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Contamination dynamics of personal protective equipment (PPE) by SARS-CoV-2 RNA in a makeshift hospital with COVID-19 positive occupants

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SUMMARY

Background: Personal protective equipment (PPE) helps protect healthcare workers (HCWs) from infection and prevents cross-contamination. Knowledge of the contamination dynamics of PPE during the management of COVID-19 patients in a makeshift hospital is limited.

Aim: To describe the rate of SARS-CoV-2 contamination in PPE and to assess the change of contamination at different time points.

Methods: HCWs were followed up for up to 4 hours with hourly collection of swab samples from PPE surfaces in a makeshift COVID-19 hospital setting. Swabs were tested using quantitative reverse transcription polymerase chain reaction (RT-qPCR) for SARS-CoV-2 RNA.

Results: SARS-CoV-2 was detected on 50.9% of the 1620 swabbed samples from 9 different sites of full-body PPE worn by HCWs. The proportion of sites contaminated with SARS-CoV-2 RNA varied from 10.6% to 95.6%. Viral RNA was most frequently detected from the sole of the outer foot cover (95.6%) and least frequently on the face shield (10.6%). The median Ct values among positive samples were 34.20 (IQR, 32.61—35.22) and 34.05 (IQR, 32.20—35.39) for ORF1ab and N genes, respectively. The highest rate of contamination with SARS-CoV-2 RNA for the PPE swab samples was found after 3 hours of use. The positive rate of outer surface of HEPA filters from air supply device was 82.1% during the full capacity period of the makeshift hospital.

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Conclusion: A higher rate of contamination was identified at 3 hours after the entrance to the COVID-19 patient care area. Virus-containing aerosols were trapped in the HEPA filter of air supply equipment, representing a potential protective factor against infection to HCWs.

Introduction

The COVID-19 epidemic was declared by the WHO as a public health emergency of international concern on January 30, 2020 [1]. On 26 November 2021 the WHO declared that the world was facing a new variant of concern: Omicron, SARS-CoV-2 variant B.1.1.529 [2,3]. Omicron's ongoing mutations would go on to change the trajectory of the COVID-19 pandemic especially in China [4,5]. A combination of increased transmissibility and immune escape likely facilitated the massive and rapid spread of Omicron subvariants [6,7]. COVID-19 is often more severe in people who have health conditions such as lung or heart disease, diabetes or conditions that affect their immune system. The elderly are especially at increased risk of morbidity and mortality from severe COVID-19 [8—10].

On August 1 2022, a cluster of COVID-19 cases caused by the Omicron subvariant of SARS-CoV-2 (BA.5.1.3) was detected in Sanya, Hainan Province, China, resulting in the territory's third wave of COVID-19 cases. By August 11 2022, the city had reported a total of 2,161 confirmed cases and 2,071 asymptomatic cases. In order to control the epidemic as soon as possible and to achieve the goal of high-quality dynamic zero COVID-19 cases in the community as well as alleviating the shortage of medical treatment resources, the International Expo Center Project (Sanya, China), that was still under construction, was converted into Sanya Second Makeshift COVID-19 Hospital. This makeshift hospital was divided into four sections (section A, B, C and D) and only COVID-19 patients with asymptomatic or mild symptoms were placed in all four sections.

In August 2021, Sanya's climate was extremely hot due to the intense sunshine. This hot climate posed a significant threat to the well-being and comfort of healthcare workers (HCWs) who wore full-body personal protective equipment (PPE). The adverse effects of PPE were associated with longer shift duration and included heat, thirst, pressure areas, headaches, the inability to use the bathroom, and extreme exhaustion, which can be exacerbated by the high temperature and humid environment [11]. To effectively control and prevent the heat stress caused by PPE worn in hot and humid environments, we introduced a medical positive pressure protective coverall (MPPPC) for HCWs who came in contact with COVID-19 cases. The MPPPC was equipped with air supply device to continuously provide clean air. The internal temperature of MPPPC could be controlled at 26°C—29°C, greatly improving the comfort of HCWs. The MPPPC provided full-coverage protection from the head to the ankle of the wearer.

Previous research has shown that any surface of PPE worn can become contaminated by SARS-CoV-2 during use and be a potential source of exposure to SARS-CoV-2 [12—14]. To protect HCWs from the risk of occupational exposure to SARS-CoV-2 and prevent cross contamination caused by doffing, it is important to track the dynamic contamination of PPE worn and to optimise doffing procedures. To explore the related mechanism of PPE contamination when selecting MPPPC, we systematically performed MPPPC sampling to evaluate SARS-CoV-2 contamination at various time intervals upon entering the patient care area and prior to PPE doffing. The findings of this investigation will provide a useful reference and shared experience for the future response to public health and safety events such as emerging respiratory infectious diseases.

Methods

Description of the makeshift COVID-19 hospital

The second makeshift COVID-19 hospital was delivered in August 11, 2022. It was a detached building covering about 21,200 square meters and 21.41 meters high, and consisted of solid masonry partition walls and glass doors, with natural ventilation by open glass doors and ventilating fans. It had a capacity of 2,000 beds. In order to manage the patients conveniently, the patient care area was divided into four sections (sections A, B, C and D). Each section included several units composed of 30—40 beds and was managed by 8—16 HCWs depending on the number of bed units for 4 hour shifts. This study was performed at the Sanya second makeshift COVID-19 hospital, China, from 16th August to 6th October 2022. From 11th August to 10th September, 2022, following the new surge of COVID-19 infections and the shortage of medical facilities, the makeshift hospital admitted over 2000 patients at full capacity during this period.

Details of medical positive pressure protective coverall (MPPPC)

HCWs caring for patients with confirmed COVID-19 routinely wore full-body personal protective equipment (PPE), including the MPPPC (Medical Positive Pressure Protective Coverall, TUOREN, Henan Tuoren Medical Device Co. Ltd.). The MPPPC consists of protective clothing, breathing tube, and air supply device (Figure 1). The protective clothing is composed of an exhalation valve, window (face shield), zipper, clothing body and air supply connector. The air supply device includes High Efficiency Particle Air (HEPA) filter film that has greater than 99.99% filtration performance on oil and non-oil particles. The MPPPC can be used for long hours in highly infective healthcare environments. It can help HCWs to avoid heat-related illness in a very hot environment with more ease than other PPE used.

