



Assessment of Air Contamination by SARS-CoV-2 in Hospital Settings

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Abstract

IMPORTANCE Controversy remains regarding the transmission routes of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2).

OBJECTIVE To review current evidence on air contamination with SARS-CoV-2 in hospital settings and the factors associated with contamination, including viral load and particle size.

EVIDENCE REVIEW The MEDLINE, Embase, and Web of Science databases were systematically queried for original English-language articles detailing SARS-CoV-2 air contamination in hospital settings between January 1 and October 27, 2020. This study was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) guidelines. The positivity rate of SARS-CoV-2 viral RNA and culture were described and compared according to the setting, clinical context, air ventilation system, and distance from patients. The SARS-CoV-2 RNA concentrations in copies per meter cubed of air were pooled, and their distribution was described by hospital areas. Particle sizes and SARS-CoV-2 RNA concentrations in copies or median tissue culture infectious dose (TCID50) per meter cubed were analyzed after categorization as less than 1 μm , from 1 to 4 μm , and greater than 4 μm .

FINDINGS Among 2284 records identified, 24 cross-sectional observational studies were included in the review. Overall, 82 of 471 air samples (17.4%) from close patient environments were positive for SARS-CoV-2 RNA, with a significantly higher positivity rate in intensive care unit settings (intensive care unit, 27 of 107 [25.2%] vs non-intensive care unit, 39 of 364 [10.7%]; $P < .001$). There was no difference according to the distance from patients (≤ 1 m, 3 of 118 [2.5%] vs >1.5 m, 13 of 236 [5.5%]; $P = .22$). The positivity rate was 5 of 21 air samples (23.8%) in toilets, 20 of 242 (8.3%) in clinical areas, 15 of 122 (12.3%) in staff areas, and 14 of 42 (33.3%) in public areas. A total of 81 viral cultures were performed across 5 studies, and 7 (8.6%) from 2 studies were positive, all from close patient environments. The median (interquartile range) SARS-CoV-2 RNA concentrations varied from 1.0×10^3 copies/ m^3 (0.4×10^3 to 3.1×10^3 copies/ m^3) in clinical areas to 9.7×10^3 copies/ m^3 (5.1×10^3 to 14.3×10^3 copies/ m^3) in the air of toilets or bathrooms. Protective equipment removal and patient rooms had high concentrations per titer of SARS-CoV-2 (varying from 0.9×10^3 to 40×10^3 copies/ m^3 and 3.8×10^3 to 7.2×10^3 TCID50/ m^3), with aerosol size distributions that showed peaks in the region of particle size less than 1 μm ; staff offices had peaks in the region of particle size greater than 4 μm .

CONCLUSIONS AND RELEVANCE In this systematic review, the air close to and distant from patients with coronavirus disease 2019 was frequently contaminated with SARS-CoV-2 RNA; however, few of these samples contained viable viruses. High viral loads found in toilets and bathrooms, staff areas, and public hallways suggest that these areas should be carefully considered.

JAMA Network Open. 2020;3(12):e2033232. doi:10.1001/jamanetworkopen.2020.33232

Key Points

Question What is the level of air contamination from severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in different hospital areas, and what factors are associated with contamination?

Findings In this systematic review of 24 studies, 17% of air sampled from close patient environments was positive for SARS-CoV-2 RNA, with viability of the virus found in 9% of cultures.

Meaning In this study, air both close to and distant from patients with coronavirus disease 2019 was frequently contaminated with SARS-CoV-2 RNA; however, few of these samples contained viable viruses.

+ Supplemental content

Author affiliations and article information are listed at the end of this article.

Introduction

The transmission modes of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) remain controversial.¹ At the emerging stage of the pandemic, many countries implemented high-level precautions, including airborne and contact precautions, to prevent the spread from patients to health care professionals (HCPs).² An emerging understanding of SARS-CoV-2 epidemiology, which is primarily transmitted from person to person through droplets, led to recommendations for droplet precautions to care for patients hospitalized with coronavirus disease 2019 (COVID-19).³ However, separating transmission dynamics into the dichotomy of droplet vs airborne transmission is probably simplistic. In some circumstances, aerosol particles (<5 µm in diameter) may be produced by individuals with infection and travel more than the 1.50 m commonly used to define transmission routes and contaminate surfaces further away.⁴

Environmental airflow may ease the spread of large particles.⁵ The switch from airborne to droplet precautions, combined with a global shortage of face masks and respirators, fed the controversy regarding respiratory protections to prevent transmission of SARS-CoV-2.^{6,7} This generated a mistrust in personal protective equipment (PPE), particularly regarding surgical masks and their ability to protect HCPs from SARS-CoV-2 transmission. As the World Health Organization recently acknowledged, airborne transmission could occur in crowded and closed environments in the community. This raises the question of whether similar transmission could occur in the hospital.¹ Viral contamination of the air surrounding patients with COVID-19 and HCPs in hospitals may have serious implications for outbreak control strategies. We reviewed the current evidence on air contamination with SARS-CoV-2 in hospital settings, the viral load, and associated factors to better assess the risk of cross-transmission of COVID-19 among HCPs and patients.

Methods

Search Strategy

We performed a systematic search of MEDLINE via PubMed, Embase, and Web of Science on October 27, 2020, with terms covering COVID-19 and air contamination in hospital settings in articles published between January 1 and October 27, 2020 (eAppendix in the [Supplement](#)). Because of potential delays in indexing of databases, we also searched selected infectious disease journals (eAppendix in the [Supplement](#)). We also searched some preprint servers, including BioRxiv and MedRxiv as well as the reference lists of identified articles to find reports of additional studies. We conducted this scoping systematic review in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analyses ([PRISMA](#)) extension for scoping reviews (eTable in the [Supplement](#)).

Inclusion and Exclusion Criteria

We included all literature related to COVID-19 published in English between January 1, 2020, and October 27, 2020, without restrictions, including original articles, research letters, and comments. We excluded experimental methods and studies performed in dental and primary care settings.

