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Environmental contamination with SARS-CoV-2 in COVID-19 hospitals in Wuhan, China, 2020

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Summary

Coronavirus disease 2019 (COVID-19) pandemic has caused high number of infections and deaths of healthcare workers globally. Distribution and possible transmission route of SARS-CoV-2 in hospital environment should be clarified. We herein collected 431 environmental (391 surface and 40 air) samples in the intensive care unit (ICU) and general wards (GWs) of three hospitals in Wuhan, China from February 21 to March 4, 2020, and detected SARS-CoV-2 RNA by real-time quantitative PCR. The viral positive rate in the contaminated areas was 17.8% (28/157), whereas there was no virus detected in the clean areas. Higher positive rate (22/59, 37.3%) was found in ICU than that in GWs (3/63, 4.8%). The surfaces of computer keyboards and mouse in the ICU were the most contaminated (8/10, 80.0%), followed by the ground (6/9, 66.7%) and outer glove (2/5, 40.0%). From 17 air samples in the contaminated areas, only one sample collected at a distance of around 30 cm from the patient was positive. Enhanced surface disinfection and hand hygiene effectively decontaminated the virus from the environment. This finding might help understand the transmission route and contamination risk of SARS-CoV-2 and evaluate the effectiveness of infection prevention and control measures in healthcare facilities.

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Introduction

Since December 2019, the COVID-19 outbreak caused by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) has become a pandemic worldwide (Carlos *et al*., 2020; Lu *et al*., 2020; Zhu *et al*., 2020). As of December 19, 2020, over 76 150 000 COVID-19 cases have been reported globally, which constitutes a public health emergency of international concern (Enrico Lavezzo *et al*., 2020; Hui *et al*., 2020; Leon *et al*., 2020; Wang *et al*., 2020a). Especially, a large number of health care workers have been infected in many countries in early phase of the pandemic, not only in China (WHO-China, 2020) but also in the USA and many European countries (CDC COVID-19 Response Team, 2020; Hunter *et al*., 2020). In addition to being the frontline of medical treatment, healthcare facilities are also at the forefront of COVID-19 prevention and control. Therefore, the elucidation of the possible contamination of SARS-CoV-2 in the hospital environment which was designed for COVID-19 patients is regarded essential to protect healthcare workers from infection and to better understand the transmission route of SARS-CoV-2 in public places (Bassetti *et al*., 2020; Cheng *et al*., 2020b).

SARS-CoV-2 has the characteristics of long incubation period, strong infectivity and general susceptibility of the population (Chen *et al*., 2020; Huang *et al*., 2020; Lei *et al*., 2020; Zhou *et al*., 2020; Zhu *et al*., 2020; Wang *et al*., 2020b). This virus has been shown to transmit mainly through respiratory droplets and close contact (Chan *et al*., 2020; GONHC, 2020; Li *et al*., 2020; Nishiura *et al*., 2020). SARS-CoV-2-containing droplets are easy to deposit on the surface of the objects. When the hands contact with these contaminated surfaces, and then touch the mouth, nose, eyes and other mucous membranes, people are very likely to be infected (Dowell *et al*., 2004; Otter *et al*., 2016; Kampf *et al*., 2020; Rothe *et al*., 2020). The virus is also detected in the faeces samples from patients with confirmed COVID-19, suggesting the risk of disease transmission through the faecal–oral transmission route (Holshue *et al*., 2020). So far, SARS-CoV-2 has been

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detected on the surface of objects including the toilet areas used by some patients with confirmed infections (Guo *et al*., 2020; Ong *et al*., 2020; Pan *et al*., 2020; Yanfang Jiang *et al*., 2020; Cheng *et al*., 2020a). However, these studies were either carried out with a small sampling size or only in one division of a hospital, which might not represent the entire situation of viral contamination in fully operational hospitals to prevent and treat COVID-19.