Donning of PPE protocol

The makeshift hospital provided surgical scrubs and special shoes to HCWs before donning PPE. Personal clothing was not

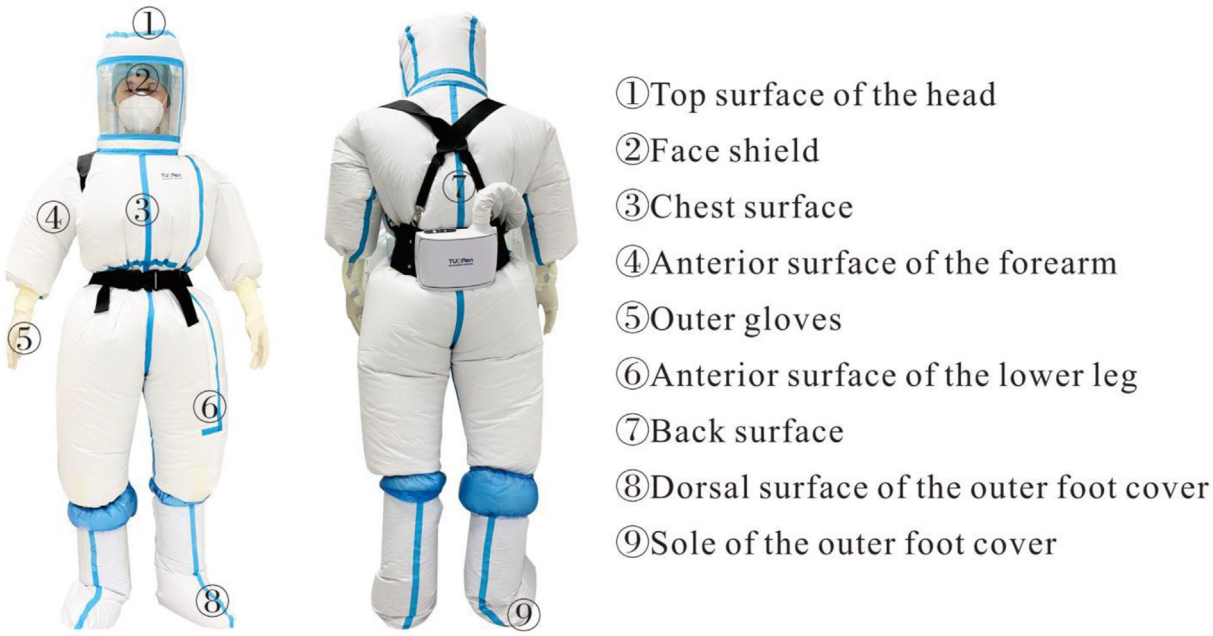

Figure 1. Schematic representation of medical positive pressure protective coverall and sampled sites. The medical positive pressure protective coverall is composed of cover body, breathing tube and air supply device. The body is composed of a cover body, a window, an air supply connector, a filter membrane, a plastic spring buckle and a tightening belt. The air supply device is composed of the lower shell of the air supply device, fan control board, battery, inner cover plate gasket, inner cover plate, filter membrane gasket, lower cover of the filter membrane, filter membrane, upper cover of the filter membrane, upper shell of the air supply device, fan gasket, fan, voltage-stabilized plate, alarm circuit board, air outlet, power switch, speed button and charging interface. Air supply device Continuous working time: greater than or equal to 8 hours. Air supply volume: the air supply volume range is 120-190L / min, the wind speed. Can be adjusted, the actual air supply volume should not be less than 120L / min.

recommended. HCWs were advised to wear surgical scrubs, special shoes, disposable medical cap, fit-tested particulate respirator (medical N95 mask), full-body MPPPC (including full face shield, and special HEPA air supply equipment), gloves, and shoe covers. All HCWs donned full-body PPE according to a protocol following these steps: (1) hand hygiene; (2) disposable medical cap; (3) medical N95 respirator; (4) inner gloves; (5) inner ankle-length shoe covers; (6) positive pressure protective clothing; (7) outer gloves; (8) outer long length shoe covers.

A dedicated room for donning was set up outside the makeshift hospital. Trained attendants were stationed in the donning room to assist HCWs. The process of donning the full-body PPE and getting ready to go into patient care area of makeshift hospital took about 20 minutes.

PPE sampling procedure

The PPE samples were collected by 5 trained personnel using a standardised technique with pre-moistened sterile swabs (MS-OF3601, Shenzhen MandeLab Co., Ltd.). Sampling of PPE was systematically performed from the top of the head to the foot dorsum and sole to evaluate SARS-CoV-2 contamination at various time intervals from entering the patient care area and prior to PPE doffing.

A total of 320 HCWs were invited to participate in this study and all of them consented to the sampling. Their activities included checking vital signs, administering oral medication, taking temperature, checking blood pressure, ultrasound examinations and electrocardiographic examination. They did not perform aerosol-generating procedures. Time points of 1 hour, 2 hours, 3 hours and 4 hours were used for sampling the PPE.

In the contaminated areas, 9 PPE samples from PPE surfaces were taken from 12 HCWs every day. Samples were collected over 15 days. The sampled PPE sites comprised dorsal surface of the outer foot cover, sole of the outer foot cover, face shield, top surface of the head, anterior surface of the forearm, back surface, anterior surface of the lower leg, chest surface and outer gloves (Figure 1).

In the doffing rooms, swabs of the accessories of the MPPPC (including HEPA filters, breathing tube, exhalation valve), the scrub shirt and pants, skin (including neck, hand and arm), sole and dorsal surface of foot, sole of the inner foot cover were taken from 4 HCWs every day.