Article Selection and Data Extraction

Two reviewers (G.B. and N.P.S.) screened all titles, abstracts, and full-text articles independently and resolved disagreements by consensus or consultation with a third reviewer (J.C.L.). The following information was then extracted: (1) setting, (2) clinical context, (3) ventilation system, (4) number of air samples performed, (5) sampling method, (6) location of sampler and distance from patients, (7) duration and air volume sampled, (8) method of SARS-CoV-2 search, (9) positivity rate, (10) viral load (SARS-CoV-2 RNA copies per m³), and (11) viral culture results.

Statistical Analysis

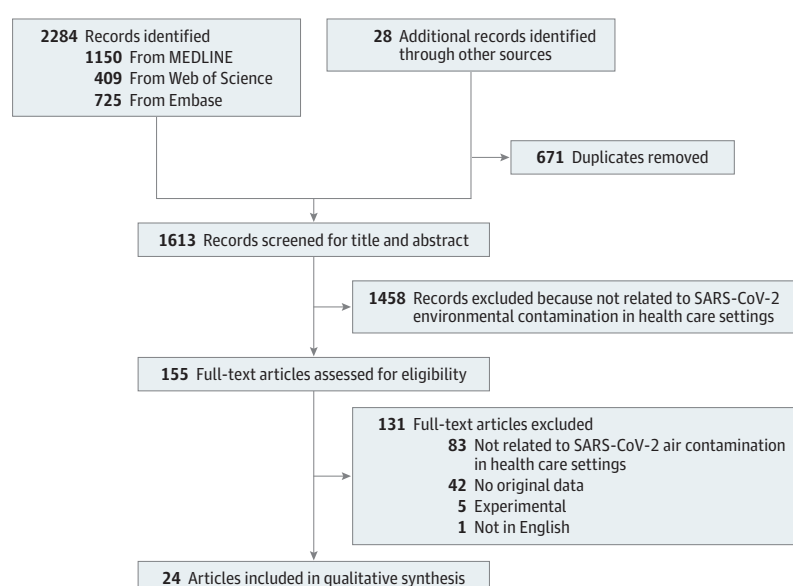
We conducted a descriptive analysis of the characteristics of the included literature. We described the setting, patient clinical contexts, ventilation, air sampling and SARS-CoV-2 search methods, and the qualitative and quantitative results according to settings and the hospital area. We categorized the location of air sampling in 5 classes of hospital areas: close patient environments (ie, patient rooms or bays), toilet or bathroom, clinical areas (ie, workstations, anterooms or buffer rooms, corridors, and other spaces in the clinical unit), staff areas (ie, changing rooms, staff rooms including office, meeting rooms, dining rooms, and other staff areas), public areas (hallways and other indoor and outdoor public areas). When possible, we also classified the setting as intensive care unit (ICU) vs non-ICU; the clinical context as severe or critical vs mild, moderate, or asymptomatic; the ventilation system as negative pressure vs natural or mechanical; and the distance from patients as 1 m or less vs greater than 1 to 5 m. The positivity rate of viral RNA and the viral culture were pooled, described, and compared according to categories using a χ^2 test. The results of SARS-CoV-2 RNA concentrations in copies per meter cubed of air were pooled, and their distribution was described by hospital areas. The Kruskal-Wallis test was used to compare the nonnormally distributed RNA concentrations across hospital areas. A 2-tailed $P < .05$ was considered statistically significant. Studies presenting the combined results of particle sizes and SARS-CoV-2 RNA concentrations in copies or median tissue culture infectious dose (TCID₅₀) per meter cubed were analyzed after categorization of sizes as less than 1 μm , 1 to 4 μm , and greater than 4 μm , the thresholds available across the 3 studies.

Results

Search Results

We identified 2284 records, 671 (29.4%) of which were excluded as duplicates. Title and abstract screening were conducted for the remaining 1613 articles, 1458 (90.4%) of which were excluded because they were unrelated to air contamination by SARS-CoV-2 in hospital settings. We retrieved the full text of the 155 remaining articles. After further screening and supplementary searching of articles published or posted between January 1 and October 27, 2020, we identified an additional article, and a total of 24 articles were included in the review (**Figure 1**).^{3,8-30}

Figure 1. Flowchart of the Search Strategy



Characteristics of Included Articles and Studies

Of the 24 included studies, all were cross-sectional observational studies. Ten studies (41.7%) were from China,^{9-11,15,18-20,22,25,29} and the remaining were from the United States (4 [16.7%]),^{12,13,26,30} Hong Kong (2 [8.3%]),^{14,21} Korea (2 [8.3%]),^{24,27} Singapore (2 [8.3%]),^{3,16} Iran (2 [8.3%]),^{8,28} the United Kingdom (1 [4.2%]),¹⁹ and Italy (1 [4.2%]).²³ Of all included articles and studies, 20 (83.3%)^{3,8-11,14-17,20-30} were published in peer-reviewed journals, and 4 (16.7%)^{12,13,17,18} were posted on preprint servers.

A total of 23 studies (95.8%)^{3,8-19,21-30} sampled the air in the close patient environments, 12 (50.0%)^{3,9-12,17-20,23,24,28} in clinical areas away from patients, 8 (33.3%)^{9-13,19,23,29} in staff areas, 6 (25.0%)^{3,9,17-19,22} in toilets and/or bathrooms, and 6 (33.3%)^{9,10,12,17,20,28} in public areas (**Table 1**). The clinical context of patients hospitalized in the targeted areas was detailed in 18 studies, of which 10 (50.0%)^{8-11,22,23,25,27-29} were performed in units hospitalizing patients with severe or critical illness, 11 (61.1%)^{3,11,12,14-16,24-26,28,30} with patients with mild, moderate, or asymptomatic disease, and 4 studies (22.2%)^{11,14,25,28} with both categories.

