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.
Multi-route transmission potential of SARS-CoV-2 in healthcare facilities

Baihuan Feng\textsuperscript{a,b,c,1}, Kajjin Xu\textsuperscript{d,1}, Silan Gu\textsuperscript{d,1}, Shufa Zheng\textsuperscript{a,b,c,1}, Qianda Zou\textsuperscript{a,b,c}, Yan Xu\textsuperscript{d}, Ling Yu\textsuperscript{d}, Fangyuan Lou\textsuperscript{d}, Fei Yu\textsuperscript{a,b,c}, Tao Jin\textsuperscript{e}, Yuguo Li\textsuperscript{f}, Jifang Sheng\textsuperscript{d}, Hui-Ling Yen\textsuperscript{a,1}, Zifeng Zhong\textsuperscript{h}, Jianjian Wei\textsuperscript{g,*,**}, Yu Chen\textsuperscript{a,b,c,d,1}

\textsuperscript{a} Department of Laboratory Medicine, The First Affiliated Hospital, College of Medicine, Zhejiang University, Hangzhou, 310000, China
\textsuperscript{b} Key Laboratory of Clinical In Vitro Diagnostic Techniques of Zhejiang Province, Hangzhou, 310000, China
\textsuperscript{c} Institute of Laboratory Medicine, Zhejiang University, Hangzhou, 310000, China
\textsuperscript{d} State Key Laboratory for Diagnosis and Treatment of Infectious Diseases, National Clinical Research Center for Infectious Diseases, Collaborative Innovation Center for Diagnosis and Treatment of Infectious Diseases, The First Affiliated Hospital, College of Medicine, Zhejiang University, Hangzhou, 310000, China
\textsuperscript{e} Institute of Refrigeration and Cryogenics, Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Zhejiang University, Hangzhou, 310000, China
\textsuperscript{f} Department of Mechanical Engineering, The University of Hong Kong, Pokfulam, 999077 Hong Kong Special Administrative Region
\textsuperscript{g} School of Public Health, Li Ka Shing Faculty of Medicine, The University of Hong Kong, 999077, Hong Kong Special Administrative Region
\textsuperscript{h} Department of Nosocomial Infection Control, College of Medicine, Zhejiang University, Hangzhou, 310000, China

\textbf{A R T I C L E I N F O}

Editor: R. Debora

Keywords:
COVID-19
SARS-CoV-2
Exhaled breath
Aerosol
Environmental sampling

\textbf{A B S T R A C T}

Understanding the transmission mechanism of SARS-CoV-2 is a prerequisite to effective control measures. To investigate the potential modes of SARS-CoV-2 transmission, 21 COVID-19 patients from 12–47 days after symptom onset were recruited. We monitored the release of SARS-CoV-2 from the patients’ exhaled breath and systematically investigated environmental contamination of air, public surfaces, personal necessities, and the drainage system. SARS-CoV-2 RNA was detected in 0 of 9 exhaled breath samples, 2 of 8 exhaled breath condensate samples, 1 of 12 bedside air samples, 4 of 132 samples from private surfaces, 0 of 70 samples from frequently touched public surfaces in isolation rooms, and 7 of 23 feces-related air/surface/water samples. The maximum viral RNA concentrations were 1857 copies/mL in sewage/wastewater samples. Our results suggest that nosocomial transmission of SARS-CoV-2 can occur via multiple routes. However, the low detection frequency and limited quantity of viral RNA from the breath and environmental specimens may be related to the reduced viral load of the COVID-19 patients on later days after symptom onset. These findings suggest that the transmission dynamics of SARS-CoV-2 differ from those of SARS-CoV in healthcare settings.

1. Introduction

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was first identified from a cluster of patients with pneumonia of unknown cause in Wuhan, China, in December 2019. SARS-CoV-2 is an enveloped, positive-sense, single-stranded RNA virus and the seventh member of the coronavirus family that infects humans. It is distinct from both severe acute respiratory syndrome coronavirus (SARS-CoV) and Middle East respiratory syndrome coronavirus (MERS-CoV) (Zhu et al., 2020).

