [37,58–60], spontaneous breathing may cause hospital-acquired infections, leading to disease progression, a prolonged hospital stay, and even death. Similar to the CO$_2$ concentrations, the mean or median PM$_{2.5}$ concentrations in the ICU wards of LSS Hospital were approximately equal to the average concentrations in the ICU wards of permanent hospitals (Fig. 8, Table S8).

To conclude, compared with the IAQ parameters of ICU wards admitting patients with COVID-19 in permanent hospitals and the requirements of AIIRs stipulated by the ASHRAE standard, in the ICU wards of LSS Hospital, the temperature was lower, which led a higher RH than the stipulated requirement. This was due to the cold weather at the time of the study and the poor thermal insulation performance of the building envelope. The CO$_2$ and PM$_{2.5}$ concentrations in the ICU wards of LSS Hospital were similar to the average levels of those in the ICU wards of permanent hospitals, which suggests that, due to the outdoor ACH in the range of 4.1 h$^{-1}$ to 8.8 h$^{-1}$, the air cleanliness during the hospitalisation of critical patients was ensured by the well-designed and well-constructed ICU wards of LSS Hospital.

4.3 Inhalation exposure and health implications

This retrospective study investigated the potential health effects of using chlorine-containing disinfectants for surface disinfection on 32 patients in the ICUs of LSS Hospital. The patients did not inhale ICU ward air during HFNC or ECMO, but they inhaled the most chloride mass from ICU ward air when receiving standard oxygen therapy, followed by spontaneous breathing. Thus, chloride inhalation exposure occurred when the patients’ respiratory function was good, that is, during the early stage of admission to the ICUs or the recovery stage of respiratory function before discharge (Fig. 6), because in these stages, the patients were not dependent on the ventilator for breathing and their main source of air for inhalation was the ward air.

There were six patients (Patient ID numbers 1, 4, 6, 8, 10, and 32) whose chloride exposure times and doses were both 0 (Fig. 9). These patients received standard oxygen therapy for an average of 0.28 h, which was significantly lower than the average of 165.54 h of standard oxygen therapy that the remaining 26 patients received ($p<0.05$). These six patients also had shorter spontaneous breathing times (0 for these six patients and 13.26 h for the other twenty-six patients). Therefore, the air inhaled by these patients was ventilator-filtered and chloride-free. This highlights an interesting phenomenon that patients with rapid recovery of pulmonary function who received standard oxygen therapy or breathed spontaneously in the ICUs were more likely to inhale chlorides.

Although some patients did not inhale chlorides, most (81.3%, 26/32) of the patients in the ICU wards did experience chloride exposure, making chloride exposure a cause for concern in these wards. According to the Health and Safety Executive and National Institute for Occupational Safety and Health, the permissible Cl$_2$ exposure limit is 0.5 ppm for a 15-min exposure [61,62]. However, the WHO Task Group proposed that the ambient Cl$_2$ level should remain below 0.034 ppm to protect the general population from sensory irritation [63]. Therefore, when using chlorine-containing disinfectants for surface disinfection, to avoid adverse health effects from excessive inhalation exposure, attention should be paid to minimise the generation of volatile chlorides, such as Cl$_2$ or HClO. In the ICUs of LSS Hospital, a single surface disinfection procedure lasted approximately 2 h, and approximately 2000 mL of a chloride-containing disinfectant was used. As mentioned, during the 2-h disinfection procedure, 2000 mg of available chloride was produced. Based on chemical reaction equations (Fig. 4), we calculated that the Cl$_2$ concentration may have reached 0.558 ppm in each ICU ward if all of the available chlorine in the TCCA effervescent disinfection tablets formed Cl$_2$ and was immediately released without ventilation. However, this was not the case, as the ICU wards were equipped with a mechanical ventilation system for dilution, and the chlorides only slowly entered the ward during the disinfection procedure. Considering the actual dilution performance of the ventilation system, the maximum Cl$_2$ concentration in the ward air during surface disinfection was 0.111 ppm when the ACH of the ICU wards reached the minimum value of 2.5 h$^{-1}$ (Table 3). However, as HClO can stick to solid surfaces, the actual amount of Cl$_2$ produced during every disinfection procedure may be less than our estimated value. Nevertheless, the estimated value (0.111 ppm) was between the two standard limits (0.5 ppm and 0.034 ppm), and thus, the resulting health risks cannot be ignored.

We next sought to assess the inflammatory response in patients who had inhaled chlorides, by observing the relationship between IL-6 and D-dimer concentrations over time. The results revealed a moderately positive and statistically significant correlation between these two variables (Fig. 10). This suggests that the health status of the patients in the ICUs of LSS Hospital was unaffected by chloride exposure; that is, we did not find patients with respiratory problems suffered secondary damage to the respiratory tract after exposure to disinfectants. Unlike the secondary airway damage reports in the United States, Spain and other countries (Table S7) [64–70], this finding may be explained by the following four reasons. First, the chloride concentration that the patients were exposed to may have been below the specified limit [61–63] and below the value we estimated. Because the ICU wards were ventilated by mechanical ventilation systems, the generated chlorides may have been diluted during the surface disinfection process and chloride-consuming reactions may have occurred on indoor environmental surfaces.
leading to mass loss of chlorides. Second, on average, the patients inhaled filtered air from the ventilator 70.4% of the time during their hospital stay, indicating that they had short periods of exposure to chlorides in the ICU ward air. Third, the lack of health risks from our findings needs to be interpreted in light of our study limitations, namely, the small sample size and the limited number of laboratory test results. Finally, the selected inflammatory marker, IL-6, may be affected by other conditions, such as sepsis, and such interfering factors could not be excluded due to limited information.

