Journal of Hospital Infection 108 (2021) 189–196

Available online at www.sciencedirect.com

Journal of Hospital Infection

journal homepage: www.elsevier.com/locate/jhin

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

G. Moore [a,*], H. Rickard [a], D. Stevenson [a], P. Aranega-Bou [a], J. Pitman [a], A. Crook [a], K. Davies [a], A. Spencer [a], C. Burton [a], L. Easterbrook [a], H.E. Love [a], S. Summers [a], S.R. Welch [a], N. Wand [a], K-A. Thompson [a], T. Pottage [a], K.S. Richards [a], J. Dunning [b,c], A. Bennett [a]

[a] National Infection Service, Public Health England, Porton Down, Salisbury, UK
[b] Emerging Infections and Zoonoses Unit, National Infection Service, Public Health England, Colindale, London, UK
[c] NIHR Health Protection Research Unit in Emerging Infections and Zoonoses, Liverpool, UK

ARTICLE INFO

Article history:
Received 1 October 2020
Accepted 25 November 2020
Available online 28 November 2020

Keywords:
SARS-CoV-2
Hospital
Environmental surfaces
Air
Environmental contamination
Infection control

SUMMARY

Background: Understanding how severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) is spread within the hospital setting is essential in order to protect staff, implement effective infection control measures, and prevent nosocomial transmission.

Methods: The presence of SARS-CoV-2 in the air and on environmental surfaces around hospitalized patients, with and without respiratory symptoms, was investigated. Environmental sampling was undertaken within eight hospitals in England during the first wave of the coronavirus disease 2019 outbreak. Samples were analysed using reverse transcription polymerase chain reaction (PCR) and virus isolation assays.

Findings: SARS-CoV-2 RNA was detected on 30 (8.9%) of 336 environmental surfaces. Cycle threshold values ranged from 28.8 to 39.1, equating to 2.2×10^5 to 59 genomic copies/swab. Concomitant bacterial counts were low, suggesting that the cleaning performed by nursing and domestic staff across all eight hospitals was effective. SARS-CoV-2 RNA was detected in four of 55 air samples taken <1 m from four different patients. In all cases, the concentration of viral RNA was low and ranged from <10 to 460 genomic copies/m^3 air. Infectious virus was not recovered from any of the PCR-positive samples analysed.

Conclusions: Effective cleaning can reduce the risk of fomite (contact) transmission, but some surface types may facilitate the survival, persistence and/or dispersal of SARS-CoV-2. The presence of low or undetectable concentrations of viral RNA in the air supports current guidance on the use of specific personal protective equipment for aerosol-generating and non-aerosol-generating procedures.

* Corresponding author. Address: Biosafety, Air and Water Microbiology Group, National Infection Service, PHE Porton Down, Salisbury, UK. Tel.: +44 (0)1980 619 944.
E-mail address: ginny.moore@phe.gov.uk (G. Moore).

https://doi.org/10.1016/j.jhin.2020.11.024

Introduction

Over the course of 2020, severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), the causative agent of coronavirus disease 2019 (COVID-19), has spread rapidly across the globe and, as of 15 August 2020, had infected 21 million people and caused over 750,000 deaths [1].

The transmission of respiratory viruses can occur through inhalation of respiratory droplets (particles >5 μm in diameter) and infectious aerosols (<5 μm in diameter), and/or contact with respiratory droplets, either directly or indirectly, via contaminated surfaces. The rapid spread of COVID-19 has led many to conclude that airborne transmission must be involved [2]. However, this is widely debated and, according to current evidence, SARS-CoV-2 is primarily transmitted via droplet and contact routes, although it is acknowledged that airborne transmission could occur in specific circumstances and settings [3].

Healthcare workers (HCWs) and others on the front line are at increased risk of infection [4]. Medical aerosol-generating procedures (AGPs) [e.g. intubation, non-invasive ventilation (NIV), airway suctioning] can produce droplets <5 μm in diameter, and have been associated with increased transmission of SARS-CoV from patients to HCWs [5]. It is argued, however, that there is limited evidence to link AGPs with the transmission of respiratory infections, including COVID-19 [6]. Air samples taken during tracheostomy procedures, high-flow nasal oxygen treatment, NIV and nebulization have not contained SARS-CoV-2 RNA [7], and HCWs exposed to unrecognized cases of COVID-19 undergoing similar high-risk AGPs have not become infected [8]. Nonetheless, occupational exposure has resulted in infection [9], and it has been estimated that patient-to-HCW transmissions could be responsible for 57% of infections among HCWs in England [10]. Nosocomial transmission may also account for 20% of infections in inpatients [10], so understanding how SARS-CoV-2 is spread within the hospital setting is essential to ensure that staff are protected adequately and effective infection control measures are implemented.

Several studies, utilizing a range of air and surface sampling methods, have been undertaken to determine the presence and prevalence of SARS-CoV-2 in the healthcare environment [11—21]. The detection of viral RNA in air samples differs between studies, with some reporting widespread airborne contamination [14,18,21] but many reporting low or non-detectable concentrations [13,15,16,19], even in samples collected 10 cm from the face of positive patients [12].