A median of 24 air samples were collected per study, varying from 2 to 160 samples. In close patient environments, a median of 10 air samples (range, 1-160) were performed, 2.5 (range, 1-7) in toilets and/or bathrooms, 11 (range, 1-69) in clinical areas, 9 (range, 1-45) in staff areas, and 10 (1-12) in public areas. Overall, 19 studies (79.2%)^{3,8-17,19,22,23,25,26,28,30} sampled the air from non-ICU patient rooms, and 12 (50.0%)^{8-11,18,19,22,23,25,27-29} in ICU rooms. Among the 19 studies^{3,8-12,14,15,18,19,21,23-30} with the available information, 360 samples were taken in patient rooms with negative pressure and 66 with natural or mechanical ventilation. When pooling the 19 studies^{3,8,10-12,14-16,18,19,22,24-30} detailing the distance from patient, a total of 118 samples were performed 1 m or less from patients and 236 from greater than 1 to 5 m.

All included studies used reverse transcription-polymerase chain reaction (RT-PCR) to identify SARS-CoV-2 RNA, with a quantification of RNA copies per meters cubed or per liter in 8 studies (33.3%). One study⁹ used a droplet digital RT-PCR method. The viral culture was planned in the methods of 6 studies (20.8%)^{12,13,17,26,27,30} but performed in 5 (12.5%) of them.^{12,13,17,26,30} The remaining did not perform viral culture due to negative RT-PCR results. Three studies (12.5%)^{9,13,16} assessed the particle size in parallel to RNA concentration or viral titer.

RT-PCR and Culture Results by Hospital Areas

A total of 893 air samples were performed across the 24 studies reviewed, including 471 (52.7%) in close patient environments, 237 (26.5%) in clinical areas, 122 (13.7%) in staff areas, 42 (4.7%) in public areas, and 21 (2.4%) in toilets and/or bathrooms (**Table 2**). Overall, 82 of 471 air samples (17.4%) from close patient environments were positive for SARS-CoV-2 RNA. Among the 107 samples performed in ICU rooms, 27 (25.2%) were positive vs 39 of 364 (10.7%) in non-ICU rooms ($P < .001$). The air RNA positivity rate was 47 of 360 (13.1%) in rooms with negative pressure and 6 of 66 (9.1%) in rooms with natural or mechanical ventilation. In toilets and/or bathrooms, 5 of 21 samples (23.8%) samples were positive. In clinical areas, the overall positivity rate was 8.4% (20 of 237), varying from 0 of 64 in anterooms or buffer rooms to 6 of 22 (27.2%) at workstations ($P < .001$). In staff areas, 15 of 122 samples (12.3%) were positive, with 5 of 26 (19.2%) in staff meeting rooms vs 2 of 51 (3.9%) in changing rooms and 8 of 45 (17.8%) in other types of staff rooms ($P = .06$). Overall, 14 of 42 samples (33.3%) in public areas were positive, with 9 of 16 (56.3%) in hallways, 2 of 18 (11.1%) in other indoor areas, and 3 of 8 (37.5%) in outdoor public areas ($P = .01$). A total of 81 viral cultures were performed across 3 studies (47 samples [58.0%] from close patient environment, 2 [2.5%] in toilets/bathroom, 13 [16.0%] in clinical areas, 4 [4.9%] in staff areas, and 15 [18.5%] in public areas). Two studies^{13,30} described positive viral cultures, both from the close patient environment (3 of 39 [7.7%];¹³ and 4 of 4 [100%]³⁰) in a non-ICU setting.

Table 1. Summary of Included Studies Evaluating the Air Contamination With SARS-CoV-2 in the Hospital Environment