Before swabbing, the swab tips were moistened with the transport medium, and then the PPE surfaces were thoroughly swabbed in a meandering manner for at least 15s. The swabbed areas were approximately 25cm^2 or adjusted according to shape. Finally, the swabs were placed in the transport container (CIDA, Guangzhou, Biotechnology Co., Ltd.). PCR testing of all the samples was performed at the laboratory of makeshift hospital.

Laboratory procedures for detection of SARS-CoV-2 RNA

Swab samples were vortexed vigorously for 20 seconds before aliquoting. Ribonucleic acid extractions were performed using

DaAn Gene nucleic acid extraction kit (DaAn Gene Co, Ltd., of Sun Yat-sen University, China) according to manufacturer's instructions. Quantitative reverse transcription polymerase chain reaction (RT-qPCR) was performed using DaAn Gene 2019-nCoV kit (DaAn Gene Co, Ltd., of Sun Yat-sen University, China). Two separate gene targets, the open reading frame 1a/1b (ORF1ab) and the nucleocapsid protein (N) genes were used to detect SARS-CoV-2 RNA. The PCR tubes were immediately transferred to an ABI 7500 RT-qPCR machine (Applied Biosystems Inc., Foster, CA, United States). The cycling conditions were as per the manufacturer's protocol. A sample was defined as positive for viral RNA if ORF1ab and/or N gene RT-qPCR assays gave a Ct value of ≤ 40. The sample was reported negative if both Ct values were > 40.

Statistical analysis

The PCR results were recorded onto a Microsoft Excel Spreadsheet® (Microsoft Corporation). Continuous variables were expressed as median with interquartile range (IQR), and were analysed by Kruskal-Wallis test, Mann-Whitney U test and one-way repeated measures ANOVA test. Descriptive statistics were used to represent data as numbers and percentages. The differences in the positive rates were compared by Pearson's Chi-Squared test. P value <0.05 was considered to be statistically significant. The above-mentioned analyses were performed using SPSS® 23.0 software (IBM, SPSS Inc., Chicago, USA).

Ethics statement

The PPE sampling was approved by the Ethics Committee of Hainan Hospital of Chinese PLA General Hospital with oral informed consent having been obtained.

Results

PPE contamination monitoring and swabbed sampling analysis

A total of 2036 swabbed samples were collected, including 1620 from PPE worn during HCWs working period. Overall, 824 (50.9%) samples yielded SARS-CoV-2 RNA (Table I), there was a significant difference between the rate of SARS-CoV-2 RNA positive samples observed across the PPE sites (Pearson Chi-Square 407.193, $P<0.001$). All sampled sites tested positive. Among them, SARS-CoV-2 RNA was most frequently detected from the sole of the outer foot cover (95.6%) and least frequently on the face shield (10.6%).

In total, the median Ct values among positive samples were 34.20 (IQR, 32.61—35.22) and 34.05 (IQR, 32.20—35.39) for ORF1ab and N genes, respectively (Table II). The Ct values of two genes were not significantly different ($P=0.344$). There were significant differences between the Ct values among 9 sites ($P < 0.001$). Except for top surface of the head and anterior surface of the forearm, the median Ct values of N gene from other samples were <35. All ORF1ab median Ct values from samples from the top surface of the head, face shield, and chest surface were >35, while other samples were <35 (Figure 2). The median Ct values of N gene for samples from sole of the outer foot cover were 31.10 (IQR, 29.54—32.29), and indicated a higher viral load than other PPE samples (Figure 2), followed by dorsal surface of the outer foot cover with median Ct values 32.69 (IQR, 31.75—33.76). The samples from the sole of the outer foot and cover had the lowest Ct values of ORF1ab with the median 32.28 (IQR, 30.36—33.59), followed by the anterior surface of the lower leg with the median Ct values 33.40 (IQR, 33.11—34.17).

The SARS-CoV-2 RNA positive rate of outer HEPA filters was 82.1% (23/28) during the period when the hospital was at full capacity. Samples from the breathing tube, exhaust valve, outer surface of medical N95 respirator, inner HEPA filters, scrub shirt and pants, skin (including neck, hand and arm) were all negative.

Contamination dynamics of PPE samples from different time points

The total SARS-CoV-2 RNA positive rate of PPE samples after 1 hour, 2 hours, 3 hours, 4 hours of use was 41.7% (169/405), 45.4% (184/405), 62% (251/405) and 54.3% (220/405), respectively. Overall, total positive rate of PPE surfaces pool contamination was the highest after 3 hours of use, with a reduction after 4 hours ($P=0.033$) (Figure 3).

There was no significant difference in the proportion of SARS-CoV-2 RNA positive samples obtained from face shield, chest surface, anterior surface of the forearm, sole of the outer foot cover and anterior surface of the lower leg from different 4 hour shifts.

An increased proportion of SARS-CoV-2 RNA positive swabs was identified from the dorsal surface of the outer foot cover and the back in the contaminated areas at various time intervals ($P<0.001$). There was an increasing trend in the proportion of positive samples for SARS-CoV-2 RNA obtained from the top surface of the head within 3 hours, while no clear difference of positive rate between 3 hours and 4 hours ($P=0.909$). Outer gloves showed the highest rate of contamination with SARS-CoV-2 RNA after 3 hours.

Discussion

SARS-CoV-2 Omicron variant is of major public health concern owning to its high infectivity and immune evasion. BA.5.1.3, a new mutation of Omicron subvariant BA.5 [15], was detected among the Sanya city's COVID-19 infections since August 1 2022. The city adopted a dynamic zero-COVID-19 strategy to respond to SARS-CoV-2 Omicron variant which had a higher transmissibility. Makeshift hospitals can respond effectively to the COVID-19 pandemic by performing essential functions such as triage, isolation, sheltering, and rapid transfer [16]. They also have some limitations, such as difficulties with heating, ventilation, and air conditioning systems [17,18]. The makeshift hospital could have yielded higher rates of positive SARS-CoV-2 RNA from surface swabs of PPE worn in the hospital because of less stringent cleaning and disinfection regimens.