Surfaces touched frequently by HCWs and/or patients are often contaminated with bacterial pathogens. Likewise, SARS-CoV-2 RNA has been detected on high-contact surfaces such as computers, bed rails and door handles. Again, the extent of this surface contamination differs between studies. Reported positivity rates range from 0.8% to >70%, with those studies reporting a higher level of airborne contamination also detecting widespread surface contamination [18,21]. In many cases, sampling was performed before routine cleaning, but the efficacy of cleaning was not assessed [11,13,15]. When comparative samples were taken, SARS-CoV-2 RNA was detected on 61% of surfaces sampled prior to cleaning but was not detected on surfaces after cleaning [17]. The proportion of surfaces contaminated with viral RNA can also differ between ward types. Some studies have detected little to no surface contamination in intensive care units (ICUs) but have detected widespread contamination within general wards [11,21]. In contrast, other studies have reported higher positivity rates within the ICU setting [14,20].

Environmental sampling can provide important information about the spread of healthcare-associated infections. However, this is resource-intensive and time-consuming; as such, many studies investigating SARS-CoV-2 and its contamination of the healthcare environment have focused on a single hospital and, in the context of the COVID-19 pandemic, a single point in time. Sampling frequency is also generally low, meaning that results often represent a snapshot in time and place.

In a rapidly evolving outbreak, there is a need to gain rapid understanding of certain trends, and whilst snapshot samples by themselves cannot be considered representative, they can, when taken together, provide useful data relating to type, level and location of environmental contamination. To date, however, differences in study setting, protocol and methodology have led to inconsistency in the results obtained, making it difficult to draw any firm conclusions relating to SARS-CoV-2 and its presence within the healthcare environment.

As part of the Public Health England (PHE) national incident response, the presence of SARS-CoV-2 in the air and on environmental surfaces around hospitalized patients, with and without respiratory symptoms, was investigated. Environmental sampling, using standard methods, was undertaken within eight acute hospital trusts in England. Trends, in terms of type and level of surface contamination and the potential for AGPs to disperse SARS-CoV-2, have been identified and these provide evidence to support current infection prevention and control guidance, including the use of personal protective equipment (PPE).

Methods

Between 3rd March 2020 and 12th May 2020, the study team visited eight hospitals (three on more than one occasion; Figure 1) and undertook environmental sampling in areas where patients infected with SARS-CoV-2 were receiving care. These included 11 negative pressure isolation rooms, 11 neutral pressure side rooms, six ICU/high-dependency unit (HDU) open cohorts and 12 non-ICU cohort bays. Whilst sampling primarily focused on 44 individual bed spaces (Table I), samples were also taken from the wider ward environment (e.g. nursing stations, patient toilet areas) and from non-COVID wards. Medical procedures being performed and obvious symptoms such as coughing were observed and recorded. Patient details (hospital number, date of admission, date of diagnosis) were collected for future correlation with clinical virology results. Details regarding routine and terminal (discharge) cleaning were also collected.

Surfaces deemed to be high-contact sites were sampled using nylon flocked swabs (Copan, Bresica, Italy) wetted with universal transport medium. Tryptone soya agar contact plates (Oxoid Ltd, Basingstoke, UK) were also used (from 27th March 2020) in order to provide an indication of general surface cleanliness. Air samples were taken using two types of active air sampler: a Coriolis μ air sampler (Bertin Instruments,

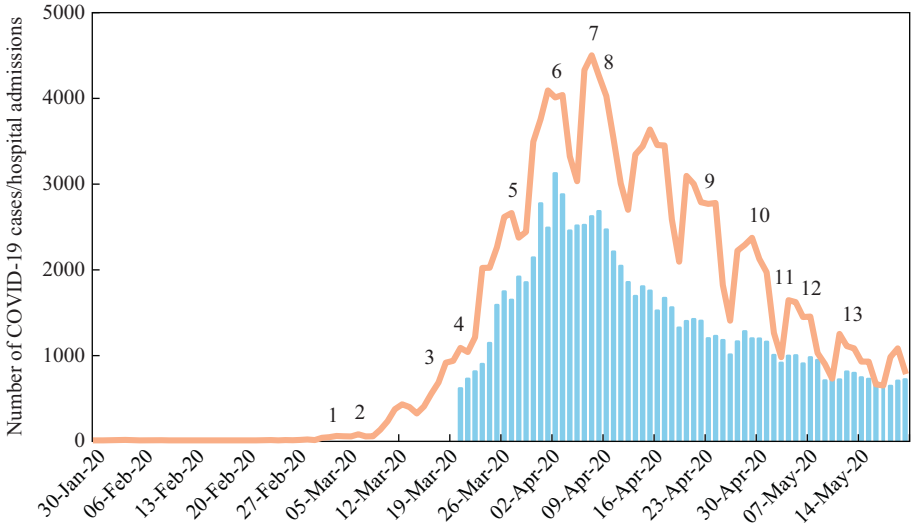

Figure 1. Sampling date in relation to the number of laboratory-confirmed cases (red line) and hospital admissions with coronavirus disease 2019 (COVID-19) (blue bars).