Source	Setting	Clinical context	Location	Air ventilation	Distance from patients, m	Duration (air volume per sample, L)	SARS-CoV-2			
							Microbiology	Viral load, RNA copies/m ³	Positivity, No./total No. (%)	
ICU patient environments										
Liu et al., ⁹ 2020	ICU	Severe	IR	Negative pressure	ND	5 h-7 d (1500-50 400)	ddPCR	31 113	NA	2/3 (66)
Faridi et al., ⁸ 2020	ICU	Severe	Multiple-bed room	Mechanical or natural	2-5	60 min (90)	RT-PCR; Ct, 38	NA	NA	0/9
Guo et al., ¹¹ 2020	ICU	Severe	IRs, bay room	12 Air supplies; 16 air discharges/h	ND	30 min (300)	RT-qPCR	Mean: 3.8 near air outlet; 1.4 near patients	NA	13/32 (41); Ct, 35.7 and 44.4
Lei et al., ²² 2020	ICU	Critical	Multiple-bed room	ND	1	4 h (1260)	RT-qPCR	NA	NA	0/1; Ct, 41.5
Li et al., ¹⁰ 2020	ICU	Severe	Multiple-bed room; 3 beds	12 Air supplies; 16 air discharges/h	1-5	5 h (21 600)	RT-PCR; Ct, <37 and >40	NA	NA	0/9
Zhou et al., ¹⁹ 2020	ICU	ND	ND	Natural ventilation	1-5	40 min (600-16 000)	RT-qPCR; Ct, 39.5	NP	NA	0/5
Razzini et al., ²³ 2020	ICU	2 Patients intubated, 1 patient not intubated	Multiple-bed room	Negative pressure	ND	40 min (2000)	RT-PCR	Mean, 22.7	NA	12/12 (100)
Ding et al., ¹⁸ 2020	ICU	Mild	IRs	Negative pressure	0.5	20-30 min (300-10 000)	RT-PCR	NA	NA	0/26
Ahn et al., ²⁷ 2020	ICU	3 Patients intubated	IRs	Negative pressure and 12 air changes/h	1	20 min (250)	rRT-PCR; Ct, <35; viral culture	NA	NP	0/3
Kenarhoohi et al., ²⁸ 2020	ICU	6 Critical	Multiple beds; 10 patients	Natural	≥2	180 min (2160)	RT-PCR; Ct, <40	NA	NA	0/6
Jin et al., ²⁹ 2020	ICU	1 Critical	IR	Negative pressure	0.5	15 min (6000)	qRT-PCR; Ct, <40	NA	NA	1/1 (100)
Tan et al., ²⁵ 2020	ICU	9 Severe or critical	Single room	Natural ventilation	1	60 min (300)	RT-PCR	NA	NA	1/10 (10)
Non-ICU patient environments										
Liu et al., ⁹ 2020	GW	Severe	4 Single and 1 multiple-bed room; 2 beds	Negative pressure	ND	5 h (1500)	ddPCR	0	NA	0/2
Faridi et al., ⁸ 2020	GW	Severe	Multiple-bed room; 2-9 beds	Mechanical or natural	2-5	60 min (90)	RT-PCR; Ct, 38	NA	NA	0/1
Ong et al., ³ 2020	GW	Moderate or mild	IRs	12 Air exchanges/h	<1 and 2-5	4 h (3600)	RT-PCR; Ct, 45	ND	NA	0/18
Santarpia et al., ¹² 2020	IW	Mild	IRs	Negative pressure	Bedside table or desk	15 min (750)	RT-PCR; Ct, 45; viral culture	NA	0/10	0/18
Guo et al., ¹¹ 2020	GW	Mild	Single bay room	8 Air supplies and 12 air discharges/h	Near patients, near air outlet	30 min (300)	RT-qPCR	0.68 near air outlet	NA	2/16 (12.5)
Chia et al., ¹⁶ 2020	GW	Mild or asymptomatic	IRs	12 Air changes/h	1 and 2.1	4 h (840)	RT-PCR	Mean (range), 1.3 (0.916-2)	NA	4/10 (40)
Lei et al., ²² 2020	IW	Critical	ND	ND	1	4 h (1260)	RT-qPCR	NA	NA	1/1 (100); Ct, 44.6
Cheng et al., ¹⁴ 2020	IW	Severe, mild, asymptomatic	IRs	12 Air changes/h, shelter	0.1	20 min (1000)	RT-PCR	0	NA	0/6
Cheng et al., ²¹ 2020	IW	ND	IRs	Negative pressure	0.1	5 min (1000)	RT-PCR	0	NA	0/8
Zhou et al., ¹⁷ 2020	IW and GW	ND	ND	ND	ND	ND (1000)	RT-qPCR; Ct, <40.4; viral culture	mean (range), 1.17 (0.16-7.04)	0/12	6/12 (50)
Li et al., ¹⁰ 2020	IW	Severe	Multiple-bed room; 3 beds	8 Air supplies; 12 air discharges/h	1-5	5 h (21 600)	RT-PCR; Ct, <37 and >40	NA	NA	0/18

(continued)

Table 1. Summary of Included Studies Evaluating the Air Contamination With SARS-CoV-2 in the Hospital Environment (continued)

Source	Setting	Clinical context	Location	Air ventilation	Distance from patients, m	Duration (air volume per sample, L)	SARS-CoV-2		
							Microbiology	Viral load, RNA copies/m ³	Positivity, No./total No. (%)
Wei et al, ¹⁵ 2020	IW	Mild or asymptomatic	IRs	12 Air exchanges/h	0.6	15 min (1500)	RT-PCR; Ct, <35	NA	0/6
Zhou et al, ¹⁹ 2020	GW	ND	IRs	Natural	1-5	40 min (600-16 000)	RT-PCR; Ct, <39.5	NA	0/16
Santarpi et al, ¹³ 2020	ND	ND	IRs	ND	ND	30 min (ND)	RT-qPCR; viral culture	2.41 TCID50/cm ³ of air	18/18 (100)
Kim et al, ²⁴ 2020	IW and GW	7 Mild and 1 asymptomatic	IRs; 5-bed room	IR with 15 air changes/h; IR without negative pressure; room without negative air pressure	2	20 min (1000)	rRT-PCR; Ct, <35	NA	0/32
Tan et al, ²⁵ 2020	IW	15 Mild	3 Patients per room	Natural ventilation	1	60 min (300)	RT-PCR	NA	1/2 (50)
Binder et al, ²⁶ 2020	IW	4 Asymptomatic; 16 mild	Single rooms	14 Air exchange/h	1, 1.4, 2.2, and 3.2	240 min (840)	RT-PCR; viral culture	NA	3/160 (1.9)
Kenarhoohi et al, ²⁸ 2020	Laboratory, radiology, internal medicine, emergency	5 Mild and 1 suspected case	Multiple rooms, 18-30 patients	Natural	≥2	180 min (2160)	RT-PCR; Ct, <40	NA	0/6
Lednicki et al, ³⁰ 2020	IW	2 Patients with mild disease	IRs	6 Air changes/h	2-4.8	180 min (ND)	RT-PCR; viral culture	Mean (range), 46 (16-94); 2-74 TCID50 U/L of air	4/4 (100)
Toilet or bathroom									
Liu et al, ⁹ 2020	Non-ICU	NA	Patient mobile toilet room	No ventilation	NA	20 h (6000)	ddPCR	1	1/1 (100)
Ong et al, ³ 2020	GW	NA	IRs	ND	NA	8 h (2400)	RT-PCR; Ct, 45	NA	0/6
Lei et al, ²² 2020	IW	NA	Patient bathroom	ND	NA	4 h (1680)	RT-qPCR	NA	2/2 (100); Ct, 35.6, 35.5
Zhou et al, ¹⁷ 2020	Cohort ward	NA	Outside patient bay, in the ward	ND	NA	ND (1000)	RT-qPCR; Ct, <40.4; viral culture	0.464	1/2 (50)
Zhou et al, ¹⁹ 2020	Fever clinic	NA	In the ward	Natural	NA	40 (16 000)	RT-PCR; Ct, <39.5	NA	0/3
Ding et al, ¹⁸ 2020	4 ICU	NA	Patient bathroom	4 With negative pressure	NA	20-30 min (420-10 000)	RT-PCR	NA	1/7 (14)
Clinical areas									
Liu et al, ⁹ 2020	Non-ICU	ND	Workstation	Natural	ND	320-1200 min (1600-6000)	ddPCR	0, 1, 1, 5, 9	4/5 (80)
Ong et al, ³ 2020	ICU and non-ICU	ND	Corridor, anteroom	NA	ND	15 min (3000); 480 min (2400)	RT-PCR; Ct, 45	NA	0/12
Santarpi et al, ¹² 2020	ND	Mild	Floor adjacent to rooms	NA	>6 ft	15 min (750)	RT-PCR; Ct, 45; viral culture	2.58, 3.76	2/3 (66)
Guo et al, ¹¹ 2020	ICU, GW	1 Severe, ND	Near office, pharmacy, nurse station, corridor, and buffer room	ND	ND	30 min (27 000-72 000)	RT-qPCR	0.54	1/34 (3)
Wu et al, ²⁰ 2020	1 ICU	Ward and various clinical rooms	ND	ND	ND	30 min (ND)	RT-PCR; Ct, 43	NA	0/69
Zhou et al, ¹⁷ 2020	ICU and non-ICU	ND	Nurse station, ward, ambulatory waiting room, Resus bay, CPAP unit	ND	ND	ND (1000)	RT-qPCR; Ct, <40.4; viral culture	0.404, 0.035, 1.922, 0.031	4/10 (40)