We observed that, in some patients, when plasma D-dimer concentrations decreased, serum IL-6 concentrations increased (Fig. S3), which may have been caused by chloride inhalation exposure. However, because the detection frequency of these two indicators was low and other unknown factors in the ward may have caused or contributed to inflammation, it was not possible to distinguish the effects of chloride exposure.

This is the first study to investigate the potential health risks to patients posed by frequent surface disinfection in hospitals. However, the depth of our research is limited and the conclusions are preliminary due to insufficient data resources. Hence, future work is warranted to further elucidate the effect of disinfectants on patients.

Little is known about the volatilisation characteristics of chlorine-containing effervescent tablets dissolved in water to form disinfectants. Furthermore, due to changes in conditions, such as light, surface-to-volume ratios, and the ACH, the generation rate and removal efficiency of HClO and Cl₂ during the use of chlorine-containing disinfectants varies between hospitals. Therefore, we recommend that hospitals conduct on-the-spot measurements of chloride concentrations in ward air during the preparation and use of disinfectants and after the disinfection procedure. Notably, disinfectants containing quaternary ammonium compounds (QACs) have also been frequently used during this pandemic [71]. An occupational study demonstrated that exposure to QACs is significantly associated with an increased risk of chronic obstructive pulmonary disease [72]. The possible health effects of patient exposure to such disinfectants should also be considered and further investigated. The average length of hospitalisation of our patients was 653.1 h and they were exposed to ward air 29.6% of this time. During the process of inhaling ward air, the patients were exposed to chlorides for 18.7% of the time (Fig. S4).

Notably, the patients may have also been exposed to other substances through inhalation that adversely affected their health, which also warrants further study.

We recommend that hospitals measure more indicators of inflammation, such as IL-4 and IL-17, and increase the detection frequency of these indicators in COVID-19 patients who have experienced long-term exposure to surface disinfection in wards, to further investigate the associated health risks. In addition, further study is warranted to identify specific biomarkers of chloride exposure.

We also recommend that hospitals record patient’s respiratory parameters and respiratory support strategies in more detail to enable further clarification of the actual level of inhalation exposure to disinfectants during hospitalisation and to facilitate multi-centre research.

Finally, we suggest wiping surfaces with water after disinfection to remove HClO deposited on the surfaces and prevent further reactions from occurring on the surfaces.

5. Conclusions

To help COVID-19 patients recover, especially those who are severely ill, it is necessary to determine the health risks posed by their inhalation exposure to disinfectants used in hospital wards. Mechanical ventilation systems play an important role, as they help to dilute the ambient concentrations of disinfectant by-products and maintain a high IAQ. As far as we know, this is the first study to evaluate the health effects of the chlorine-containing disinfectant have on patients as well as the effectiveness of ventilation dilution in reducing patients’ exposure.

In this study, outdoor ventilation and IAQ characteristics were determined, patients’ exposure time to chlorides from disinfectants was estimated, and the longitudinal changes in inflammatory parameters of patients were assessed in the ICU wards of LSS Hospital from February to April 2020.

The following conclusions were drawn:

(1) Based on CO₂ and PM2.5 concentrations, an outdoor ACH of 4.1 h⁻¹ is sufficient to maintain indoor air cleanliness in 14-bed ICU wards of a temporary hospital to a similar extent as the air cleanliness in ICU wards of permanent hospitals.

(2) In the ICU wards of LSS Hospital, a 1000 mg/L chlorine-containing disinfectant was used for surface disinfection twice per day. No hospital-acquired infections due to surface pollution or adverse health effects on patients were observed. This suggests that this surface disinfection measure is appropriate and effective.

(3) When using high concentrations of chlorine-containing disinfectants for frequent surface disinfection, testing for the generation of chlorides is recommended in the ICU wards during disinfection procedure to prevent adverse health effects on patients due to acute and chronic exposure. Attention should be paid to maintaining adequate ventilation to dilute the HClO and Cl₂ generated by the use of chlorine-containing disinfectants in ICU wards and other places where surfaces are disinfected, such as at home. In addition, the cleaner should wipe surfaces with clean water after disinfection to eliminate the HClO adsorbed on the surfaces.

Future studies should pay attention to the health risks to patients with COVID-19 or other pulmonary symptoms, especially to their respiratory system, posed by exposure to disinfectants, and investigate cost-effective ways of implementing ventilation to protect patients’ health.

Ethical approval

This study was approved by the ethics committee of Zhongnan Hospital of Wuhan University (Number 2020075K).

CRediT authorship contribution statement

Yifan Li: Writing – original draft, Visualization, Methodology, Formal analysis. Yiran Lu: Writing – original draft, Visualization, Methodology, Formal analysis. Ying Wang: Writing – review & editing, Resources, Investigation. Li Liu: Writing – review & editing, Supervision, Funding acquisition. Hao Zhou: Investigation. Borong Lin: Supervision. Zhiyong Peng: Writing – review & editing, Resources. Yufeng Yuan: Writing – review & editing, Supervision, Resources.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgements

The study was supported by the National Natural Science Foundation of China [52178080, 51778520] and Tsinghua University Spring Breeze Fund [2020Z9CF025]. The authors appreciate the healthcare workers and all other people working in the Leishenshan Hospital, Wuhan, China.