Montigny-le-Bretonneux, France), operating at 300 L/min and collecting into 15 mL RNase-free phosphate buffered saline (PBS); and an MD8 air sampler (Sartorius, Göttingen, Germany), operating at 50 L/min and collecting on to a gelatine membrane filter. Both samplers were positioned close to patients (<1 m) with and without respiratory symptoms and operated for 10 min. The type and duration of AGP, if any, was noted. Ambient temperature and relative humidity were monitored.

All samples were returned to PHE Porton Down. Agar contact plates were incubated at 37°C for 48 h whilst the air and swab samples (for virus detection) were frozen at -80°C prior to processing. Laboratory-based validation experiments confirmed that neither the transport nor storage conditions had an adverse effect on subsequent reverse transcription polymerase chain reaction (RT-PCR) analysis.

RNA was extracted from aliquots (140 μL) of each swab and Coriolis air sample using the QIAamp Viral RNA Mini Kit (Qiagen Ltd, Manchester, UK). The remaining Coriolis sample was concentrated to <1 mL using a Vivaspin 20 centrifugal concentrator. Each gelatine membrane was dissolved in 10 mL Minimum Essential Medium (MEM). Aliquots (140 μL) of both were extracted.

In total, 425 samples [surface swabs (N=336) and air (N=89)] were analysed for SARS-CoV-2 using RT-PCR. All samples were screened in duplicate using one of the following targets: RNA-dependent RNA polymerase (RdRp) with probe 2, envelope (E) or nucleocapsid (N) and ORF1ab (Viasure; CerTest Biotec, Zaragoza, Spain). A sample was considered positive when amplification was detected in both replicates, or 'suspect' when it was detected in a single replicate. 'Suspect' samples were re-analysed and considered positive if amplification was detected in both replicates. All positive samples were quantified using the N target on the Viasure platform. Amplification in a single replicate was considered sufficient for quantification. Samples that could not be quantified were re-extracted and quantification was re-attempted.

Virus isolation was performed on all positive samples with a cycle threshold (Ct) value <34. Vero E6 cells (Vero C1008; ATCC CRL-1586) in culture medium [MEM supplemented with GlutaMAX-I, 10% (v/v) fetal bovine serum (FBS), 1X (v/v) non-essential amino acids and 25 mM HEPES] were incubated at 37°C. Cells (1 x 10^6 cells/25 cm^2 flask) were washed with 1X PBS and inoculated with ≤1 mL environmental sample and incubated at 37°C for 1 h. Cells were washed with 1X PBS and maintained in 5 mL culture medium (4% FBS) with added antibiotic–antimycotic (4X), incubated at 37°C for 7 days and monitored for cytopathic effects (CPE). Cell monolayers that did not display CPE were subcultured up to three times, providing continuous cultures of ~30 days.

Results

Environmental sampling was undertaken in and around the bed space of 44 different patients, 35 (80%) of whom were male (Table I). Twenty-three patients had been admitted to an ICU (N=15) or a respiratory HDU (N=8), whilst 21 patients occupied beds in a non-ICU setting. These included 10 patients who, after being diagnosed early in the outbreak, were admitted to infectious diseases units. At the time of sampling, 21 patients were receiving mechanical ventilation either invasively (N=8) or non-invasively (N=13), six patients were receiving oxygen via a Venturi mask, and three patients required drugs or saline to be administered by nebulization. All patients had tested positive for SARS-CoV-2 and the median time since diagnosis was 5 days (range 1–44 days). Time since symptom onset ranged from 3 to 45 days.

In total, 336 surfaces were sampled for bacteria and/or SARS-CoV-2. The mean aerobic colony count was 1 colony-forming unit (cfu)/cm^2. Of those surfaces with more extensive bacterial contamination (>2.5 cfu/cm^2), 18 (70%) were associated with a patient's bed (bed rail, bed control, nurse call button) or mobile phone. SARS-CoV-2 RNA was detected on 30 (8.9%) of the 336 surfaces sampled (Table II). Of the 44 individual bed spaces, 10 were contaminated with viral RNA and accounted for 19 (63%) of all positive sites. In addition to

Table I
Sampling primarily focused on individual bed spaces (44 different patients)