The role of aerosols in the airborne transmission of SARS-CoV-2 remains debatable. SARS-CoV-2 aerosol particles refer to the suspension of small particles or droplets (diameter <5 μm) containing the virus (Seto *et al*., 2013; Wu *et al*., 2019), which can float in the air for a long time, spreading widely (Lam *et al*., 2007; Cao *et al*., 2011; Anderson *et al*., 2017; Mubareka *et al*., 2019). Currently, there is no clear evidence that SARS-CoV-2 can be transmitted through aerosols (a Meselson, 2020; Ram, 2021; Wilson *et al*., 2020; WHO, 2020a; Rabaan *et al*., 2021). A study conducted in Singapore demonstrated a positive virus test in the air very close to a patient with COVID-19 symptoms (Ong *et al*., 2020). In contrast, another updated study detected virus-highly positive air at about 4 m from patients in ICU equipped with a highly efficient negative-pressure ventilation system (Guo *et al*., 2020).

Taken together, the SARS-CoV-2 exposure risk through close contacts in hospital wards has not been systematically evaluated, and the transmission route of SARS-CoV-2 still needs more scientific verification (Bassetti *et al*., 2020; WHO, 2020b). The environmental contamination and distribution of SARS-CoV-2 in designated COVID-19 hospitals require further clarification. Hence, in this study, the virus distribution was determined by testing surface and air samples from the ICUs and GWs of three hospitals designated for COVID-19 patients including Huoshenshan Hospital in Wuhan, China. Furthermore, the effectiveness of infection control measures to reduce the presence of the viruses in the hospitals was also evaluated.

Materials and methods

Hospital settings

The general characteristics of the three hospitals designed for care of COVID-19 patients in Wuhan were listed and compared in Table 1. The three hospitals, A, B and C, had 1000, 860 and 800 beds respectively, all of which were fully occupied. Hospital A was newly built with two ICUs (30 beds) for severely ill COVID-19 patients and 17 general units for non-severely ill patients. Each ICU room was equipped with negative pressure ventilation, with air delivered 12 times and exhausted 16 times per hour. In each GW, air was supplied eight times and removed 12 times per hour. Hospitals B and C were transformed from ordinary non-communicable disease hospitals. No negative pressure ventilation system was provided in both ICUs and GWs due to the constraints of the architectural pattern and original conditions. Compared to the 30 ventilators used in the ICUs of Hospital A, only 10 or 9 ventilators were used in the ICUs of Hospitals B and C. Some of the patients in ICU were intubated and on ventilator, while the patients in general wards were not. The contaminated areas included patient wards, ICU nurse stations, disposal rooms, waste rooms, patient admission rooms, discharge treatment rooms, and so on. These areas were used for diagnosis and treatment of confirmed and suspected patients with COVID-19, as well as temporary storage and disposal of items contaminated with blood, body fluids, secretions and excreta of patients. A clean area referred to the place that was not contaminated by patients' blood, body fluids, pathogenic microorganisms and other substances, including medical staff office, duty room, toilet room, dressing room, bathroom, storage room, catering room and other areas that patients were not allowed to enter. All patients in ICU were suffered from severe COVID-19 infection. The characteristic for these patients was mainly fever, cough, and myalgia or fatigue; less common symptoms were sputum production, headache, haemoptysis and diarrhoea, as similar as reported by Dr. Bin Cao (Huang *et al*., 2020) and Dr. Li Zhang (Chen *et al*., 2020) in *The Lancet*.

Sampling and collection

From February 21 to March 4, 2020, on different days, swab samples were collected as described previously

Table 1. Brief characteristics of three hospitals for COVID-19 patients in Wuhan, 2020.

Hospital characteristics	Hospital A	Hospital B	Hospital C
No. of total beds	1000	860	800
Negative pressure ventilation in general wards	Yes	No	No
No. of beds in ICU	30	20	52
Negative pressure ventilation in ICU	Yes	No	No
No. of ventilators in ICU	30	10	9
Construction	Newly built	Transformed	Transformed

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Table 2. SARS-CoV-2 RNA in the object surfaces and air of different departments in the three hospitals.