Infection with SARS-CoV-2 may result in a wide range of clinical manifestations from asymptomatic infection to critical illness. As of August 11, 2020, COVID-19 has caused a worldwide pandemic, with nearly 20 million confirmed cases and 0.74 million deaths (World Health Organization, 2020a).

SARS-CoV-2 is believed to spread efficiently, but the exact transmission routes, especially the fomite, airborne (or aerosol), and fecal-oral routes, remain under debate (World Health Organization, 2020b). Viral RNA has been detected from various surfaces of isolation rooms
and intensive care units in which COVID-19 patients are treated, but
detection from air has been relatively difficult (Chia et al., 2020; Ong
et al., 2020). The probable explanation is either that patients released
limited virus during the sampling period or that patient’s exhaled breath
(EB) is readily diluted by the room’s ventilation before it can be
sampled, which is consistent with the proximity effect in the trans-
mission of respiratory infections (Liu et al., 2017). Although
SARS-CoV-2 may be transmitted by transmission routes similar to those
of other coronaviruses, such as large droplets, aerosols, or contact, the
potential of transmission via each route requires systematic
investigation.

Nosocomial transmission of the virus has been reported in China:
more than 3000 medical staff members have been infected during
medical practice (Zhang, 2020). According to a single-center case series
involving 138 hospitalized patients in Wuhan, China, nosocomial
transmission was suspected to occur via 29 % of infected medical staff
and 12.3 % of hospitalized patients (Wang et al., 2020). Similarly, the
transmission of virus from a single health care worker to several other
patients and health care workers was assumed to be responsible for the
hospital outbreak of SARS-CoV-2 in the University Hospital of Münster,
Germany (Schwierzek et al., 2020). An accumulating body of evidence
suggests that although COVID-19 patients are mostly infectious during
the early stage of infection, the high viral loads in their sputum and feces
specimens during later stages of infection may still pose a risk to
healthcare workers (Zheng et al., 2020). This hypothesis has yet to be
systematically evaluated.

In this study, we aimed to investigate the EB and the hospital envi-
ronmental contamination by COVID-19 patients in the later stage of
infection. To that end, we sampled the EB, exhaled breath condensate
(EBC), surfaces of isolation wards, and personal necessities of 21 pa-
tients with laboratory-confirmed COVID-19 and hospital drainage sys-
tems from 12–47 days after symptom onset and subjected the samples to
SARS-CoV-2 detection by quantitative reverse transcription polymerase
chain reaction (RT-qPCR).

2. Methods

2.1. Patients

Twenty-one patients with laboratory-confirmed COVID-19 who were
hospitalized in the First Affiliated Hospitals, College of Medicine, Zhe-
jiang University, from February 13, 2020, to March 5, 2020, were
enrolled in this study. We collected samples of EB, EBC, size-segregated
aerosols from the air, frequently touched surfaces, and the drainage
system. Patients’ sputum and feces specimens were collected daily by
the hospital staff for purposes of routine diagnosis. The patients’ clinical
data were obtained from hospital electronic medical records. This study
protocol was approved by the Clinical Research Ethics Committee of the
First Affiliated Hospital, College of Medicine, Zhejiang University.

2.2. EB sampling

An exhaled aerosol collection system was developed (Fig. S1), and
the patients were asked to breath normally through a mask for 30 min,
during which they were asked to perform 10 forced coughs. The mask
did not interrupt the patient’s oxygen inhalation. The exhaled air was
sampled by the NIOSH bioaerosol sampler, which collected air at 3.5 L/
min (105-L air was sampled during the 30-min sampling) and separated
virus-laden aerosols into three size fractions: <1 μm, 1–4 μm, and >4 μm
(Lindsay et al., 2010). After collection of EB samples, the NIOSH bio-
aerosol sampler was disassembled in a biosafety cabinet, and 1 mL of
viral transport medium was added to each collection tube and PTFE
filter to suspend virus particles.

2.3. EBC sampling

The EBC samples were collected using a sterile laboratory-made EBC
collection system comprising a 15-mL centrifuge tube with the bottom
cut off and a 50-mL centrifuge tube (Fig. S2). The patients were asked to
blow into the 15-mL centrifuge tube for 10 min. Approximately 200–500
μL of EBC was collected from each patient for further analysis.