Containment of COVID-19 remains a great challenge in both community and healthcare facilities, especially in makeshift COVID-19 hospitals. HCWs are key in controlling the pandemic, and how to protect HCWs using PPE has been controversial [19—21]. It can be reasonably assumed that the effective control of COVID-19 spread goes together with the protection of HCWs. It is unclear which type of PPE protects best, what is

Table I
The rate of SARS-CoV-2 contamination in PPE sites at different time points

Type of sample	No. of RNA positive samples/Total no. of collected samples (%)	Time points in the patient care areas					
		1 hour	2 hours	3 hours	4 hours	X^2	*P* value
Total	824/1620 (50.9)	169/405 (41.7)	184/405 (45.4)	251/405 (62.0)	220/405 (54.3)	40.249	<0.001
1. Top surface of the head	85/180 (47.2)	7/45 (15.6)	12/45 (26.7)	35/45 (77.8)	31/45 (68.9)	51.069	<0.001
2. Face shield	19/180 (10.6)	3/45 (6.7)	4/45 (8.9)	7/45 (15.6)	5/45 (11.1)	1.98	0.628
3. Chest surface	58/180 (32.2)	10/45 (22.2)	13/45 (28.9)	21/45 (46.7)	14/45 (31.1)	6.614	0.094
4. Anterior surface of the forearm	58/180 (32.2)	16/45 (35.6)	10/45 (22.2)	20/45 (44.4)	12/45 (26.7)	6.003	0.122
5. Outer gloves	85/180 (47.2)	16/45 (35.6)	21/45 (46.7)	32/45 (71.1)	16/45 (35.6)	15.225	0.002
6. Anterior surface of the lower leg	90/180 (50)	25/45 (55.6)	19/45 (42.2)	26/45 (57.8)	20/45 (44.4)	3.289	0.349
7. Back surface	101/180 (56.1)	15/45 (33.3)	21/45 (46.7)	29/45 (64.4)	36/45 (80)	22.807	<0.001
8. Dorsal surface of the outer foot cover	156/180 (86.7)	32/45 (71.1)	39/45 (86.7)	40/45 (88.9)	45/45 (100)	16.538	0.001
9. Sole of the outer foot cover	172/180 (95.6)	45/45 (100)	45/45 (100)	41/45 (91.1)	41/45 (91.1)	7.486	0.028

the best way to put PPE on (donning) or to remove PPE (doffing), and how to train HCWs to use the PPE as instructed. The choice of PPE is based on the risk of exposure and the possible modes transmission [22]. PPE does not remove the hazards. It protects the individuals and it is only effective if correct procedures are followed to put it on and take it off (donning and doffing) [23]. Given the hot and humid climate of Sanya and the field setting of a makeshift COVID-19 hospital, we recommended the MPPPC for all HCWs who came into close contact with patients infected with COVID-19.

The use of a full-body MPPPC with a powered, purifying-air supply device, may protect against the risk of contamination better than a combination of medical N95 mask and protective clothing, but the MPPPC is more difficult to don and doff. In most cases, donning and doffing the MPPPC requires up to 22 separate steps and the help of trained attendants to ensure that it is done correctly. Many HCWs have never worked in a full-body MPPPC, and there are no data available about the rates of MPPPC contamination by SARS-CoV-2 during COVID-19 patient care. The present study of a real-world setting reinforced the importance of adherence to contact precautions and to appropriate PPE donning and doffing procedures for preventing HCWs self-contamination [23]. Some errors in PPE doffing can result in HCWs contamination, which creates the potential risk of cross-transmission of SARS-CoV-2 to other HCWs [24]. Therefore, the need for proper PPE and training for HCWs should be highlighted. Providing HCWs with formal and enhanced training may improve the donning and doffing of PPE in the future [25,26].

Table II
The median Ct values of positive PPE sites based on RT-qPCR

Type of sample	N gene		ORF1ab gene	
	Median	IQR	Median	IQR
Total	34.05	32.20—35.39	34.20	32.61—35.22
1.Top surface of the head	35.25	34.11—36.04	35.46	34.19—36.74
2.Face shield	34.78	34.26—36.35	35.20	34.85—35.67
3.Chest surface	34.84	34.16—35.49	35.13	34.51—35.81
4.Anterior surface of the forearm	35.84	33.39—36.17	34.96	33.40—38.07
5.Outer gloves	34.77	33.86—35.16	34.70	34.09—34.78
6.Anterior surface of the lower leg	34.70	33.44—36.35	33.40	33.11—34.17
7.Back surface	34.78	32.28—36.17	33.76	32.17—35.74
8.Dorsal surface of the outer foot cover	32.69	31.75—33.76	34.21	32.55—35.00
9.Sole of the outer foot cover	31.10	29.54—32.29	32.28	30.36—33.59

HCWs experience close contact with the immediate surroundings of COVID-19 patients as well as the virus-bearing aerosols produced by the patient's respiratory movement. The activities of HCWs ranged from general contact such as administering medication, reading the monitors for temperature etc., distributing daily necessities or cleaning, to closer physical contact such as physical examination, electrocardiographic examination, bedside ultrasonography, or collection of oropharyngeal swab samples. In theory, the contamination rate of MPPPC would be expected to increase with the duration of the working hours in the makeshift hospital. Real-time monitoring of the contamination dynamics of MPPPC by SARS-CoV-2 RNA with the timing of work shift could support and provide evidence for the development and evaluation of strategies for infection prevention and control in the workplace.