	Contaminated area[a,b]						
Sites	ICU wards	General wards	Clinical Lab.[d]	Radiological examination	Subtotal	Clean area[c]	Total
Object surface							
Keyboard and mouse	8/10,80.0%	0/5	0/3	0/1	8/19,42.1%	0/61	8/80,10.0%
Desktop	0/2	0/8	0/3	0/1	0/14	0/52	0/66
Bed rails	0/3	1/5,20.0%	–/–	2/2100.0%	3/10,30.0%	–/–	3/10,30.0%
Ground	6/9,66.7%	0/12	0/3	0/4	6/28,21.4%	0/52	6/80,7.5%
Medical instruments	0/2	0/4	1/3,33.3%	0/3	1/12,8.3%	0/1	1/13,7.7%
Door handle	1/4,25.0%	0/8	0/3	0/2	1/17,5.9%	0/62	1/79,1.2%
Walkie-talkie	0/1	–/–	–/–	–/–	0/1	0/11	0/12
Specimen transfer window	–/–	–/–	0/3	–/–	0/3	0/1	0/4
Garbage bag handle	1/4,25.0%	–/–	–/–	–/–	1/4,25.0%	–/–	1/4,25.0%
Lift button	–/–	–/–	–/–	–/–	–/–	0/4	0/4
Water tap	–/–	–/–	–/–	–/–	–/–	0/3	0/3
Front surface of N95 mask	1/4,25.0%	0/2	–/–	–/–	1/6,16.7%	–/–	1/6,16.7%
Outer glove of medical staffs	2/5,40.0%	2/12,16.7%	0/1	–/–	4/18,22.2%	0/4	4/22,18.2%
Ground of room for PPE PPE removal	0/2	–/–	–/–	–/–	0/2	–/–	0/2
Air	1/9,11.1%	0/5	0/2	0/1	1/17,5.9%	0/23	1/40,2.5%
Air outlet fan	2/4,50.0%	0/2	–/–	–/–	2/6,33.3%	–/–	2/6,33.3%
Total	22/59,37.3%	3/63,4.8%	1/21,4.8%	2/14,14.3%	28/157,17.8%	0/274	28/431,6.5%

[a]Includes patient ward, nurse station in intensive care unit (ICU), disposal room, waste room, patient admission and discharge treatment room, and so on, which are used for diagnosis and treatment for confirmed and suspected patients and for temporary storage and disposal objects contaminated by blood, body fluids, secretions, excreta of patients.
[b]Results are shown as number of positive samples/number of total samples, positive rate.
[c]Includes the place where it is not easy to be polluted by blood, body fluids, pathogenic microorganisms and other substances of patients and that should not be entered by patients, referring to the office of medical staffs, duty room, toilet, dressing room, bathroom, storage room, catering room, and so on.
[d]Lab. – laboratory.

(Ong *et al*., 2020) from potentially contaminated object surfaces in patients' wards (as shown in Table 2) and clean areas. All samples were collected at a short time (0.5–1 h) before regular cleaning. Briefly, an area of 5 cm × 5 cm was wiped four times with a cotton swab pre-moistened with virus protection solution (containing Hanks liquid base, gentamicin, fungal antibiotic, bovine serum albumin, cryoprotectant, biological buffer and amino acid, etc.) in accordance with the technical specifications (GB15982-2012). To detect the possible aerosol exposure, an automatic bioaerosol sampler (WB-15, DINGBLUE TECH, Beijing) based on the combination of cyclone separation and impact was adopted to continuously collect air samples for 40 min at a flow rate of 14 L min^{-1}. Five air samples were collected at about 30 cm from the mouth of one corresponding patient who did not wear a surgical mask in the ICU as illustrated in Fig. 1. In particular, in order to avoid cross-contamination that often occurred in nucleoid acid detection, all core components in the sampler, including the sampling head and pipelines were replaced for each air sampling. All samples were temporarily stored in the virus protection solution at 4 °C, and the SARS-CoV-2 RNA test was carried out within 2–3 h.