2.4. Room air and frequently touched surface sampling in isolation rooms

For sampling of isolation room air, a NIOSH sampler was placed on a
tripod 1.2 m in height and 0.2 m away from the bed at the side of the
patient’s head (Fig. S3). The sampling duration was 30 min, and a total
of 105-L room air was sampled.

Frequently touched public and private surfaces in isolation rooms
were sampled, as illustrated in Fig. S3 and Table S1. The standard
sampling area was 10 × 10 cm² (swab applied in horizontal followed by
vertical and diagonal sweeps). For surfaces smaller than 10 × 10 cm²,
the entire touchable surface was swabbed. After sampling, the swabs
were immediately placed into 1.5 mL of viral transport medium.

2.5. Drainage-related sampling

Virus-laden aerosols may be generated during flushing in the toilet
and in sewage pipes, accounting for potential fecal-oral transmission of
SARS-CoV-2. For lavatory bioaerosol sampling, a NIOSH sampler was
placed on a tripod 1.2 m in height and 0.5 m away from the toilet bowl in
the lavatory of the isolation rooms; the 30-min sampling period began
when the patient used the toilet for defection. After the patient exited
the toilet, the toilet bowl and floor drain were also swabbed for sam-
ping. In addition, water samples were taken in 15-mL centrifuge tubes
from the main sewage pipe and wastewater pipe of the building in which
the COVID-19 patients were isolated (Fig. S4).

2.6. RT-qPCR

Viral RNA was extracted from all collected clinical or environmental
specimens using Magna Pure LC 2.0 (Roche, Basel, Switzerland). RT-
qPCR was performed using a China Food and Drug Administration-
approved commercial kit specific for SARS-CoV-2 detection (Da’an
Gene Co., Ltd., Guangzhou, Guangdong, China) according to the man-
ufacturer’s protocol. Specimens with quantification cycle (Cq) values of
40 or lower were considered positive for SARS-CoV-2 RNA. Specimens
with Cq values higher than 40 were tested again, and those with repeat
Cq values that were higher than 40 or undetectable were considered
negative for SARS-CoV-2 RNA. The standard curve was generated by 10-
fold serial dilutions of positive control and the fitted relationship be-
 tween Cq value and virus concentration in the tested medium, C (copies/ 
 mL), is as follows

\[
\text{Log}(C) = \left(46.12 - \text{Cq}\right)/3.331
\]

3. Results and discussions

3.1. Detection of SARS-CoV-2 RNA among various types of samples

A total of 21 moderately to critically ill patients with COVID-19
(aged 13–72 years; median, 61 years) were recruited. Sampling was
performed 12–47 DAO (median, 29 days). The patients’ details are listed in
Table 1. All recruited patients were in the recovery period with
normal body temperature and improved lung infection conditions ac-
cording to computed tomography scan. Viral loads in the sputum spec-
imens were detected varying from negative to 1.2 × 10^{10} copies/mL
(median, 1.3 × 10^9), and those in feces specimens from negative to 1.9 ×
Of the 254 samples (9 EB samples, 8 EBC samples, 12 bedside air samples, 202 public/private surface samples from isolation rooms, and 23 feces-related air/surface/water samples), 14 tested positive, as summarized in Table 2, suggesting the potential for nosocomial transmission of SARS-CoV-2 via multiple routes. The viral RNA concentrations were 1112 copies/m$^3$ and 745 copies/m$^3$ respectively in the <1 $\mu$m and >4 $\mu$m fractions of the only positive air sample. The maximum viral RNA concentrations were 38 copies/cm$^2$ in sampled private surfaces of COVID patients (excluding the toothbrush) and 3092 copies/mL in sewage/wastewater samples. These findings prioritize areas for effective environmental disinfection practices to reduce virus transmission and support the need for strict adherence to personal hygiene. However, the positive detection rates and virus contents in these positive samples were relatively low, indicating that patients release limited virus particles into the environment more than 10 DAO.