(continued)

Table 1. Summary of Included Studies Evaluating the Air Contamination With SARS-CoV-2 in the Hospital Environment (continued)

Source	Setting	Clinical context	Location	Air ventilation	Distance from patients, m	Duration (air volume per sample, L)	SARS-CoV-2			
							Microbiology	Viral load, RNA copies/m ³	Viral culture, No./total No. (%)	Positivity, No./total No. (%)
Li et al, ¹⁰ 2020	ICU and non-ICU	Severe	Corridor, clinic, buffer room	1 With negative pressure	ND	250 min (21 600)	RT-PCR; Ct, <37 and >40	NA	NA	0/45
Zhou et al, ¹⁹ 2020	ND	ND	Corridor and preroom	Natural	ND	40 min (16 000)	RT-PCR; Ct, <39.5	NA	NA	0/18
Razzini et al, ²³ 2020	ND	ND	Corridor	ND	ND	40 min (16 000)	RT-PCR	NA	NA	8/8 (100); Ct, 31.1
Ding et al, ¹⁸ 2020	IW	3 Mild, ND for others	Ward, corridor, nurse station, and storage room	3 Negative pressure, ND for others	ND	20–30 (300–10 000)	RT-PCR	NA	NA	1/12 (8); Ct, 37.8
Kim et al, ²⁴ 2020	IW and GW	7 Mild and 1 asymptomatic	5 Anterooms, regardless of room type	ND	ND	20 min (1000)	RT-PCR; Ct, <35	NA	NA	0/20
Kenarhoohi et al, ²⁸ 2020	ICU entrance	NA	NA	Natural	NA	180 min (2160)	RT-PCR; Ct, <40	NA	NA	0/1
Staff areas										
Liu et al, ⁹ 2020	ICU	NA	Changing, meeting, and dining rooms, warehouse	Natural and/or mechanical, small air purifier	NA	300–1200 min (1500–6000)	ddPCR	Mean, 13.8	NA	10/13 (77)
Santarpia et al, ¹² 2020	IW	NA	Personal air sample	NA	ND	NA	RT-PCR; Ct, 45	Mean, 20.037	NA	4/4 (100)
Guo et al, ¹¹ 2020	ICU and GW	NA	Dressing rooms	NA	ND	30 min (45 000–108 000)	RT-qPCR	NA	NA	0/36
Santarpia et al, ¹³ 2020	ND	NA	Staff and changing rooms	NA	ND	ND (1000)	RT-qPCR; Ct, <40.4; viral culture	0.249	0/4	1/4 (25)
Li et al, ¹⁰ 2020	ICU and IW	NA	Conference room and clean zone	2/3 With negative pressure	ND	270–540 min (21 600–43 200)	RT-PCR; Ct, <37 and >40	NA	NA	0/45
Zhou et al, ¹⁹ 2020	ND	NA	Waste storage	Natural	ND	40 min (16 000)	RT-PCR; Ct, <39.5	NA	NA	0/2
Razzini et al, ²³ 2020	ND	NA	Changing and locker rooms	NA	ND	40 min (8000–14 000)	RT-PCR	ND	NA	0/17
Jin et al, ²⁹ 2020	ICU	NA	Changing room	Negative pressure	Middle	15 min (6000)	qRT-PCR; Ct, <40	NA	NA	0/1
Public areas										
Liu et al, ⁹ 2020	NA	NA	Pharmacy, hall, office, store, and supermarket	Mechanical, natural, outdoor	NA	300–1000 min (1500–5000)	ddPCR	3, 7, 11, 3	NA	4/11 (36)
Santarpia et al, ¹² 2020	NA	NA	Hallway	ND	NA	ND (ND)	RT-PCR; Ct, 45; viral culture	0.979–8.688	0/12	8/12 (67)
Wu et al, ²⁰ 2020	NA	NA	Public area	ND	NA	30 min (ND)	RT-PCR; Ct, 43	NA	NA	0/6
Zhou et al, ¹⁷ 2020	NA	NA	Main entrance, toilet entrance, and lift area	ND	NA	ND (1000)	RT-qPCR; Ct, <40.4; viral culture	1.574, 1.545	0/3	2/3 (67)
Li et al, ¹⁰ 2020	NA	NA	Public area	ND	NA	270 min (21 600)	RT-PCR; Ct, <37 and >40	NA	NA	0/9
Kenarhoohi et al, ²⁸ 2020	Hospital entrance	NA	NA	Natural	NA	180 min (2160)	RT-PCR; Ct, <40	NA	NA	0/1

Abbreviations: CPAP, continuous positive airway pressure; Ct, cycle threshold; ddPCR, droplet-digital polymerase chain reaction; GW, general ward; ICU, intensive care unit; IW, isolation room; LW, isolation ward; NA, not applicable; ND, not detailed; NP, not performed; RT-PCR, reverse transcription–polymerase chain reaction; RT-qPCR, quantitative reverse transcription–polymerase chain reaction; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2.