Visit[a] (hospital)	Patient	Ward	Location	Days since symptom onset	Days since admission	Days since first SARS-CoV-2-positive swab	Notable treatment	No. of surfaces 'positive' for SARS-CoV-2 RNA	SARS-CoV-2 RNA detected in the air
1 (A)	1	ID	Single room (negative pressure)	7	5	5	None	0	No
	2	ID	Single room (negative pressure)	··	4	5	None	0	No
	3	ID	Single room (negative pressure)	··	3	··	None	0	No
	4	ICU	Single room (negative pressure)	10	4	5	O_2 (Venturi)	0	No
2 (B)	5	ID	Single room (negative pressure)	11	··	6	None	0	No
	6	ID	Single room (negative pressure)	13	··	10	None	0	No
	7	ID	Single room (negative pressure)	7	··	3	None	4	No
3 (C)	8	ID	Single room (negative pressure)	10	6	7	None	0	No
	9	ID	Single room (negative pressure)	5	3	3	O_2 (Venturi)	0	No
	10	ID	Single room (negative pressure)	8	1	1	None	0	No
	11	ID	Single room (negative pressure)	10	3	3	None	2	No
4 (D)	12	ICU	Cohort bay	4	4	4	ECMO	0	No
	13	ICU	Cohort bay	9	9	1	ECMO	0	No
	14	ICU	Cohort bay	11	10	11	ECMO	0	No
	15	ICU	Cohort bay	6	6	6	ECMO	0	No
	16	ICU	Cohort bay	12	12	11	ECMO	0	No
	17	ICU	Cohort bay	17	17	17	ECMO	0	No
5 (D)	18	GW	Cohort bay	9	5	5	O_2 (Venturi)	0	No
	19	GW	Cohort bay	6	2	1	O_2 (Venturi)	1	Yes
	20	GW	Cohort bay	8	6	6	None	0	Yes
	21	GW	Cohort bay	9	1	1	Nebulizer	0	No
6 (E)	22	GW	Side room (neutral pressure)	10	3	3	CPAP	1	No
	23	GW	Side room (neutral pressure)	4	2	2	O_2 (Venturi)	0	No
	24	ICU	Side room (neutral pressure)	17	7	7	Intubated	0	No
	25	ICU	Cohort bay	9	4	3	Intubated	0	No
7 (F)	26	HDU	Side room (neutral pressure)	10	4	4	CPAP	1	Yes
	27	HDU	Side room (neutral pressure)	8	7	7	CPAP	0	Yes
8 (G)	28	HDU	Cohort bay	12	10	9	CPAP	2	No
	29	HDU	Cohort bay	26	16	16	CPAP	0	No
	30	HDU	Cohort bay	19	12	12	O_2 (Venturi)	0	No
	31	HDU	Cohort bay	15	8	8	CPAP	2	No
9 (H)	32	ICU	Side room (neutral pressure)	9	4	4	NIV	0	No
	33	ICU	Cohort bay	7	2	2	CPAP	0	No
	34	GW	Side room (neutral pressure)	··	··	6	NIV	2	No
	35	ICU	Cohort bay	26	16	2	Nebulizer	1	No
10 (H)	36	ICU	Cohort bay	10	6	1	NIV	0	No
	37	ICU	Cohort bay	6	16	1	Nebulizer	0	No
11 (F)	38	HDU	Side room (neutral pressure)	··	··	2	CPAP	0	No
	39	HDU	Side room (neutral pressure)	··	··	4	CPAP	0	No
12 (H)	40	ICU	Side room (neutral pressure)	··	··	··	CPAP	0	No
13 (D)	41	GW	Cohort bay	··	34	34	None	0	No
	42	GW	Side room (neutral pressure)	3	3	3	None	3	No
	43	GW	Cohort bay	45	45	44	None	0	No
	44	GW	Cohort bay	14	14	13	None	0	No

SARS-CoV-2, severe acute respiratory syndrome coronavirus-2; ID, infectious diseases; ICU, intensive care unit; HDU, high-dependency unit; GW, general ward; CPAP, continuous positive airway pressure; NIV, non-invasive ventilation; ECMO, extracorporeal membrane oxygenation; O_2 (Venturi), oxygen via a Venturi mask; ··, data not available/collected.
[a] See Figure 1.

nurse call buttons (N=4), bed control panels (N=3) and mobile phones (N=3), viral RNA was also detected on bedside equipment (e.g. monitor screens, syringe drivers, computer keyboards), particularly in the ICU/HDU setting. However, in the non-ICU setting, 27% of surfaces contaminated with SARS-CoV-2 RNA were located outside the patient bed area. These included toilet door handles and portable vital signs monitors, which together accounted for 26% of all positive sites.

RT-PCR Ct values ranged from 28.8 to 39.1 which, when quantified, equated to 2.2 x 10^5 to 59 genomic copies/swab.

Table II
Severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2) RNA was detected on 30 of 336 surfaces sampled across eight acute hospital trusts. All positive samples were quantified using the N target on the Viasure platform (CerTest Biotec, Zaragoza, Spain)