### 3.2. Potential of respiratory bioaerosols in transmitting SARS-CoV-2

Respiratory droplets, or bioaerosols, are carriers of pathogens and are responsible for the transmission of respiratory infectious diseases. They are produced during respiratory activities such as coughing, sneezing, talking, and normal breathing. To test the potential of respiratory bioaerosol in transmitting SARS-CoV-2, 9 EB and 8 EBC specimens were collected from 15 patients between 13 and 43 DAO in the present study. The aerosol collection system in this study directly sampled patients’ EB before it was highly diluted by the room air, but all samples in three size fractions tested negative for viral RNA (positive detection in sputum samples; see Table 2), though 10 forced coughs were performed by each patient. Two of the eight EBC samples tested positive for the virus (Patients 9 and 17), with the virus concentration as 216.0 copies/mL and 222.0 copies/mL, respectively. This detection rate was likely attributable to the high collection efficiency of both fine and coarse aerosols and the low possibility of dilution by air or viral transport medium. Furthermore, 1 (Patient 9) of the 12 air samples from the patients’ bedside (24–43 DAO) tested positive (sputum viral loads between negative and 4.5 $\times$ 10$^3$ copies/mL); RNA was detected in two size fractions from that air sample, with virus concentrations of 1111.9 copies/m$^3$ and 744.6 copies/m$^3$ in the <1 $\mu$m and >4 $\mu$m fractions, respectively. One of the two positive EBC samples and the positive
The sampling date were 6.3 × 10^6 copies/mL and 3.2 × 10^6 copies/mL, respectively. These findings are consistent with a sampling event in two Wuhan hospitals where viral RNA in aerosols detected in isolation wards and ventilated rooms was very low (Liu et al., 2020). In another sampling event with NIOSH samplers, viral RNA was readily detected from the air of isolation rooms where patients were at 5 D.A.O.; the highest sampling event with NIOSH samplers, viral RNA was readily detected from the air of isolation rooms where patients were at 5 D.A.O.; the highest

| Sampling type | Time of sample collection (DAO) | Viral load of sputum/feces specimen (log10 copies/mL) | Positive rates | Viral RNA concentration in positive samples |
|---------------|---------------------------------|-----------------------------------------------------|----------------|--------------------------------------------|
| Exhaled breath | 13-28 (median, 20)              | 3.5-10.1/5.9-9.3                                    | 0/9            | /                                          |
| Exhaled breath condensate | 27-43 (median, 30)              | Neg*–6.3/ Neg–5.3                                    | 2/8            | 216 copies/mL, Patient 9                   |
| Room air at patient’s bedside |                                    | 1/12                                                 |                | 222 copies/mL, Patient 17                  |
| Private surfaces in isolation rooms | 23-43 (median, 31)              | Neg–5.7/ Neg–4.6                                    | 4/132          | 1112 copies/m³ (<1 μm) and 745 copies/m³ (<4 μm), Patient 9 |
| Public surfaces in isolation rooms |                                    | 0/70                                                  |                | 9 copies/cm², Patient 10                    |
| Drainage systems (lavatory air, toilet bowl, floor drain) | 12-28 (median, 21.5)              | 6.1–10.1/5.3–6.7                                    | 0/6, 2/6       | 35 copies/cm², towel, Patient 15            |
| Drainage systems (Sewage, wastewater) |                                    | /                                                     | 4/5            | 1045 copies in total, and the bedside wall of Patient 18 |
| * Sputum or feces specimens of the patients were occasionally not delivered for PCR analysis on the sampling date and were not considered in the statistics. 10 mL water was used to rinse the toothbrush, and the water was directly analyzed by the PCR kit.  

* Neg is short for negative.

bedside air sample belonged to Patient 9; his sputum viral load values on the sampling date were 6.3 × 10^6 copies/mL and 3.2 × 10^6 copies/mL, respectively. These findings are consistent with a sampling event in two Wuhan hospitals where viral RNA in aerosols detected in isolation wards and ventilated rooms was very low (Liu et al., 2020). In another sampling event with NIOSH samplers, viral RNA was readily detected from the air of isolation rooms where patients were at 5 D.A.O.; the highest concentration was 1384 copies/m³ and 2000 copies/m³ in the 1–4 μm and >4 μm fractions, respectively, and no viral RNA was detected in <1 μm size fraction (Chia et al., 2020).