Our study did aim to evaluate the extent and severity of the SARS-CoV-2 contamination on MPPPC over time. The highest rate of contamination with SARS-CoV-2 RNA for swabbed PPE samples pool was found after 3 hours' of use. We suggest that the decline in total positive rate of swabs after 4 hours compared to 3 hours was related to the decrease of the positive rate of outer gloves after 4 hours. The hand hygiene compliance of HCWs improved before leaving the patient care

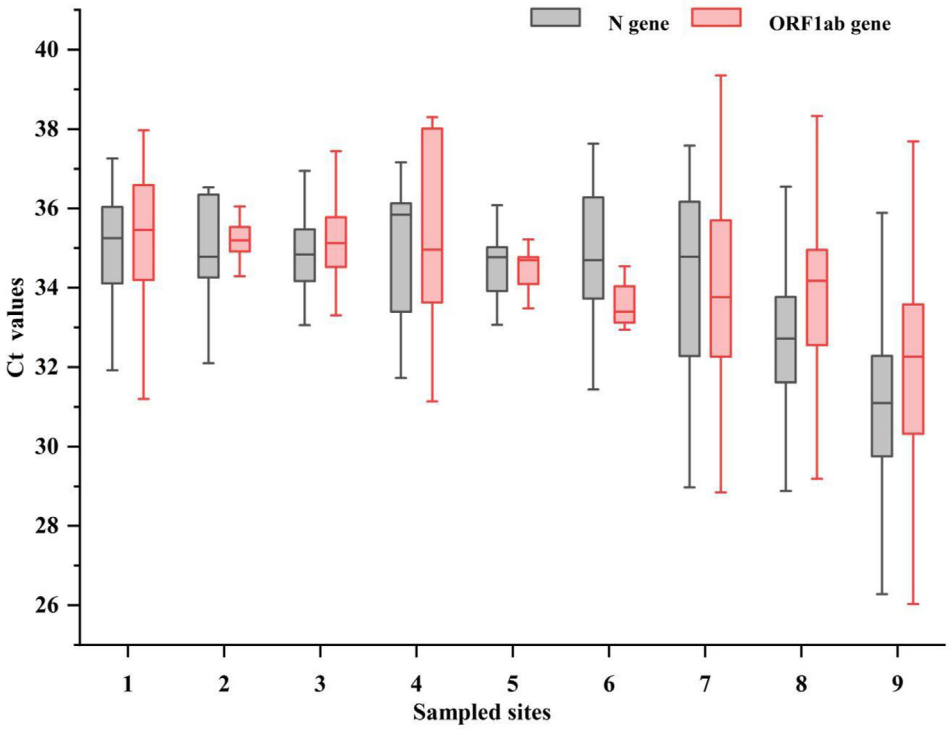

Figure 2. The trajectory of Ct values of ORF1ab and N genes for positive PPE samples. Numbering of sampled sites corresponds to the numbering in Table I in the present article. The sampled PPE sites comprised: 1.top surface of the head; 2. face shield; 3. chest surface; 4.anterior surface of the forearm; 5. outer gloves; 6. anterior surface of the lower leg; 7. back surface; 8. dorsal surface of the outer foot cover; and sole of the outer foot cover (Fig. 1). Except for top surface of the head and anterior surface of the forearm, the median Ct values of N gene from other samples were < 35. All ORF1ab median Ct values of the top surface of the head, face shield, and chest surface were > 35, while other samples were < 35.

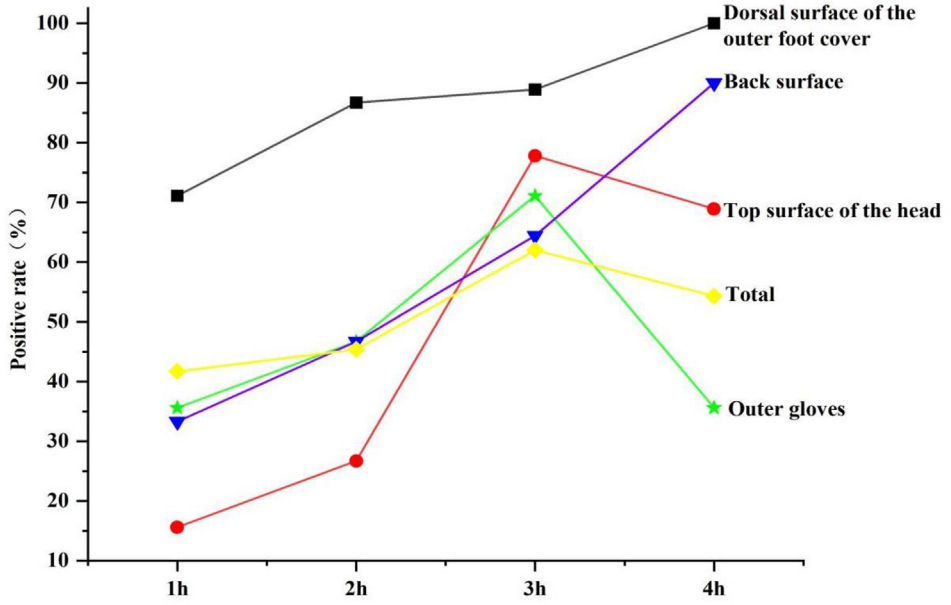

Figure 3. The trajectory of positive rate of PPE samples over the time points in the patient care areas. The total curve indicates the rate of contamination with SARS-CoV-2 RNA for swabbed PPE samples pool at different time points with an increasing contamination rate. In addition, the positive rate of 4 sampled PPE sites (dorsal surface of the outer foot cover, back surface, top surface of the head and outer gloves) which have significantly difference at different shifts are showed in the figure.

areas, which resulted a decline in the contamination rate of the outer gloves. The sole of the outer foot cover (95.6%), dorsal surface of the outer foot cover (86.7%), and back surface (56.1%) showed the highest frequency of SARS-CoV-2 RNA contamination. The findings of present study are not consistent with the results of some previous studies which indicated that the PPE of HCWs was not contaminated extensively during the management of patients with COVID-19 [27—33].