Sample location		Surface sampled	Mean Ct value	Mean genomic copies/swab
General ward	Wider ward	Toilet door handle	28.80	2.19×10^5
General ward	Wider ward	Toilet door handle	38.94	1.90×10^2
General ward	Cohort bay	Toilet door handle	38.16	1.56×10^2
Infectious diseases	Isolation room	Toilet door handle	38.45	3.72×10^2
General ward	Side room	Door handle	37.95	9.94×10^1
General ward	Side room	Nurse call button	30.71	2.89×10^4
Infectious diseases	Isolation room	Nurse call button	33.30	9.80×10^3
General ward	Side room	Nurse call button	36.21	1.27×10^3
HDU	Side room	Nurse call button	36.26	1.26×10^3
HDU	Wider ward	Portable vital signs monitor	35.89	1.58×10^3
General ward	Cohort bay	Portable vital signs monitor	36.70	9.03×10^2
General ward	Cohort bay	Portable vital signs monitor	37.82	4.17×10^2
General ward	Cohort bay	Portable vital signs monitor	38.97	1.87×10^2
Infectious diseases	Isolation room	Mobile phone	30.34	7.49×10^4
General ward	Cohort bay	Mobile phone	36.98	4.15×10^2
General ward	Cohort bay	Mobile phone	37.26	3.08×10^2
General ward	Side room	Bed rail	35.56	1.01×10^3
Infectious diseases	Isolation room	Bed control	35.12	2.76×10^3
General ward	Cohort bay	Bed control	38.10	3.43×10^2
HDU	Cohort bay	Bed control	38.92	Unable to quantify[a]
HDU	Cohort bay	Monitor	35.72	8.97×10^2
HDU	Cohort bay	Monitor	36.11	7.41×10^2
HDU	Cohort bay	Syringe driver	37.02	3.64×10^2
ICU	Cohort	Bedside computer	39.11	5.91×10^1
General ward	Side room	Bedside computer	38.71	Unable to quantify[a]
Infectious diseases	Isolation room	Chair arm	37.84	4.23×10^2
General ward	Cohort bay	Curtain	37.98	3.72×10^2
General ward	Side room	Windowsill	38.05	7.63×10^1
Infectious diseases	Isolation room	Air vent	37.52	2.75×10^2
A&E	Resuscitation bay	Trolley drawer	37.89	8.66×10^1

Ct, cycle threshold; ICU, intensive care unit; HDU, high-dependency unit; A&E, accident and emergency.
[a] SARS-CoV-2 detected on initial screening but quantification was unsuccessful.

Samples with a Ct value <34 were incubated on Vero E6 cells. No CPE or decrease in Ct values across the course of three serial passages were observed, suggesting that the samples did not contain infectious virus.

Ambient temperature and relative humidity differed between wards and ranged from 21°C to 25°C and from 21% to 41%, respectively. Air samples were collected using two types of high-volume air sampler, but SARS-CoV-2 RNA was only detected in four (7.3%) of the 55 samples taken using the Coriolis μ sampler. Two of these samples were taken in two different single rooms (neutral pressure). In both cases, the sampler was positioned close (<1 m) to a patient being treated with continuous positive airway pressure (CPAP) via a mask that covered the nose and mouth. Time since diagnosis was 4 and 7 days, with both patients reporting symptoms at least 8 days prior to sampling.

Viral RNA was also detected in two air samples taken in two four-bed cohort bays. On one of these occasions, the air sampler was positioned close to a patient who was receiving oxygen via a Venturi mask. This patient had tested positive for SARS-CoV-2 the previous day with a Ct value of 21.35. The second patient, diagnosed 6 days earlier (Ct value of 17.68), was not receiving any notable treatment. However, approximately 30—40 min before sampling was undertaken, there was a 'crash call' elsewhere within the bay. There was no intubation or cardiopulmonary resuscitation, but a significant increase in staff activity was observed and may have facilitated the dispersal of airborne particles.

The total volume of each air sample was 3 m^3, and the associated Ct values ranged from 37 to 39 which, when quantified, equating to 460 to <10 genomic copies/m^3 air.

Discussion

When sampling the healthcare environment, many variables can impact the results obtained. This can make interpretation of the data difficult, particularly if a frame of reference is lacking. In this study and to provide context, agar contact plates were used to provide an aerobic bacterial colony count and an indication of surface cleanliness. Whilst no microbiological standards exist for healthcare surfaces, a benchmark of <2.5 cfu/cm^2 has been suggested [22].

'Universal' disinfectant/detergent wipes were used for damp dusting in all but one of the wards visited, where a chlorine-dioxide-based solution with disposable cloths was

used instead. Terminal cleaning was chlorine-based. SARS-CoV-2 RNA was detected on 30 (8.9%) of the 336 surfaces sampled (Table II). The proportion of surfaces positive for viral RNA differed between hospitals and ranged from 0% to 27%. This likely reflects the fact that sampling was undertaken on different types of ward occupied by different types of patient requiring different types of care and/or treatment (Table I), rather than differences in cleaning product or protocol. Overall, however, the results are similar to those of other studies [13,15,20] and suggest that, whilst SARS-CoV-2 can contaminate healthcare surfaces, widespread contamination is unlikely [17]. The bacterial load on the majority (89%) of surfaces sampled was <2.5 cfu/cm^2 suggesting that, in general and despite increased pressure on beds and workload, the routine cleaning performed by the nursing and domestic staff across all eight hospitals was effective.

Nonetheless, contamination of the healthcare environment can occur, and SARS-CoV-2 RNA was detected on the same type of surface in multiple hospitals (Table II), implying that, despite the effectiveness of the cleaning protocols employed, some types of surface could facilitate the survival, persistence and/or dispersal of SARS-CoV-2.