SARS-CoV-2 RNA detection by real-time fluorescence quantitative PCR

Total nucleic acid of each sample was extracted by using an automatic nucleic acid extraction Kit (Kingfisher Flex, Thermo, USA) and RNA kit prepackaged with magnetic beads (Fisher Scientific™ LabServ™) according to the manufacturer's instructions. Two target genes for SARS-CoV-2, highly conserved open reading frame *1a*/*b* and nucleoprotein (*N)* genes, were detected using a real-time fluorescent quantitative PCR detection kit (GXZZ 20203400064, Shengxiang Biotechnology). Meanwhile, human *RNaseP* gene was used as a reference gene. Briefly, the 50 μl reaction system contained 20 μl of RNA templates and 30 μl reaction mixture. Thermal cycling was performed at 50°C for 30 min for reverse transcription, followed by 95°C for 1 min and then 45 cycles of 95°C for 15 s and 60°C for 30 s on SLAN96PPCR instrument (Shengxiang Biotechnology). The criterion of cycle threshold (CT) value of RT-PCR was 40 (CT value <40 was positive). The relative content of SARS-CoV-2 was presented and compared by RT-qPCR CT value assuming that the collection volume and the experimental procedure of each sample were identical. This multicentre

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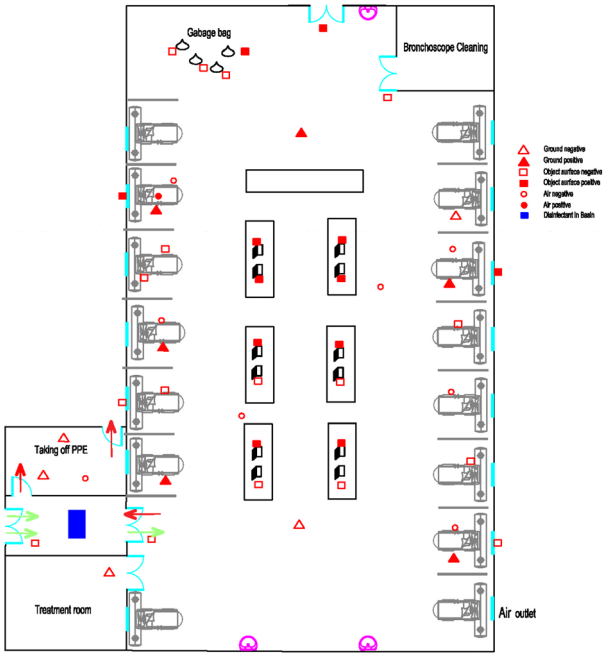

Fig. 1. Schematic diagram of the distribution of SARS-CoV-2 in ICU. Generally, the ICU is composed of cubicles, treatment room, PPE undressing room, bronchoscope cleaning room and sanitary waste disposal area. Each cubicle had one patient bed open to the central open area. Except for the samples from masks and gloves worn by medical staff, the position of the collected samples was marked with a red triangle (ground), square (object surfaces) or circle (air) symbol, and positive samples were marked with a solid.

study was approved by the institutional review board, and written informed consent was obtained.

Statistical analysis

Chi-square test was used to examine the differences of SARS-CoV-2 RNA positive rate in different areas or departments. A *p*-value of <0.05 was considered to be statistically significant. Statistical analysis was performed using R v3.6.3 (https://www.r-project.org/).

Results

More SARS-CoV-2 contamination in ICUs than in GWs

A total of 431 environmental samples were collected from three hospitals, including 157 from the contaminated areas and 274 from the clean areas (Table 2). A total of 28 samples were tested positive in the contaminated areas, with a positive rate of 17.8%, whereas no viral RNA was detected in the clean areas of different departments including the offices and the passage ways for medical staff ($p < 0.001$). This result verified the good effects of strict implementation of infection control measures in these hospitals, especially the removal of personal protection equipment (PPE), which in turn provided a safe and clean environment outside the contaminated areas. The positive rate of SARS-CoV-2 RNA in ICUs was much higher (22/57, 37.3%) than that in GWs (3/63, 4.8%), radiology department (2/14, 14.3%) and clinical laboratories (1/21, 4.8%) ($p < 0.05$). Moreover, the SARS-CoV-2 RNA positive rate (25/109, 22.9%) in the contaminated area of Hospital A was much higher than that of Hospital B (2/26, 7.7%) and Hospital C (1/17, 5.9%).