Although some COVID-19 patients evaluated during the later stage of infection in our study had a relatively high viral load in their sputum specimen, shedding of virus particles from the respiratory tract into the environment was limited, which is in agreement with previous findings that viral load in nasal or throat samples is high in the early stage of infection and decreases to a low level at around 9 DAO (Woelfel et al., 2020; Zou et al., 2020). Virus-laden respiratory droplets from the deep lung tend to deposit and accumulate into the respiratory mucous, but difficult to follow the respiratory airflow to enter the indoor environment (Kleinsteuber and Zhang, 2010). The transmission characteristics of SARS-CoV-2 differ from those of SARS because the viral loads in the respiratory specimens of SARS-infected patients peak at 10 DAO (Peiris et al., 2003), and considerable positive rates of surface swabs have been detected in SARS patients’ rooms at 5–15 DAO (Dowell et al., 2004). However, the virus-shedding course of SARS-CoV-2 is similar to that of influenza virus (Tsang et al., 2015; Zou et al., 2020), and the NIOSH bioaerosol sampler has also successfully detected influenza virus in samples of 32 out of 38 influenza-positive patients, 60 % of whom had symptom onset within 3 days (Lindsley et al., 2010). This finding highlights the importance of early control measures for COVID-19 patients and suggests a relief for medical staff working in isolation rooms and intensive care units with recovering (later stage) patients.

3.3. Personal necessities function as potential vehicles for SARS-CoV-2 transmission

Surfaces may be contaminated by deposition of virus-laden droplets or by contact of patients’ hands, and lead to fomite transmission of SARS-CoV-2. Four of the 202 surface samples obtained from seven isolation rooms tested positive. These positive samples were from private surfaces of COVID-19 patients, namely the towels of Patient 5 (9 copies/cm²) and Patient 6 (35 copies/cm²), the toothbrush of Patient 15 (1045 viral RNA copies in total), and the bedside wall of Patient 18 (38 copies/cm²) (Table 2). This positive detection can be attributed to contamination with respiratory secretions. It is worth noting that although both sputum specimen of Patient 16 and 18 tested negative, viral RNA was still detected from their towel or room (the bedside wall), which might be shed days ago. Viruses may survive on surfaces for hours to days and might infect susceptible individuals (van Doremalen et al., 2020). The viral survival, the transmission efficiency of the virus from surfaces and hands to respiratory mucosa, and the dose-response rate after the virus is introduced onto the mucosa are all important factors that influence the exposure risk of the susceptible individuals. Our results are in line with that of a previous study that revealed that towels in hospitals are frequently contaminated with respiratory pathogens (Hassan et al., 2019). These findings suggest that personal necessities function as potential vehicles for virus transmission. Therefore, measures that target the proper use of personal necessities, including avoidance of sharing with others, frequent cleaning with disinfectant, and hand hygiene practices after use, may help to limit virus transmission.

Studies have reported much high positive rates from public surface samplings near COVID-19 patients within 5 DAO (Chia et al., 2020; Ong et al., 2020). However, no viral RNA was detected from samples taken from frequently touched public surfaces in the isolation rooms over 7 h after routine sanitization, further indicating limited transmission potential via the fomite route during our sampling period. In previous studies, viral RNA were readily detected from public surfaces in isolation rooms of patients in the early stage of infection (Chia et al., 2020; Ong et al., 2020). The viral loads of the sputum and feces specimen of 12 patients from the isolation rooms (Table S1) in our study were negative–4.5 × 10^3 copies/mL and negative–3.7 × 10^3 copies/mL, respectively, on the sampling date.

3.4. Potential of fecal-oral and fecal-aerosol routes in transmitting SARS-CoV-2

COVID-19 patients have a long virus shedding course in feces specimen, and viral RNA, even viable virus particles, has been detected in the feces-related specimens of patients with confirmed COVID-19 (Guan et al., 2020; Tian et al., 2020). Moreover, previous studies have
suggested that the viral loads of feces specimens peak late after the symptom onset and may last for a longer duration compared with those of respiratory specimens (Xing et al., 2020). Thus, fecal-oral and fecal-aerosol transmission have been suspected as potential routes of SARS-CoV-2 (McDermott et al., 2020; Tian et al., 2020).