Patients consider the nurse call button a direct conduit to care, and many patients were observed to hold the button close even whilst dozing. Intensity and frequency of contact can increase microbial transfer from hands to surface [23], and SARS-CoV-2 RNA was detected on four (17%) of the nurse call buttons sampled. Ct values ranged from 30.8 to 36.2, equating to 2.9×10^4 to 1.2×10^3 genomic copies/swab (Table II).

To reduce the risk of transmission of SARS-CoV-2 in the hospital setting, it is recommended that surfaces such as overbed tables, bed rails and nurse call buttons should be cleaned at least twice daily [24]. The median number of bacteria recovered from nurse call buttons was 50 cfu/25cm^2 (2 cfu/cm^2). Fewer bacteria (<1 cfu/cm^2) were recovered from tables and bed rails, suggesting that these surfaces are (and can be) cleaned effectively. Heavy contamination of the nurse call button has been described previously [25], and staff should be reminded that routine cleaning should include all aspects of the patient bed. Future consideration should be given to design modification and/or improving the ability to clean nurse call buttons.

Patient mobility can contribute greatly to the spread of bacteria within a ward [25]. Similarly, SARS-CoV-2 RNA has been detected on patient contact sites outside the immediate bed space [13,17] and, in the current study, outside of cohort bays – specifically, toilet door handles. The presence of SARS-CoV-2 RNA on door handles has been reported previously [13,14,20], and the contact area between the hand and handle and the grip pressure likely facilitates transfer to and from the hands. In this study, the amount of SARS-CoV-2 RNA detected on one door handle was 2.2×10^5 genomic copies/swab, implying significant transfer from a contaminated hand. Despite this, the authors were unable to culture viable virus. The lowest genomic copy number (N gene) required to isolate virus from clinical samples is reportedly 5×10^5 genomic copies/mL [26], which is higher than the copy number in any of the environmental samples collected during this study. Subjecting the samples to multiple freeze–thaw cycles may also have impacted infectivity by disrupting virion and genome integrity [26]. Regardless, there is potential for viable virus to contaminate a single door handle and to be transferred to the hands of numerous successive contacts and, as a consequence, to other inanimate surfaces [27].

SARS-CoV-2 RNA was detected on 4.9% (7/143) and 13.8% (22/159) of surfaces sampled in the ICU/HDU and non-ICU wards, respectively. In contrast to patients admitted to cohort wards, patients in ICUs/HDUs are more likely to be bed bound and be receiving mechanical ventilation. Reduced patient mobility likely contributed to the less-frequent detection of SARS-CoV-2 in ICUs/HDUs. However, viral RNA was still detected on staff contact sites (e.g. monitor screens, syringe drivers; Table II).

Disposable gloves are an important element of PPE and can prevent the hands of HCWs from acquiring pathogens. However, during routine patient care, the glove surface itself can become contaminated. If gloves are not changed regularly and appropriately, contamination of surfaces via gloved hands can occur [19]. When caring for patients with COVID-19, particularly in the ICU/HDU setting, the requirement to don full PPE presents additional challenges in terms of preserving PPE and ensuring that staff know how to implement appropriate hand hygiene within an outbreak setting [14,19].

Non-critical medical devices (e.g. blood pressure cuffs, temperature probes) have been implicated in nosocomial infection [28]. SARS-CoV-2 was detected on four (31%) of 13 portable vital signs monitors (Table II). The highest level of viral RNA (1.6×10^3 genomic copies/swab) was detected on a fingertip pulse oximeter associated with a machine that had been removed from a single room occupied by a patient with COVID-19. The other three machines were located in cohort bays. When (or on whom) these machines were last used or when they were last cleaned was not known, and the results demonstrate the presence and/or persistence of viral RNA and not infectious virus. Nonetheless, contact pressure has been shown to significantly affect viral transfer to and from fingerpads [29]. In the absence of cleaning, fingertip pulse oximeters could facilitate transmission of SARS-CoV-2, particularly between asymptomatic and non-infected patients.

SARS-CoV-2 RNA was not detected in any air sample taken using the MD8 sampler. This may have been due to the relatively low volume of air sampled (0.5 m^3) and/or the inability to concentrate the viscous dissolved gelatine membrane. In contrast, viral RNA was detected in four (7.3%) of the high volume (3 m^3) air samples taken using the Coriolis μ sampler. It is not known what may have contributed to this airborne contamination, but two of these samples were taken <1 m from two patients receiving CPAP therapy (Table I). CPAP is considered to be an AGP. However, air samples were taken close to 11 other patients receiving NIV, seven of whom had also tested positive for COVID-19 <7 days earlier. No viral RNA was detected. The make/model of CPAP machine used to treat these two patients was not used elsewhere, and it is possible that the equipment used to deliver NIV to patients may promote the generation and/or release of aerosols [30]. How the apparatus is used or tolerated may also have an effect. During sampling, one of the two patients was observed to turn over in bed multiple times, and on one occasion, disconnected the CPAP machine to aid movement.