SARS-CoV-2 RNA Concentrations in Copies per Meters Cubed of Air, According to Hospital Areas

Among studies with SARS-CoV-2 positive air samples^{11-13,16,17,23,30} that performed a quantitative RT-PCR, the median (interquartile range [IQR]) RNA concentrations varied from 1.0×10^3 copies/m³ (0.4×10^3 to 3.1×10^3) in clinical areas to 9.7×10^3 (5.1×10^3 to 14.3×10^3) in the air of toilets and/or bathrooms (**Figure 2**). The median (IQR) concentration found in close patients environments was 3.8×10^3 (1.2×10^3 to 3.3×10^3) copies/m³ ($P < .001$). Among the 3 studies^{9,13,16} that assessed the particle size in air sampled in parallel with the viral load, 1 study¹⁶ found an RNA concentration of 2.0×10^3 copies/m³ for particles greater than 4 μ m and 1.3×10^3 for particles sized 1 to 4 μ m in 1 patient room, and 927 and 916 copies/m³ of those sizes, respectively, in a second room, both at a distance of 1.0 to 2.1 m from patients (**Figure 3**). A second study⁹ of 2 PPE removal rooms found 40.0×10^3 and 12.0×10^3 copies/m³ for particles less than 1 μ m, and 2.0×10^3 to 8.0×10^3 copies/m³ for particles sized 1 to 4 μ m in 2 PPE removal rooms. A concentration of 7.0×10^3 copies/m³ was found for particles less than 1 μ m and 13.0×10^3 copies/m³ for particles sized 1 to 4 μ m in medical staff offices.³¹ For the third study that performed viral cultures with air samples from 6

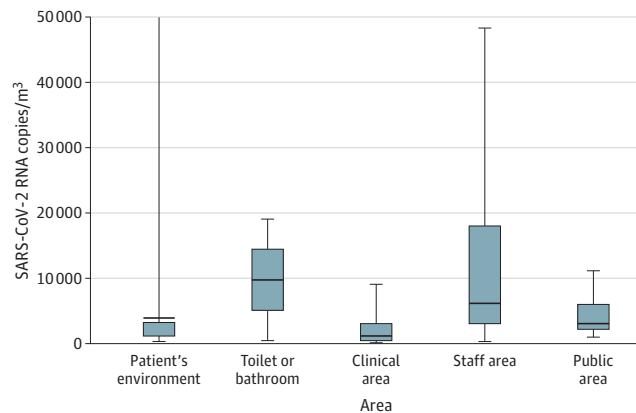
Table 2. Description of Reverse Transcription-Polymerase Chain Reaction and Culture Results Categorized by Hospital Areas

	SARS-CoV-2				
	Viral RNA			Viral culture	
Area	No./total No.	Positivity, %	P value	No./total No.	Positivity, %
Patient environments					
All	82/471	17.4	NA	7/47	14.9
Ward					
ICU	27/107	25.2	<.001	NA	NA
Non-ICU	39/364	10.7		7/47	14.9
Ventilation					
Negative pressure	47/360	13.1	.37	0/13	0
Mechanical or natural	6/66	9.1		4/4	100
Distance from patient, m					
≤1	3/118	2.5	.22	NA	NA
1-5	13/236	5.5		4/7	57.1
Clinical context					
Severe or critical	20/96	20.8	<.001	NA	NA
Mild, moderate, or asymptomatic	23/303	7.6		4/17	23.5
Patient toilets or bathrooms	5/21	23.8	NA	0/2	0
Clinical areas					
All	20/237	8.4	NA	0/13	0
Corridor	9/48	18.7	<.001	NA	NA
Workstation	6/22	27.2		0/5	0
Anteroom or buffer room	0/64	0		NA	NA
Others	5/103	4.8		0/8	0
Staff areas					
All	15/122	12.3	NA	0/4	0
Changing room	2/51	3.9	.06	0/1	0
Meeting or staff room	5/26	19.2		0/3	0
Others	8/45	17.8		NA	NA
Public areas					
All	14/42	33.3	NA	0/15	0
Hallways	9/16	56.2	.01	0/14	0
Other, indoor	2/18	11.1		0/1	0
Outdoor	3/8	37.5		NA	NA

Abbreviations: ICU, intensive care unit; NA, not applicable; SARS-CoV-2, severe acute respiratory syndrome coronavirus 2.