More SARS-CoV-2 contamination SARS-CoV-2 on object surfaces but less in the air

There were 391 samples obtained from the environmental surfaces and 40 from the air. The surfaces of the computer keyboard and mouse in the centre of the ICU contaminated areas had the highest virus-positive rate of 80.0% (8/10), which strongly hinted that the source of contamination came from the hand contact of medical staff (as illustrated in Fig. 1). Among the nine samples collected on the ICU floor, six samples were tested virus-positive. Intriguingly, five of six (83.3%) positive samples were obtained from nearby patients' beds (<1.5 m) (Fig. 1). In contrast, no virus-positive sample was found on the ground of the GWs (0/12) (as illustrated in Fig. 2) and other departments (0/7). Regarding PPE, one out of four samples from the front surface of the N95 mask worn in ICU was positive. Two of five samples from the gloves worn in ICU and two of 12 glove samples in GWs were positive.

Totally, 17 air samples were collected in the contaminated areas (nine in ICU, five in GWs, two in clinical laboratory and one in radiological examination room). Only one of the five air samples collected closely around the patient's mouth, which came from the ICU of Hospital B, was found to be positive. No viral RNA was detected in the air 2 m away from the patients, in the air of GWs (0/5, illustrated in Fig. 2) and clean areas (0/23). Two of the four surface samples from the ICU air outlet filter were tested positive, and none positive sample was found on the surface of GW air outlet (Figs 1 and 2).

Furthermore, in order to estimate the relative load of viruses in different positive samples, the RT-qPCR CT values of the viruses were compared. As demonstrated in Fig. 3, the viral load on the computer keyboard and mouse, the ground and the outer gloves worn by medical staff in the ICU remained high, while the viral load in the air, on the air outlet and bed rails in the CT examination room was comparably low, but no significant difference was observed.

Enhanced infection control intervention effectively reduced viral contamination

According to the above findings, infection control measures were immediately strengthened in the areas where

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Fig. 2. Schematic diagram of the distribution of SARS-CoV-2 in general wards (GWs). A GW usually has two patient beds, a buffer room and a toilet and two corridors located on each side of the ward with one for patients (only in Hospital A) and the other for medical staff. Except for the collected samples from the mask and gloves worn by medical staff, the position of the collected samples was marked with a red triangle (ground), square (object surfaces) or circle (air) symbol, and positive samples were marked with a solid.

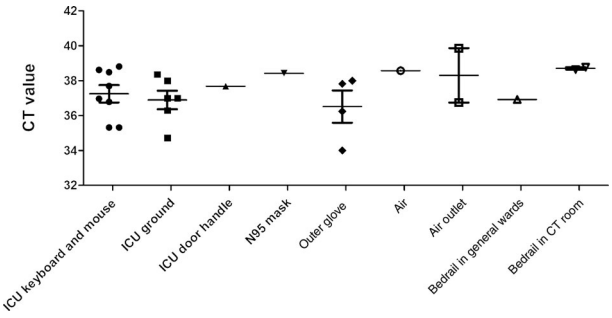

Fig. 3. Comparison of RT-qPCR CT values of SARS-CoV-2 RNA from positive environmental samples in three hospitals.

viral RNAs were detected. Major intervention measures included: (i) enhancing hand hygiene compliance, in which the frequency and standardization of medical staff hand hygiene were strengthened according to the WHO guidelines and strictly supervised by video surveillance; (ii) increasing the frequency of disinfection on the surfaces of objects, frequently touched by medical staff from two times to three times per day using disinfectant containing 500 mg L^{-1} effective chlorine or 75% alcohol, and disinfection frequency on the ground of the wards to three times per day using disinfectant containing 1000 mg L^{-1} effective chlorine; (iii) installation of alcohol-based hand rub next each door handle to support high compliance of hand hygiene; and (iv) dipping the sole of shoes in a basin filled with disinfectant before walking out of the wards to reduce ground contamination caused by the movements of the medical staff. After infection control intervention, the existence of SARS-CoV-2 RNA was re-evaluated by sampling. As demonstrated in Table S1, in the contaminated areas of one ICU in Hospital A, the positive rate of viral RNA on object surfaces was significantly reduced to 2.2% ($p < 0.01$). Only one of the two samples from the surface of air outlet filter was positive. No alive virus was found after infection control. These data indicated that the decontamination measures were effective, especially on the ICU air outlets that were easily contaminated. More importantly, none of the medical staff in the three hospitals was infected throughout the fight against the COVID-19 epidemic in Wuhan, which fully proved the effectiveness of environmental infection control measures in the hospitals.