We sampled lavatory air, toilet bowl, floor drain and sewage, apart from the public lavatory surfaces as described above and in Fig. S3. Two of the six samples from toilet bowl after defecation and toilet flushing tested positive for the viral RNA, namely 4 copies/cm² and 2 copies/cm², respectively (viral loads for positive detection in the feces specimens, 2.1 × 10⁴ copies/mL-5.0 × 10⁴ copies/mL). Further, one of six floor drain samples tested positive, with a viral concentration of 2 copies/cm², indicating that virus-laden aerosol transmission by the drainage system (as illustrated in Graphical Abstract) is probable. None of the six lavatory aerosol samples tested positive; although patients’ feces specimens were test high in viral loads, the toilet didn’t produce detectable amount of virus-laden aerosols in our sampling event. Moreover, four of the five water samples from the drainage system tested positive. The viral RNA concentration of the sewage is as high as 3092 copies/mL, but the sewage treatment station worked well to reduce it below the detection limit (Fig. S4).

The detection of SARS-CoV-2 in the toilet bowl and sewage samples in this study is consistent with that finding, indicating high viral loads in the patients’ feces-related specimens. Notably, one sample from the floor drainage tested positive, which was probably contaminated by the virus-laden bioaerosols from the drainage system. The toilet flushing process produces large numbers of bioaerosols in the sewage pipe, which may re-enter vertically-aligned lavatories in the same building through the floor drain. This likely explains the SARS cluster outbreak that occurred in Amoy Garden in 2003 (Yu et al., 2004).

4. Implications

Our findings provide important health implications for the control of nosocomial infection and personal protection: (1) ensure good ventilation for each isolation ward to reduce the potential risk of transmission via aerosols; (2) in addition to routine disinfection practices, perform frequent and thorough environmental cleaning and disinfection of areas not easy to clean; (3) perform ventilation and disinfection after using the toilet to reduce aerosolization of virus and contamination of surrounding surfaces, and preserve tap water seals to prevent the re-entry of bioaerosols from pipes; (4) do not share personal necessities, and disinfect and replace them regularly. However, the major limitation is that we only detected the presence of the nucleic acid (RNA) of SARS-CoV-2 and did not perform viral culture due to the low virus quantity in the positive samples. The presence of nucleic acid does not confirm the existence of viable virus, nor does it indicate that fomite contact is an important route for SARS-CoV-2 transmission.

CRediT authorship contribution statement

Baihuan Feng: Conceptualization, Data curation, Methodology, Writing - original draft, Writing - review & editing. Kaijin Xu: Data curation, Methodology. Silan Gu: . Shufa Zheng: Data curation, Methodology. Qianda Zou: Data curation, Validation. Yan Xu: Data curation, Validation. Ling Yu: . Fangyuan Lou: Data curation, Validation. Fei Yu: Data curation, Validation. Tao Jin: Project administration. Yuguo Li: Project administration. Jifang Sheng: Project administration. Hui-Ling Yan: Project administration. Zifeng Zhong: Project administration. Jianjian Wei: Funding acquisition, Project administration, Supervision, Writing - original draft, Writing - review & editing. Yu Chen: Project administration, Supervision, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

The authors thank Dr. William G. Lindsley for providing the NIOSH bioaerosol samplers. This work was financially supported by the National Natural Science Foundation of China (Grant No. 51808488) and Zhejiang University special scientific research fundfor COVID-19 prevention and control.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jhazmat.2020.123771.

References

Chia, P.Y., Coleman, K.K., Tan, Y.K., Ong, S.W.X., Gumi, M., Lai, S.K., Lim, X.F., Lim, A.S., Sutjipto, S., Lee, P.H., Son, T.Y., Young, B.E., Milton, D.K., Gray, G.C., Schuster, S., Barkham, T., Chen, Y., Chan, M., Aug, B.S.P., Tan, B.H., Leo, Y.S., Ng, O.-T., Woeg, M.S.Y., Marimuthu, K., Team, S.N.C.O.R, 2020. Detection of air and surface contamination by SARS-CoV-2 in hospital rooms in hospitalized patients. Nat. Commun. 11 (1), 2800.