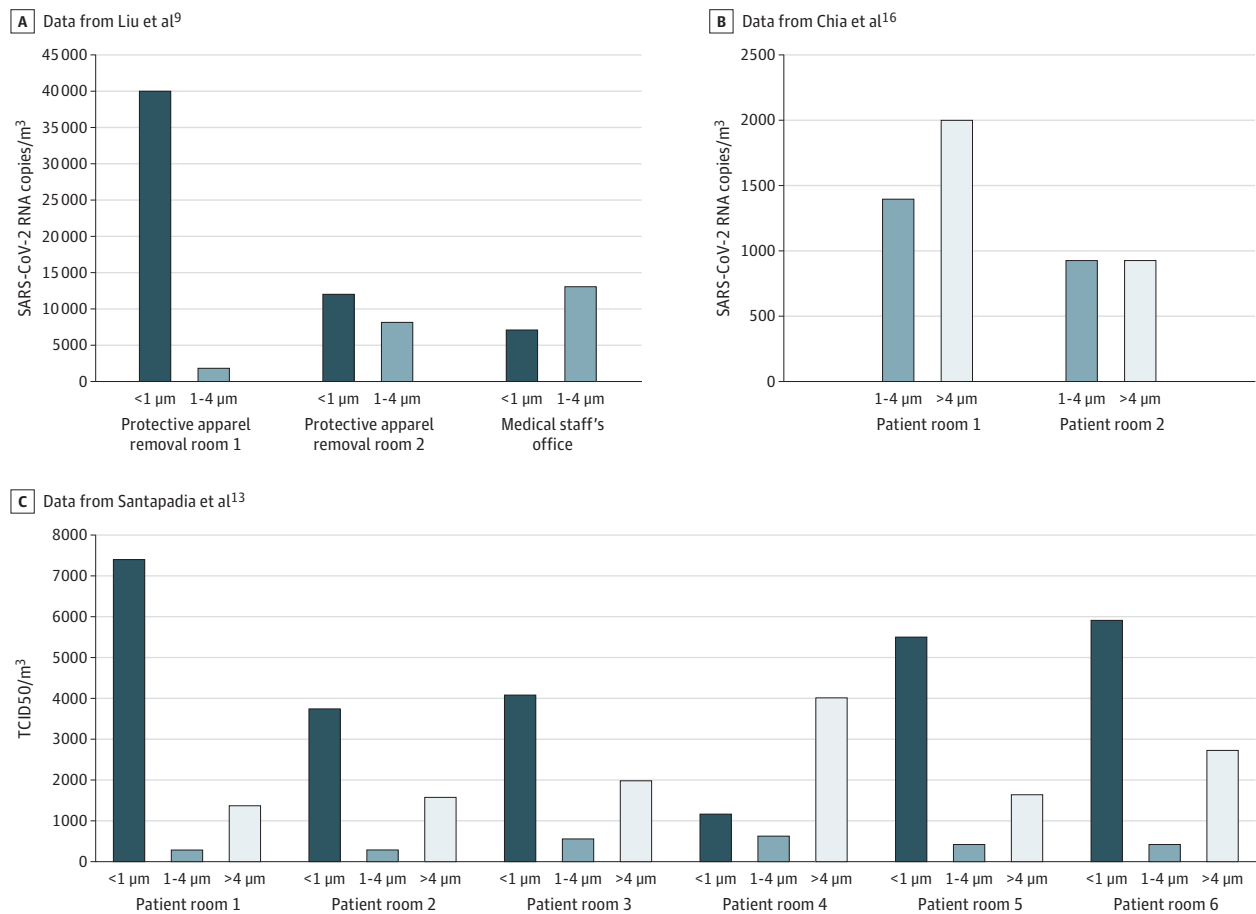
different patients' room,¹³ the median (IQR) viral concentration was 4.8 (3.3-5.8) TCID₅₀/m³ for particles less than 1 µm, 4.27 (2.96-5.48) TCID₅₀/m³ for particles sized 1 to 4 µm, and 1.82 (1.6-2.55) TCID₅₀/m³ for particles greater than 4 µm.¹³

Figure 2. Distribution of Pooled Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) RNA Concentrations in Copies per Meter Cubed of Air, by Hospital Area



In patient's environment, there was an outlier, with 1 sample finding 94 000 SARS-CoV-2 RNA copies/m³ in 1 non-intensive care unit room.³⁰

Figure 3. Concentration of Airborne Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) in Different Aerosol Sizes



TCID₅₀ indicates median tissue culture infectious dose.

Discussion

This scoping systematic review of the literature suggests that air near and distant from patient environments, including toilets and/or bathrooms, staff areas, and public areas, may carry viral RNA. However, the infectivity of the virus assessed by viral culture was only reported by 2 studies in non-ICU patient rooms. PPE removal and patient rooms had high concentrations per titer of SARS-CoV-2 with aerosol size distributions that showed peaks of particles sized less than 1 μm ; for staff offices, the size distribution peaked for particles sized greater than 4 μm .

The results of positivity rate in ICU and non-ICU patient environments were highly heterogeneous and appeared superior in the ICU when pooling the results. In the ICU, 7 of 12 studies did not find SARS-CoV-2 RNA, whereas the remaining did, with 37.5% to 100% positive samples. In non-ICU patient environments, 11 of 19 did not find SARS-CoV-2 RNA, and 8 studies found viral RNA present in from 1.9% to 100% of samples. This heterogeneity may be explained either by a different case mix or by a difference in the methods used for air sampling. The level of severity of patients' infections was not associated with increased air contamination. Several studies^{32,33} suggested higher viral loads might be associated with severe clinical outcomes. However, the association between clinical conditions and air contamination may be more complex. The potential opportunistic airborne contamination occurring during aerosol-generating procedures (AGPs) and ventilation at the time of sampling could inform the results. All these factors were poorly detailed in the articles analyzed. The sampling method, including the sampler used; its position in the clinical unit and in relation to patients; the duration of sampling; the volume sampled; and the conditions for transfer to the laboratory were highly variable across studies. The volume of a single room is approximately 40 m^3 . However, most sample volumes were less than 10 m^3 , at various airflow rates, for a duration of less than or equal to 1 hour, potentially not reflecting the reality of air contamination. The climatic conditions (eg, temperature and hygrometry) were poorly detailed in studies reviewed, but they may affect the capacity for viral particles to persist in the air.³⁴ The methods for RNA detection varied, especially the cycle threshold (Ct) for PCR positivity, which also varied from 37 to 45. The RT-PCR Ct values are strongly associated with a cultivable virus. The probability of culturing virus declines to 8% in samples with Ct of greater than 35.³⁵ Only 2 studies^{13,30} described a positive viral culture on samples with SARS-CoV-2 RNA on RT-PCR, suggesting that most samples did not contain enough infectious virus. Most sampling methods affect viral infectivity, which may partly explain these results.³⁶ Future studies should consider these points for better accuracy and comparability of data.