There is a possibility that the contamination of PPE would be more frequent when managing patients with COVID-19 in general wards without negative pressure [34]. The airflow and ventilation of indoor space can affect the deposition of viral particles onto environmental surfaces, thus it is expected that environmental contamination would be higher in neutral pressure space [35]. Moreover, perhaps it could also be explained because the HCWs in some studies spent a shorter time in the patient's room than in the present study [36]. The HCWs in this study stayed in patient care areas for a relatively long period (4 hours) and in addition, were in closer contact with patients and thus there may be a higher chance of PPE contamination. It may also be related to the sampling method and the sample size. The sampling method has not been standardised and its sensitivity and specificity have not been determined. The sample size was relatively small in recent reported studies [27—33].

The contamination risk of full-body PPE in the makeshift COVID-19 hospital setting is further influenced by existing infection prevention and control practices and engineering interventions, such as adequate ventilation and negative pressure space [37]. This study found that HEPA filters contaminated by SARS-CoV-2 was more common. The positive rate of outer surface of HEPA filters from air supply device was 82.1% during the full capacity period of the makeshift hospital. The contaminated surfaces of HEPA filters could be used as a marker to identify other PPE items at higher risk of contamination and could support the long-range aerosol transmission (traditionally known as airborne transmission) of SARS-CoV-2 under certain conditions such as prolonged exposure in enclosed spaces with inadequate ventilation. We agree that the presence of SARS-CoV-2 on the surfaces of full-body PPE items could be through aerosol particles deposited in the air by droplets, in addition to contamination via direct contact from touching. This study showed that SARS-CoV-2 RNA was most frequently detected from the sole of the outer foot cover. The contamination of soles could be due to respiratory droplets that fall to the floor and which are spread to other areas of the makeshift COVID-19 hospital through attaching to HCW's shoes. As the HCWs did not habitually touched their heads because of the height of full-body PPE, the top of the head may have been contaminated with airborne particles. As contamination of PPE by SARS-CoV-2 is complex and dependent on several factors, the awareness of contamination modes is important to effectively mitigate the potential risk of exposure for HCWs infection. In present study, Ct values of all samples were >30, suggesting that the overall risk of infection is not high. However, it is of note that the detection of viral RNA from PPE surfaces does not necessarily represent infectivity.

To our knowledge, the present study is the first to characterise the SARS-CoV-2 contamination of the full-body MPPPC in a makeshift COVID-19 hospital setting. This study finds a high rate of contamination of MPPPC with SARS-CoV-2 and we recommend the following measures to reduce the risk of SARS-CoV-2 contamination or infection for HCWs working in the COVID-19 patient care area. These measures include: (1) the help of a trained attendant during donning of PPE; (2) double layers of gloves and double layers of foot covers when donning of PPE; (3) face-to-face spoken instruction during doffing of PPE; (4) extra sanitation of full-body PPE surfaces before doffing with 3% hydrogen peroxide; (5) disinfection of gloves during each step of doffing with alcohol-based hand rub; (6) one-step removal of outer layer gloves, foot covers, and protective clothing; (7) proper disposal of PPE worn to prevent and control the transmission of SARS-CoV-2. All PPE worn within the makeshift COVID-19 hospital was to be properly discarded into biohazard containers.

Our study was limited in that correlation between viral load of consecutive COVID-19 patients hospitalised and full-body PPE contamination was unclear, due to the limited understanding of dynamics of SARS-CoV-2 shedding. SARS-CoV-2 RNA is more stable and likely found in greater concentration on fomites than infective SARS-CoV-2, the presence of viral RNA is not an indication of infectivity [38]. In this study, we only tested the presence or absence of SARS-CoV-2 RNA on the surfaces of full-body MPPPC and did not to assess viral infectivity or viability. The reported positive SARS-CoV-2 RNA detection rates identified in this study may be markers of previous viral presence from non-viable virus. Good hygienic and regular disinfection practices appeared to reduce the incidence of PPE contamination, although there is no robust evidence of viral infectivity or transmissibility via fomites to date [39]. Recent studies found similar contamination of PPE after patient contact and exposure to contaminated environment [40]. We also assessed the details of environmental contamination status by SARS-CoV-2 RNA in the other study, and the experimental data is under statistical analysis and has not been published. Preliminary analysis showed a high success rate in detecting the presence of SARS-CoV-2 RNA from the makeshift COVID-19 hospital setting. The correlation of contamination level between PPE and environmental in the makeshift COVID-19 hospital setting needs further analysis. Overall, the present study also showed that challenge with evaluating extent and severity of SARS-CoV-2 contamination for PPE worn. The sampled PPE sites with higher contamination rate also have lower Ct values, indicating that the highly contaminated PPE sites may have higher SARS-CoV-2 viral loads.

Conclusions

Protective clothing should be used according to the risk of contamination, the predominant route of SARS-CoV-2 transmission, and the period of exposure. Swabs of full-body MPPPC have identified with SARS-CoV-2 contamination in a makeshift COVID-19 hospital setting, although the use of RT-qPCR for detection may not necessarily represent the presence of viable virus. The foot dorsum and sole showed the highest frequency of SARS-CoV-2 RNA contamination possibly because gravity and air flow can cause the virus to fall to the floors. A higher rate of contamination was identified from PPE worn at 3 hours after the entrance to the COVID-19 patient care area. Virus-containing aerosols were trapped in HEPA filter of air supply equipment, representing a potential protective factor against SARS-CoV-2 infection to HCWs. HCWs should pay particular attention to the risk of contamination of hands and inner

clothing during PPE removal. PPE in conjunction with hand hygiene and routine cleaning and disinfection of patient care environment may protect HCWs from infection with SARS-CoV-2 during the management of patients with COVID-19.

Conflict of interest statement

None declared.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.infpip.2023.100309.

References

[1] Cheng VC, Wong SC, Tong DW, Chuang VW, Chen JH, Lee LL, et al. Multipronged infection control strategy to achieve zero nosocomial coronavirus disease 2019 (COVID-19) cases among Hong Kong healthcare workers in the first 300 days of the pandemic. Infect Control Hosp Epidemiol 2022;43:334—43. https://doi.org/10.1017/ice.2021.119.