The dispersal distance of exhaled air from a jet nebulizer and Venturi-type oxygen mask is estimated to be 0.8 m and 0.4 m, respectively [30]. In this study, SARS-CoV-2 was not detected in any air samples collected during drug nebulization. Viral RNA was detected <1 m from one of six patients receiving

oxygen. Time since diagnosis and time since symptom onset were 1 and 6 days, respectively, which were comparatively earlier than many of the other patients (Table I). Others hypothesize that the concentration of SARS-CoV-2 in the air and/or on high-touch surfaces is highest during the first week of illness [11], suggesting that new admissions to hospital may have greater potential to transmit the virus to others. It has been suggested that placing suspected cases of COVID-19 in single rooms or bays that are fully disinfected between admissions could reduce nosocomial infection rates by 80% [10].

No formal assessment of air exchange and ventilation efficiency was performed as part of this study. It was assumed that, in accordance with UK guidelines [31], the pressure differential between isolation rooms and corridors was monitored continually (and that negative pressure was maintained), and that the air change rate in critical care areas was higher than in neutral pressure single rooms and general wards, including those areas in which SARS-CoV-2 RNA was detected in the air. Whilst this could infer the benefit of increased air exchange, in this study, air samples were taken <1 m from patients so the impact of ventilation on aerosol levels would have been minimal.

In all four cases where SARS-CoV-2 was detected in air samples, the concentration of viral RNA was low and ranged from 460 to <10 genomic copies/m^3 air. As discussed, samples containing this level of viral nucleic acid are unlikely to contain viable (infectious) virus [27], and this finding, together with the inability to detect SARS-CoV-2 RNA in all other air samples, supports current guidance on the use of specific PPE for AGPs and non-AGPs. It is acknowledged, however, that many of the procedures believed to generate aerosols and droplets were not captured during this study, and that samples were only collected over a 10-min period. Unprotected, prolonged exposure to an infected patient has been linked to transmission [9].

In a rapidly evolving outbreak situation, there is a need to gain rapid understanding of certain trends; in this case, contamination of the healthcare environment. Despite its limitations, this multi-centre study supports the findings of other studies [13,15,19,20] and should provide assurance to HCWs. SARS-CoV-2 may be present on frequently touched surfaces, but effective cleaning should reduce the risk of fomite transmission [21] and limit the concentration of SARS-CoV-2 in aerosols [17]. Recommendations to clean frequently touched surfaces regularly are warranted, and the need to clean items such as door handles, nurse call buttons and multi-use patient monitoring equipment should be emphasized. In wards caring for patients with COVID-19, viral RNA in the air was either not detected or was present at a very low concentration. These results suggest that, if worn and used correctly, the PPE recommended in the UK, including components to protect against aerosol exposures when indicated, should provide adequate protection against the potential virus exposure risks identified in this study.

Acknowledgements

The authors wish to thank the staff and patients at the hospitals that participated in this study. The views expressed in this article are those of the authors and are not necessarily those of PHE or the Department of Health and Social Care.

Conflict of interest statement
None declared.

Funding source
This multi-centre study was funded by PHE. Validation of the sampling techniques and protocol(s) was funded by the Medical Research Council as part of a larger laboratory-based study investigating environmental and airborne routes of transmission.

References

[1] World Health Organization. Coronavirus disease 2019. Geneva: WHO; 2020. Available at: https://www.who.int/emergencies/diseases/novel-coronavirus-2019 [last accessed August 2020].
[2] Morawska L, Milton DK. It is time to address airborne transmission of coronavirus disease 2019 (COVID-19). Clin Infect Dis 2020;71:2311–3.
[3] World Health Organization. Transmission of SARS-CoV-2: implications for infection prevention precautions recommendations. Geneva: WHO; 2020. Available at: https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions [last accessed August 2020].
[4] Baker MG, Peckham TK, Seixas NS. Estimating the burden of United States workers exposed to infection or disease: a key factor in containing risk of COVID-19 infection. PLoS One 2020;15:e0232452.
[5] Tran K, Cimon K, Severn M, Pessoa-Silva CL, Conly J. Aerosol generating procedures and risk of transmission of acute respiratory infections to healthcare workers: a systematic review. PLoS One 2012;7:e35797.
[6] Harding H, Broom A, Broom J. Aerosol-generating procedures and infective risk to healthcare workers: SARS-CoV-2 — the limits of the evidence. J Hosp Infect 2020;105:717–25.
[7] Cai Y, Wu X, Zhang Y, Xia J, Lin M, Feng Y, et al. Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) contamination in air and environment in temporary COVID-19 ICU wards. 2020. https://doi.org/10.21203/rs.3.rs-21384/v1.
[8] Wong SCY, Kwong RT, Wu TC, Chan JWM, Chu MY, Lee SY, et al. Risk of nosocomial transmission of coronavirus disease 2019: an experience in a general ward setting in Hong Kong. J Hosp Infect 2020;105:119–27.
[9] Heinzerling A, Stuckey MJ, Scheuer T, Xu K, Perkins KM, Resseger H, et al. Transmission of COVID-19 to health care personnel during exposures to a hospitalized patient — Solano County, California, February 2020. MMWR Morb Mortal Wkly Rep 2020;69:472–6.
[10] Evans S, Agnew E, Vynnycky E, Robotham JV. The impact of testing and infection prevention and control strategies on within-hospital transmission dynamics of COVID-19 in English hospitals. medRxiv 2020. https://doi.org/10.1101/2020.05.12.20095562.
[11] Chia PY, Coleman KK, Tan YK, Ong SWX, Gum M, Lau SK, et al. Detection of air and surface contamination by SARS-CoV-2 in hospital rooms of infected patients. Nat Commun 2020;11:2800.
[12] Cheng VCC, Wong SC, Chen JHK, Yip CCY, Chuang VWM, Tsang OTY, et al. Escalating infection control response to the rapidly evolving epidemiology of the coronavirus disease 2019 (COVID-19) due to SARS-CoV-2 in Hong Kong. Infect Control Hosp Epidemiol 2020;41:493–8.
[13] Ding Z, Qian H, Xu B, Huang Y, Miao T, Yen HL, et al. Toilets dominate environmental detection of SARS-CoV-2 virus in a hospital. Sci Total Environ 2021;753:141710.
[14] Guo ZD, Wang ZY, Zhang SF, Li X, Li L, Li C, et al. Aerosol and surface distribution of severe acute respiratory syndrome coronavirus 2 in hospital wards, Wuhan, China, 2020. Emerg Infect Dis 2020;26:1583–91.