Dowell, S.F., Simmons, J.M., Erdman, D.D., Wu, J.S.J., Chaoanvich, A., Javadi, M., Yang, J.Y., Anderson, L.J., Tong, S.X., Ho, M.S., 2004. Severe acute respiratory syndrome coronavirus on hospital surfaces. Clin. Infect. Dis. 39 (5), 652–657.

Guo, W., Ni, Z., Hu, Y., Liang, W., Ou, C., He, J., Liu, L., Shan, H., Li, C., Hei, D.S.C., Du, B., Li, L., Zeng, G., Yuan, K.Y., Chen, R., Tang, C., Wang, T., Chen, P., Xiang, L., Li, S., Wang, J.-I., Liang, Z., Peng, Y., Wei, L., Liu, Y., Hu, Y.-H., Peng, P., Wang, J.-M., Liu, J., Chen, Z., Li, G., Zheng, Q., Qu, S., Luo, J., Ye, C., Zhu, S., Zhong, N., China Med Treatment Expert, G, 2020. Clinical characteristics of coronavirus disease 2019 in China. J. Engl. J. Med. 382 (18), 1708–1720.

Hassan, M.Z., Sturm-Ramirez, K., Rahman, M.Z., Hossain, K., Aleem, M.A., Bhuiyan, M.U., Islam, M., Rahman, M., Gurley, E.S., 2020. Contamination of hospital surfaces with respiratory pathogens in Bangladesh. PloS One 14 (10), e100281.

Kleinstreuer, C., Zhang, Z., 2010. Airflow and particle transport in the human respiratory system. Annu. Rev. Fluid Mech. 42, 301–334.

Lindsley, W.G., Blachere, M.F., Thevis, R.E., Vishnu, A., Davis, K.A., Cao, G., Palmer, J.E., Clark, K.E., Fisher, M.A., Khakoo, R., Beenholt, D.H., 2010. Measurements of airborne influenza virus in aerosol particles from human coughs. PloS One 5 (11), e15100.

Li, L., Li, Y., Nielsen, P.V., Wei, J., Jensen, R.L., 2017. Short-range airborne transmission of respiratory droplets between two people. Indoor Air 27 (2), 452–462.

Liu, Y., Ning, Z., Chen, Y., Guo, M., Liu, Y., Gali, N.K., Sun, L., Duan, Y., Cai, Y., Jai, S., Westerdahl, D., Liu, X., Xu, K., Ho, K.-F., Kan, H., Fu, Q., Lan, K., 2020. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. Nature 582, 557–560.

McDermott, C.V., Alicic, R.Z., Harden, N., Cox, E.J., Scanlan, J.M., 2020. Put a lid on it: Are faecal bio-aerosols a route of transmission for SARS-CoV-2? J. Hosp. Infect. 105 (3), 397–398.

Ong, S.W.X., Tan, Y.K., Chia, P.Y., Lee, T.H., Ng, O.T., Wong, M.S.Y., Marimuthu, K., 2020. Air, surface environmental, and personal protective equipment contamination by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) from a symptomatic patient. Jama 323 (16), 1610–1612.

Peiris, J.S.M., Cho, C.M., Cheng, V.C.C., Chan, K.S., Hung, I.F.N., Poon, L.L.M., Law, K.I., Tang, B.S.F., Hon, T.Y.W., Chan, C.S., Chan, K.H., Ng, J.S.C., Zheng, B.J., Ng, W.L., Lai, R.W.M., Guan, Y., Yuan, K.Y., Grp, H.U.S.S., 2003. Clinical progression and viral load in a community outbreak of coronavirus-associated SARS pneumonia: a prospective study. Lancet 361 (9371), 1767–1772.

Schwierzeck, V., König, J.C., Kühn, J., Mellmann, A., Correa-Martínez, C.L., Omran, H., Konrad, M., Kaiser, T., Kampmeier, S., 2020. First reported nosocomial outbreak of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in a pediatric dialysis unit. Clin. Infect. Dis. 491, 1–21.

Tian, Y., Rong, L., Nian, W., He, Y., 2020. Review article: gastrointestinal features in COVID-19 and the possibility of faecal transmission. Aliment Pharm Ther 51 (9), 843–851.