[2] CDC COVID-19 Response Team. SARS-CoV-2 B.1.1.529 (Omicron) Variant - United States, December 1-8, 2021. MMWR Morb Mortal Wkly Rep 2021;70:1731—4. https://doi.org/10.15585/mmwr.mm7050e1.

[3] Abulsoud AI, El-Husseiny HM, El-Husseiny AA, El-Mahdy HA, Ismail A, Elkhawaga SY, et al. Mutations in SARS-CoV-2: Insights on structure, variants, vaccines, and biomedical interventions. Biomed Pharmacother 2023;157:113977. https://doi.org/10.1016/j.biopha.2022.113977.

[4] Pan Y, Wang L, Feng ZM, Xu H, Fu Li, Shen Y, et al. Characterisation of SARS-CoV-2 variants in Beijing during 2022: an epidemiological and phylogenetic analysis. Lancet 2023;401:664—72. https://doi.org/10.1016/S0140-6736(23)00129-0.

[5] Chen Z, Deng X, Fang L, Sun K, Wu Y, Che T, et al. Epidemiological characteristics and transmission dynamics of the outbreak caused by the SARS-CoV-2 Omicron variant in Shanghai, China: a descriptive study. Lancet Reg Health West Pac 2022;29:100592. https://doi.org/10.1016/j.lanwpc.2022.100592.

[6] Tegally H, Moir M, Everatt J, Giovanetti M, Scheepers C, Wilkinson E, et al. Emergence of SARS-CoV-2 Omicron lineages BA.4 and BA.5 in South Africa. Nat Med 2022;28:1785—90. https://doi.org/10.1038/s41591-022-01911-2.

[7] Chatterjee S, Bhattacharya M, Nag S, Dhama K, Chakraborty C. A Detailed Overview of SARS-CoV-2 Omicron: Its Sub-Variants, Mutations and Pathophysiology, Clinical Characteristics, Immunological Landscape, Immune Escape, and Therapies. Viruses 2023;15:167. https://doi.org/10.3390/v15010167.

[8] Dhama K, Patel SK, Natesan S, Vora KS, Iqbal Yatoo M, Tiwari R, et al. COVID-19 in the elderly people and advances in vaccination approaches. Hum Vaccin Immunother 2020;16:2938—43. https://doi.org/10.1080/21645515.2020.1842683.

[9] Zhang J, Dong X, Liu G, Gao Y. Risk and Protective Factors for COVID-19 Morbidity, Severity, and Mortality. Clin Rev Allergy Immunol 2023;64:90—107. https://doi.org/10.1007/s12016-022-08921-5.

[10] Fadl N, Ali E, Salem TZ. COVID-19: Risk Factors Associated with Infectivity and Severity. Scand J Immunol 2021;93:e13039. https://doi.org/10.1111/sji.13039.

[11] Davey SL, Lee BJ, Robbins T, Randeva H, Thake CD. Heat stress and PPE during COVID-19: impact on healthcare workers' performance, safety and well-being in NHS settings. J Hosp Infect 2021;108:185—8. https://doi.org/10.1016/j.jhin.2020.11.027.

[12] Peng LH, Chen YJ, Yang SY, Wang GJ, Gu YH, Shen BL, et al. Viral contamination on the surfaces of the personal protective equipment among health care professionals working in COVID-19 wards: A single-center prospective, observational study. Am J Infect Control 2023;51:276—81. https://doi.org/10.1016/j.ajic.2022.10.017.

[13] Brandner JM, Boor P, Borcherding L, Edler C, Gerber S, Heinemann A, et al. Contamination of personal protective equipment during COVID-19 autopsies. Virchows Arch 2022;480:519—28. https://doi.org/10.1007/s00428-021-03263-7.

[14] Yao Y, Cui Y, Gao X, Qian Y, Hu B. Contamination of personal protective equipment and environmental surfaces in Fangcang shelter hospitals. Am J Infect Control 2022;51:926—30. https://doi.org/10.1016/j.ajic.2022.11.016.

[15] Shuai H, Chan JF, Hu B, Chai Y, Yuen TT, Yin F, et al. Attenuated replication and pathogenicity of SARS-CoV-2 B.1.1.529 Omicron. Nature 2022;603:693—9. https://doi.org/10.1038/s41586-022-04442-5.

[16] Rolle B, Kiran R, Straub J. A Pathfinding Algorithm for Lowering Infection Exposure of Healthcare Personnel Working in Makeshift Hospitals. Healthcare (Basel) 2022;10:344. https://doi.org/10.3390/healthcare10020344.

[17] Chen C, Zhao B. Makeshift hospitals for COVID-19 patients: where health-care workers and patients need sufficient ventilation for more protection. J Hosp Infect 2020;105:98—9. https://doi.org/10.1016/j.jhin.2020.03.008.

[18] Shi F, Li H, Liu R, Liu Y, Liu X, Wen H, et al. Emergency Preparedness and Management of Mobile Cabin Hospitals in China During the COVID-19 Pandemic. Front Public Health 2022;9:763723. https://doi.org/10.3389/fpubh.2021.763723.