[15] Jiang Y, Wang H, Chen Y, He J, Chen L, Liu Y, et al. Clinical data on hospital environmental hygiene monitoring and medical staff protection during the coronavirus disease 2019 outbreak. medRxiv 2020. https://doi.org/10.1101/2020.02.25.20028043.
[16] Liu Y, Ning Z, Chen Y, Guo M, Liu Y, Gali NK, et al. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. Nature 2020;582:557—60.
[17] 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.
[18] Santarpia JL, Rivera DN, Herrera VL, Morwitzer MJ, Creager HM, Santarpia GW, et al. Aerosol and surface contamination of SARS-CoV-2 observed in quarantine and isolation care. Sci Rep 2020;10:12732.
[19] Wu S, Wang Y, Jin X, Tian J, Liu J, Mao Y. Environmental contamination by SARS-CoV-2 in a designated hospital for coronavirus disease 2019. Am J Infect Control 2020;48:910—4.
[20] 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.
[21] Zhou J, Otter JA, Price JR, Cimpeanu C, Garcia DM, Kinross J, et al. Investigating SARS-CoV-2 surface and air contamination in an acute healthcare setting during the peak of the COVID-19 pandemic in London. Clin Infect Dis 2020. https://doi.org/10.1093/cid/ciaa905.
[22] White LF, Dancer SJ, Robertson C, McDonald J. Are hygiene standards useful in assessing infection risk? Am J Infect Control 2008;36:381—4.
[23] Wolfensberger A, Clack L, Kuster SP, Passerini S, Mody L, Chopra V, et al. Transfer of pathogens to and from patients, healthcare providers and medical devices during care activity — a systematic review and meta-analysis. Infect Control Hosp Epidemiol 2018;39:1093—107.
[24] Public Health England. COVID-19: infection prevention and control guidance. London: PHE; 2020. Available at: https://www.gov.uk/government/publications/wuhan-novel-coronavirus-infection-prevention-and-control [last accessed August 2020].
[25] Moore G, Muzslay M, Wilson APR. The type, level and distribution of microorganisms within the ward environment: a zonal analysis of an intensive care unit and a gastrointestinal surgical ward. Infect Control Hosp Epidemiol 2013;34:500—6.
[26] Huang CG, Lee KM, Hsiao MJ, Yang SL, Huang PN, Gong YN, et al. Culture-based virus isolation to evaluate potential infectivity of clinical specimens tested for COVID-19. J Clin Microbiol 2020;58:e01068-20.
[27] Rheinbaben F, Schünemann S, Groß T, Wolff MH. Transmission of viruses via contact in a household setting: experiments using bacteriophage ϕX174 as a model virus. J Hosp Infect 2000;46:61—6.
[28] Eyre DW, Sheppard AE, Madder H, Moir I, Moroney R, Quan TP, et al. A *Candida auris* outbreak and its control in an intensive care setting. N Engl J Med 2018;379:1322—31.
[29] Mbithi JN, Springthorpe VS, Boulet JR, Sattar SA. Survival of hepatitis A virus on human hands and its transfer on contact with animate and inanimate surfaces. J Clin Microbiol 1992;30:757—63.
[30] Hui DSC, Chan MTV, Chow B. Aerosol dispersion during various respiratory therapies: a risk assessment model of nosocomial infection to healthcare workers. Hong Kong Med J 2014;20(Suppl. 4):9—13.
[31] Department of Health/Estates and Facilities Division. Health technical memorandum 03-01: specialised ventilation for healthcare premises. Part A — design and installation. London: The Stationery Office; 2007.