Discussion

This multicentre study, for the first time, provided a general description of SARS-CoV-2 environmental contamination in three hospitals designed for COVID-19 patients in Wuhan, China. The overall positive rate of SARS-CoV-2 RNA in the environmental samples of these three hospitals was 6.5% (28/431). The ICU was at the top position with the highest virus-positive rate, especially on the object surfaces that were frequently touched with gloves worn by medical staff. This could be related to higher frequency of invasive respiratory droplet-producing operations, such as endotracheal intubation, extubation, bronchoscopy and sputum aspiration, for ICU patients, but not for non-severely ill in GWs. These procedures contaminated the environment surrounding patients, posing a higher risk of virus contamination to medical staff who made frequent hand contact with patients during these therapeutic operations and nursing processes. SARS-CoV-2 contamination was spread due to poor hand hygiene compliance and the movements of medical staff. The highest positivity of viral RNA was found on the surfaces of computer keyboard and mouse in the central nurse station and also the surfaces of gloves worn by medical staff. These exposed areas and objects were considered to be critical transmission media for SARS-CoV-2 (GONHC, 2020; WHO, 2020b).

Viral RNA was also detected on the ground of ICU (6/9) with high frequency. In the present study, five of six positive ground samples were collected near the patients'

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bed (around 1.5 m), implying short-distance dissemination of virus-laden particles due to gravity. No viral contamination was observed on the treatment room ground far from the patient's bed and on the floor of the dressing room where PPE was taken off. This finding was different from an early report that showed a heavy overall ICU ground contamination (70%, 7/10) (Guo *et al*., 2020). Interestingly, no positive sample was found near the patients' bed in the GWs from the three hospitals. This indicated that most of the ground contamination might be caused by certain procedures that produced respiratory droplets, which were more likely to be performed in the ICU rather than in the GW. Furthermore, routine disinfection of the ground and dipping the shoe sole in a basin containing disinfectant before walking out of the wards could effectively reduce ground contamination caused by the movements of medical staff. The extremely high viral contamination reported in this research might be rare seldom under normal infection control measures.

Compared with the relatively high level of surface contamination, SARS-CoV-2 was less detected in the air. Only one air sample collected at about 30 cm from the patient's mouth showed positive for SARS-CoV-2 RNA in the ICU of Hospital B, indicating that the virus indeed existed in the air of the patient room. However, the positive rate was rather low in the contaminated areas (1/17). Moreover, no positive air sample was detected in either the GWs, despite the presence of the virus on the bed rails and gloves worn by the medical staff, or in the ICU of Hospital C without a ventilation system. Supported by all these data, we could speculate that SARS-CoV-2 might not spread through aerosols, but was more likely to fall on the core of droplets near the patient bed. These small virus-laden droplets could drift with the airflow and deposit on the air outlet filter. This phenomenon was verified by the positive existence of viral RNA on the exhaust screen of the ward. Compared with droplet transmission, aerosols could spread farther due to their smaller size and less mass, leading to a higher risk of virus transmission. Our data-based observations did not support the spreading of SARS-CoV-2 through aerosols, providing a scientific basis for hospital infection control of SARS-CoV-2. This result was consistent with many previous studies (Ong *et al*., 2020; Yanfang Jiang *et al*., 2020; Cheng *et al*., 2020a). In a recent JAMA article, it was reported that although some patients had a certain amount of virus shedding, with 13 of 15 (87%) room sites (including air outlet fans) and three of five (60%) toilet sites (toilet bowl, sink and door handle) returning to positive results, all samples in the surrounding air were negative (Ong *et al*., 2020). The team at the Queen Mary Hospital in Hong Kong did not find the virus even in the close range (10 cm from the patient's chin) of positive patients (Cheng *et al*., 2020a). A team of Jilin University (Yanfang Jiang *et al*., 2020) also reported only one positive case in 19 air samples of the isolation ward for COVID-19 patients. One exceptional study showed an unusually high positive rate in the air of the ICU equipped with a high-efficient negative-pressure air ventilation system, designed for COVID-19 patients (Guo *et al*., 2020). Due to the discrepancy in results, many influencing factors, such as sampling time and location, operation efficiency of the ventilation system during sampling, sampling efficiency of air sampler, and most importantly, whether the sampler was prone to cross-contamination during nucleic acid sampling, should be investigated and clarified further.