[19] Furtado SV, Perikal PJ, Narayanaswamy M, Ravikumar TV, John L, Harish K. Assessing efficacy of instructor based orientation to donning doffing protocols and modifications to doffing area infrastructure in reducing SARS-CoV-2 infection among Doctors

assigned to COVID-19 patient care. Infect Prev Pract 2023;5:100279. https://doi.org/10.1016/j.infpip.2023.100279.
[20] Greaves SW, Alter SM, Ahmed RA, Hughes KE, Doos D, Clayton LM, et al. A Simulation-based PPE orientation training curriculum for novice physicians. Infect Prev Pract 2023;5:100265. https://doi.org/10.1016/j.infpip.2022.100265.
[21] Ong SWX, Tan YK, Chia PY, Lee TH, Ng OT, Wong MSY, et al. Air, surface environmental, and personal protective equipment contamination by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) from a symptomatic patient. JAMA 2020;323:1610—2. https://doi.org/10.1001/jama.2020.3227.
[22] Zhang M, Wang L, Yu S, Sun G, Lei H, Wu W. Status of occupational protection in the COVID-19 Fangcang Shelter Hospital in Wuhan, China. Emerg Microbes Infect 2020;9:1835—42. https://doi.org/10.1080/22221751.2020.1803145.
[23] Lei N, Li BX, Zhang KF, Bao H, Ding J, Wang Y. Analysis of the Protective Effect of Infection Controllers Supervising Third-Party Personnel Entering and Leaving Shanghai Fangcang Shelter Hospital. Infect Drug Resist;15:7519-7527. https://doi.org/10.2147/IDR.S388707.
[24] Tian Z, Stedman M, Whyte M, Anderson SG, Thomson G, Heald A. Personal protective equipment (PPE) and infection among healthcare workers - What is the evidence? Int J Clin Pract 2020;74:e13617. https://doi.org/10.1111/ijcp.13617.
[25] Wong SC, Chan VW, Yuen LL, AuYeung CH, Leung JO, Li CK, et al. Infection of healthcare workers despite a high vaccination rate during the fifth wave of COVID-19 due to Omicron variant in Hong Kong. Infect Prev Pract 2023;5:100261. https://doi.org/10.1016/j.infpip.2022.100261.
[26] Hockaday S, Krause K, Sobieski C, Li JN, Hurst R, Ryan B, et al. Protocols for Personal Protective Equipment in a COVID-19 Medical Shelter. Disaster Med Public Health Prep 2020;14:551—7. https://doi.org/10.1017/dmp.2020.244.
[27] Aumeran C, Henquell C, Brebion A, Noureddine J, Traore O, Lesens O. Isolation gown contamination during healthcare of confirmed SARS-CoV-2-infected patients. J Hosp Infect 2021;107:111—3. https://doi.org/10.1016/j.jhin.2020.11.004.
[28] Jung J, Kim JY, Bae S, Cha HH, Kim EO, Kim MJ, et al. Contamination of personal protective equipment by SARS-CoV-2 during routine care of patients with mild COVID-19. J Infect 2020;81:e165—7. https://doi.org/10.1016/j.jinf.2020.06.021.
[29] Feldman O, Meir M, Shavit D, Idelman R, Shavit I. Exposure to a Surrogate Measure of Contamination From Simulated Patients by Emergency Department Personnel Wearing Personal Protective Equipment. JAMA 2020;323:2091—3. https://doi.org/10.1001/jama.2020.6633.
[30] Ong SWX, Tan YK, Sutjipto S, Chia PY, Young BE, Gum M, et al. Absence of contamination of personal protective equipment (PPE) by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). Infect Control Hosp Epidemiol 2020;41:614—6. https://doi.org/10.1017/ice.2020.91.
[31] Wei L, Huang W, Lu X, Wang Y, Cheng L, Deng R, et al. Contamination of SARS-CoV-2 in patient surroundings and on personal protective equipment in a non-ICU isolation ward for COVID-19 patients with prolonged PCR positive status. Antimicrob Resist Infect Control 2020;9:167. https://doi.org/10.1186/s13756-020-00839-x.
[32] Yung CF, Kam KQ, Wong MSY, Maiwald M, Tan YK, Tan BH, et al. Environment and personal protective equipment tests for SARS-CoV-2 in the isolation room of an infant with infection. Ann Intern Med 2020;173:240—2. https://doi.org/10.7326/M20-0942.
[33] Ye G, Lin H, Chen S, Wang S, Zeng Z, Wang W, et al. Environmental contamination of SARS-CoV-2 in healthcare premises. J Infect 2020;81:e1—5. https://doi.org/10.1016/j.jinf.2020.04.034.
[34] Moore G, Rickard H, Stevenson D, Aranega-Bou P, Pitman J, Crook A, et al. Detection of SARS-CoV-2 within the healthcare environment: a multi-centre study conducted during the first wave of the COVID-19 outbreak in England. J Hosp Infect 2021;108:189—96. https://doi.org/10.1016/j.jhin.2020.11.024.
[35] Bulfone TC, Malekinejad M, Rutherford GW, Razani N. Outdoor Transmission of SARS-CoV-2 and Other Respiratory Viruses: A Systematic Review. J Infect Dis 2021;223:550—61. https://doi.org/10.1093/infdis/jiaa742.
[36] Jung J, Song KH, Jeong H, Ham SY, Kim ES, Kim HB. Are coveralls required as personal protective equipment during the management of COVID-19 patients? Antimicrob Resist Infect Control 2021;10:164. https://doi.org/10.1186/s13756-021-01017-3.
[37] Shah A, Zhuang E, German J, Tai S, Schanz M, Glendening G, et al. Surface Contamination of Reusable Respirators and Face Shields During Care of Critically Ill COVID-19 Patients. Workplace Health & Saf 2023;71:137—43. https://doi.org/10.1177/21650799221135583.
[38] Ben-Shmuel A, Brosh-Nissimov T, Glinert I, Bar-David E, Sittner A, Poni R, et al. Detection and infectivity potential of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) environmental contamination in isolation units and quarantine facilities. Clin Microbiol Infect 2020;26:1658—62. https://doi.org/10.1016/j.cmi.2020.09.004.
[39] Kampf G, Brüggemann Y, Kaba HEJ, Steinmann J, Pfaender S, Scheithauer S, et al. Potential sources, modes of transmission and effectiveness of prevention measures against SARS-CoV-2. J Hosp Infect 2020;106:678—97. https://doi.org/10.1016/j.jhin.2020.09.022.
[40] Zeng C, Liu H, Jiang Y, Fu Y, Liu Y, Chang W, et al. How to reduce the exposure risk of medical staff from SARS-CoV-2 by reducing environmental contamination: Experience from designated hospitals in China. Front Public Health 2022;10:963999. https://doi.org/10.3389/fpubh.2022.963999.