The concentration of SARS-CoV-2 RNA in aerosols detected in isolation wards and in areas where patients were receiving ventilation was very low. However, a higher concentration of viral RNA was found in patient toilets, public areas, and in some medical staff areas. The finding of high concentrations in staff rooms (ie, meeting and dining rooms) is consistent with the possible cross-transmission of COVID-19 among HCPs during breaks. During these periods, face masks are frequently removed in small areas without ventilation. Toilets and staff rooms are often small and poorly ventilated. The presence of SARS-CoV-2 RNA in stool samples has been described in several studies.^{37,38} Toilet flushing may lead to the aerosolization of RNA in small and nonventilated toilets or bathrooms. In an epidemic setting, public areas are often crowded, with both a high patient flow and high incidence of COVID-19. These factors have to be considered to control the transmission of COVID-19 between nonmasked HCPs in hospitals, especially staff rooms and lockers.

Only 3 studies^{9,13,16} assessed the size of particles found when searching for SARS-CoV-2. Regarding aerosols of submicrometer size that were observed in PPE removal and patient rooms, the authors of those studies hypothesized the resuspension of virus-laden aerosols from the surfaces of PPE worn by medical staff. The submicrometer virus-laden aerosols may originally come from direct deposition of respiratory droplets or airborne SARS-CoV-2 from a patient to the PPE. On the other hand, floor-deposited SARS-CoV-2 could be the source of virus-laden aerosols greater than 4 μm that were then carried across different areas by medical staff.

The findings of this scoping systematic review are consistent with the accumulated knowledge on other respiratory viruses. SARS-CoV-1 is commonly recognized to be mainly transmitted through large droplets, requiring particular conditions to be airborne transmitted, such as AGPs.^{39,40} For other respiratory viruses, a 2019 review described the frequent presence of nucleic material (RNA or DNA) in the air around patients with influenza, respiratory syncytial virus, adenovirus, rhinovirus, and other coronaviruses but rarely the presence of viable viruses.⁴¹ The current available evidence on hospital air contamination by SARS-CoV-2 leans toward the effectiveness of surgical face masks in most circumstances to prevent cross-transmission of COVID-19 in hospital settings.⁴² In contrast, AGPs on the respiratory tract require wearing a respirator (N95 or FFP2) to prevent transmission and protect HCPs.^{5,43} However, the validation of these hypothesis regarding the transmission mode of COVID-19 and the associated efficacy of PPE requires more robust studies. A randomized clinical trial comparing the surgical face mask with respirator may provide important information for recommendations regarding respiratory protection for HCPs in settings in addition to AGPs. Assessing SARS-CoV-2 RNA and viable virus contamination of surgical face masks and respirators worn by HCP according to a panel of procedures with patients with COVID-19 would provide information on exposure in routine practice.

Limitations

This study has limitations. First, the context (ie, location, ventilation, distance, and clinical context) were infrequently detailed in studies. Misclassification may have occurred when variables were categorized without enough detail. Moreover, the sampling and microbiology methods were highly heterogeneous across studies. As explained earlier, these flaws potentially affected the comparability of data and the reliability of pooled data analysis. This issue was avoided by performing categorization only when data were available. Second, for a better clarity of analysis, we did not include surface contamination. However, air and surface contamination are potentially correlated and may ease the understanding of resuspension. Third, we included articles not validated by a peer review process.

Conclusions

In this study, the air around patients hospitalized with COVID-19 was frequently contaminated with SARS-CoV-2 RNA but rarely with viable viruses. The available data suggest that COVID-19 requires particular conditions to be transmitted through the air (such as AGPs), leaning toward the effectiveness of surgical face masks in most circumstances. High viral loads found in toilets and/or bathrooms, staff areas, and public hallways argue for a careful consideration of these areas for the prevention of COVID-19 transmission. However, the presence of viable viruses should be primarily considered, given that it is a required link for the potential of cross-transmission.

ARTICLE INFORMATION

Accepted for Publication: November 18, 2020.

Published: December 23, 2020. doi:10.1001/jamanetworkopen.2020.33232

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Author Contributions: Dr Birgand had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

Concept and design: Birgand, Peiffer-Smadja, Fournier, Lucet.

Acquisition, analysis, or interpretation of data: Birgand, Peiffer-Smadja, Fournier, Kerneis, Lescure.

Drafting of the manuscript: Birgand, Fournier, Lucet.

Critical revision of the manuscript for important intellectual content: Birgand, Peiffer-Smadja, Kerneis, Lescure.

Statistical analysis: Birgand.

Supervision: Lescure, Lucet.

Conflict of Interest Disclosures: Dr Kerneis reported receiving personal fees, grants, and nonfinancial support from bioMérieux, travel fees from Accelerate Diagnostics, and personal fees from MSD outside the submitted work. Dr Lescure reported receiving personal fees from bioMérieux, Gilead, and MSD outside the submitted work. No other disclosures were reported.

Funding/Support: The research was funded by the National Institute for Health Research Health Protection Research Unit in Healthcare Associated Infection and Antimicrobial Resistance at Imperial College London in partnership with Public Health England. The support of Economic and Social Research Council as part of the Antimicrobial Cross Council initiative supported by the 7 UK research councils and also the support of the Global Challenges Research Fund is gratefully acknowledged.

Role of the Funder/Sponsor: The funders had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Disclaimer: The views expressed are those of the authors and not necessarily those of the National Health Service, the National Institute for Health Research, the Department of Health, or Public Health England.

Meeting Presentation: These results have been presented at the virtual ESCMID Conference on Coronavirus Disease (ECCVID); September 23, 2020.

Additional Contributions: Marta Castrica, MSc (Department of Health, Animal Science and Food Safety VESPA, University of Milan, UNIMI), and Laura Menchetti, MSc (Faculty of Veterinary Medicine, Università degli Studi di Perugia, UNIPG) assisted with data collection. They were not compensated for their time.

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SUPPLEMENT.

eAppendix. Supplementary Methods

eTable. Evaluation of the Quality of Included Studies