Regarding the low virus-positive rate in GWs, the GW patients had mild or moderate symptoms such as cough, fever and shortness of breath, however, there were fewer operations that generated aerosols or splashes compared to ICU. The good compliance of patients wearing masks and the less aerosol-generating operations might be a reason for less viral shedding from the patients. Certainly, further studies were warranted to clarify this issue.

Another interesting finding was that the contaminated area of Hospital A had much higher positive rate (25/109, 22.9%) than that of Hospital B (2/26, 7.7%) and Hospital C (1/17, 5.9%). This discrepancy might be due to the following facts. First, more critically ill patients were admitted to Hospital A when compared to other two hospitals. Second, the ICU of Hospital A had three times the number of ventilators in Hospitals B and C. The frequency of invasive procedures that were prone to respiratory splashes including endotracheal intubation, extubation and bronchoscopy in Hospital A (approximately once every 2 days) was significantly higher than in Hospitals B and C (data not shown).

The effectiveness of these bundled infection control interventions to remove the virus contamination provided us with great confidence in preventing the transmission of this disease and also laid an important foundation to ensure the safety of healthcare workers. However, the re-detection of viral RNA on the exhaust filter indicated a rather quick and frequent contamination through virus-laden droplets released from patients, so continuous infection control interventions were essential.

We have noticed that some new variants of SARS-CoV-2 have emerged worldwide. The occurrence of new variants might partly modify the contamination routes of COVID-19, which should be further investigated. The data here in present study referred only to the 'early' strain.

Finally, this study had several limitations. First, no virus culture was utilized to confirm the viral activity. Considering that SARS-CoV-2 was an RNA virus, it was extremely inactive and not easily detectable *in vitro*, so the positivity of nucleic acid in environmental samples was still a

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strong indicator. Several experimental studies have cultured live viruses from aerosols (Chin *et al*., 2020; van Doremalen *et al*., 2020; Zhu *et al*., 2020) and surfaces (Fears *et al*., 2020) hours after inoculation, while the real-world studies that detected viral RNA in the environment reported very low levels, and few has isolated viable virus (Lednicky *et al*., 2020; Meyerowitz *et al*., 2020; Santarpia *et al*., 2020). The COVID-19 virus in the environmental samples may not be further cultured. However its presence provided sufficient evidence that the sample location had ever been contaminated by the virus, and there was still the risk of infection and transmission according to previous studies. Second, certain work restrictions during the pandemic led to smaller sample sizes in some areas, but most of the high-frequency contact points on environmental surfaces have been covered already. Third, the amount of air samples collected only accounted for a small part of the total air volume. The air exchange in the room, especially the directional air flow in the negative pressure ward, would also reduce and dilute the presence of SARS-CoV-2 in the air.

Conclusion

SARS-CoV-2 distribution was more likely to be seen on the environmental surfaces rather than in the air of patients' wards. ICUs had higher surface viral contamination than GWs owing to the care for more critically ill patients and the higher frequency of invasive respiratory droplet-producing operations. We supposed that SARS-CoV-2 might not spread through aerosols, but was more likely to fall on the core of droplets close to the patient bed. Infection control measures such as surface disinfection and hand hygiene of healthcare workers were quite effective in removing SARS-CoV-2 from the environment.

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Authors' Contributions

L. Han and C. J. Wang conceived the project; S. H. Fan, R. Z. Jia, Q. Tan, Y. Chen, H. F. Li, L. F. Zhan, Y. H. Ke, L. L. Jia, X. Liu, D. Li and L. Zhang collected the samples; W. Liu and C. J. Yang conducted the RNA analysis; D. C. Li and F. Y. Chen analysed data and wrote the manuscript; L. Han evaluated all results. All authors read and approved the final manuscript.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Table S1. Detection of SARS-CoV-2 RNA before and after infection control intervention in an ICU from Hospital A.

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