Tong, T., Crowling, B.J., Fang, V.J., Chan, K.-H., Ip, D.K.M., Leung, G.M., Peiris, J.S.M., Cauchemez, S., 2015. Influenza A virus shedding and infectivity in households. J Infect Dis 212 (9), 1420–1428.

van Doremalen, N., Bushmaker, T., Morris, D.H., Holbrook, M.G., Gamble, A., Williamson, B.N., Tamin, A., McDade, J.T., Gerber, S.I., Lloyd-Smith, J.O., de Wit, E., Munster, V.J., 2020. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. Nature 582, 170–173.

Wang, D., Hu, B., Hu, C., Zhu, F., Liu, X., Zhang, J., Wang, B., Xiang, Z., Xiong, Y., Zhao, Y., Li, Y., Yang, W., Peng, Z., 2020. Clinical characteristics of 138 hospitalized patients with 2019 novel coronavirus-infected pneumonia in Wuhan, China. JAMA 323 (11), 1061–1069.

Woelfel, R., Gorman, V.M., Guggemos, W., Seilmaier, M., Zange, S., Mueller, M.A., Niemeyer, D., Jensen, T.C., Vollmar, P., Rothe, C., Hoehler, M., Bleicker, T., 2020.
Bruenink, S., Schneider, J., Ehmann, R., Zwiglmaier, K., Drosten, C., Wendtner, C., 2020. Virological assessment of hospitalized patients with COVID-19. Nature 581, 465–469.

World Health Organization, 2020. Coronavirus Disease 2019 (COVID-19): Situation Report, 204.

World Health Organization, 2020. Infection Prevention and Control During Health Care When Novel Coronavirus (nCoV) Infection Is Suspected: Interim Guidance, 19 March 2020, WHO/2019-nCoV/IPC/2020.3.

Xing, Y.-H., Ni, W., Wu, Q., Li, W.-J., Li, G.-J., Wang, W.-D., Tong, J.-N., Song, X.-F., Wing-Kin Wong, G., Xing, Q.-S., 2020. Prolonged viral shedding in feces of pediatric patients with coronavirus disease 2019. J Microbiol Immunol. 53 (3), 473–480.

Yu, I.T.S., Li, Y.G., Wong, T.W., Tam, W., Chan, A.T., Lee, J.H.W., Leung, D.Y.C., Ho, T., 2004. Evidence of airborne transmission of the severe acute respiratory syndrome virus. N. Engl. J. Med. 350 (17), 1731–1739.

Zhang, Y., 2020. The epidemiological characteristics of an outbreak of 2019 novel coronavirus diseases (COVID-19)-China, 2020. China CDC Weekly 2, 1–10.

Zheng, S., Fan, J., Yu, F., Feng, B., Lou, B., Zou, Q., Xie, G., Lin, S., Wang, R., Yang, X., Chen, W., Wang, Q., Zhang, D., Liu, Y., Gong, R., Ma, Z., Lu, S., Xiao, Y., Gu, Y., Zhang, J., Yao, H., Xu, K., Lu, X., Wei, G., Zhou, J., Fang, Q., Cai, H., Qiu, Y., Sheng, J., Chen, Y., Liang, T., 2020. Viral load dynamics and disease severity in patients infected with SARS-CoV-2 in Zhejiang province, China, January-March 2020: retrospective cohort study. BMJ 369.

Zhu, N., Zhang, D., Wang, W., Li, X., Yang, B., Song, J., Zhao, X., Huang, B., Shi, W., Lu, R., Niu, P., Zhan, F., Ma, X., Wang, D., Xu, W., Wu, G., Gao, G.F., Tan, W., 2020. A Novel coronavirus from patients with pneumonia in China, 2019. N Engl J Med 382 (8), 727–733.

Zou, L., Ruan, F., Huang, M., Liang, L., Huang, H., Hong, Z., Yu, J., Kang, M., Song, Y., Xia, J., Gao, Q., Song, T., He, J., Yen, H.L., Peiris, M., Wu, J., 2020. SARS-CoV-2 viral load in upper respiratory specimens of infected patients. N. Engl. J. Med. 382 (12), 1177–1179.