

REVIEW

Hidden hazards of SARS-CoV-2 transmission in hospitals: A systematic review

Noach Leon Ribaric¹  | Charles Vincent²  | Günther Jonitz^{3,4}  | Achim Hellinger⁵  | Goran Ribaric^{6,7} 

¹Faculty of Medicine, University Medical Center Hamburg-Eppendorf, University of Hamburg, Hamburg, Germany

²Department of Experimental Psychology, University of Oxford, Oxford, UK

³German Medical Association, Berlin, Germany

⁴State Chamber of Physicians Berlin, Berlin, Germany

⁵Department of General, Visceral, Endocrine and Oncologic Surgery, Fulda Hospital, University Medicine Marburg Campus Fulda, Fulda, Germany

⁶Johnson & Johnson Institute, Norderstedt, Germany

⁷MedTech Europe, Antimicrobial Resistance (AMR) and Healthcare Associated Infections (HAI) Sector Group, Brussels, Belgium

Correspondence

Noach Leon Ribaric, Faculty of Medicine, University Medical Center Hamburg-Eppendorf, University of Hamburg, Martinistraße 52, 20246 Hamburg, Germany.
Email: noach.ribaric@studium.uni-hamburg.de

Abstract

Despite their considerable prevalence, dynamics of hospital-associated COVID-19 are still not well understood. We assessed the nature and extent of air- and surface-borne SARS-CoV-2 contamination in hospitals to identify hazards of viral dispersal and enable more precise targeting of infection prevention and control. PubMed, ScienceDirect, Web of Science, Medrxiv, and Biorxiv were searched for relevant articles until June 1, 2021. In total, 51 observational cross-sectional studies comprising 6258 samples were included. SARS-CoV-2 RNA was detected in one in six air and surface samples throughout the hospital and up to 7.62 m away from the nearest patients. The highest detection rates and viral concentrations were reported from patient areas. The most frequently and heavily contaminated types of surfaces comprised air outlets and hospital floors. Viable virus was recovered from the air and fomites. Among size-fractionated air samples, only fine aerosols contained viable virus. Aerosol-generating procedures significantly increased ($OR_{air} = 2.56$ (1.46–4.51); $OR_{surface} = 1.95$ (1.27–2.99)), whereas patient masking significantly decreased air- and surface-borne SARS-CoV-2 contamination ($OR_{air} = 0.41$ (0.25–0.70); $OR_{surface} = 0.45$ (0.34–0.61)). The nature and extent of hospital contamination indicate that SARS-CoV-2 is likely dispersed conjointly through several transmission routes, including short- and long-range aerosol, droplet, and fomite transmission.

KEYWORDS

aerosol, COVID-19, fomites, hospital infections, masks, transmission

1 | INTRODUCTION

In the European Union, up to 4.6 million patients per year acquire a healthcare-associated infection (HAI) during their hospital stay, affecting 5.7% of all hospitalized patients and accounting for more deaths than all other infectious diseases combined.^{1,2} On average, HAIs consume around 6% of the public hospital budget.²

The COVID-19 pandemic has created new and unique challenges for hospitals as frequent and intense exposure to COVID-19 patients, asymptomatic individuals, and potentially contaminated hospital environments have significantly increased risks of nosocomial transmission. Recent evidence has shown that 11–15% of SARS-CoV-2 infections of hospitalized COVID-19 patients were acquired in hospitals.^{3–7} Secondary attack rates reached 39% when non-COVID-19

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2021 The Authors. *Indoor Air* published by John Wiley & Sons Ltd.

patients shared multi-bed patient rooms with undiagnosed, but infectious COVID-19 patients, even though being more than 1.83 m apart from each other and separated by closed curtains.⁸ Despite their prevalence, dynamics of hospital-associated COVID-19 are still not well understood.

Most HALs are considered to be avoidable through better infection prevention and control. Their burden, including COVID-19, can be reduced by implementing a series of preventive measures.^{9,10} Key elements of effective infection prevention and control strategies in hospitals comprise the creation of a dedicated infection control team, continuous staff training to ensure behavioral compliance to evidence-based guidelines, healthcare-associated infection surveillance as well as strict maintenance of environmental hygiene and audit.^{2,11}

As repeated exposure to air- and surface-borne SARS-CoV-2 contamination constitutes the prerequisite of hospital-associated COVID-19, its assessment can help understand which hospital areas present the greatest hazards of SARS-CoV-2 transmission, how far contaminated droplets can spread through the air and the impact COVID-19 interventions, the built environment and clinical procedures have.

The aim of this systematic review is to assess the nature and extent of air and surface contamination of SARS-CoV-2 in hospitals, to identify hazards of viral dispersal, thus enabling more precise targeting of infection prevention and control as well as improving the safety of patients and healthcare professionals (HCPs).

2 | MATERIALS AND METHODS

2.1 | Search strategy and inclusion criteria

A systematic literature search and cross-referencing of articles in any language were performed within the online databases of PubMed, ScienceDirect, and Web of Science, published at any time up until June 1, 2021. The search strategy followed the identification and screening guidelines established by the PRISMA statement.¹² Search terms were related to air and surface samples, nosocomial transmission, hospital contamination with SARS-CoV-2 and are listed in the Supporting Information.

Articles were screened by title and, after duplicates were excluded, the remaining unique citations were evaluated by review of abstracts. The selection of articles for full-text review was performed by two investigators working independently; disparities between them were resolved by discussion.

Articles were included if they offered primary data on indoor hospital contamination with SARS-CoV-2. This applied to studies sampling air or both air and surfaces inside hospitals. Articles collecting surface swabs but no air samples and those sampling outdoors, in other healthcare facilities apart from hospitals or targeting specific procedures exclusively were excluded after full-text review. Studies reporting contamination from both hospital

Practical Implications

- SARS-CoV-2 contamination presents a notable hazard of hospital-associated COVID-19.
- Significant SARS-CoV-2 contamination can arise through normal breathing and speech, even from asymptomatic patients.
- Air and surface contamination with SARS-CoV-2 are not limited to close contact with COVID-19 patients or specific hospital areas.
- The type of ventilation, the presence of effective air filtration, purification, or sufficient fresh-air supply as well as more than 16 air changes per hour are crucial in ensuring appropriate dilution for infection prevention.
- Protective measures in hospitals need to address all air- and surface-mediated transmission routes.

and other settings, from indoor and outdoor hospital areas, or from COVID-19 and non-COVID-19 patients were included, but only indoor hospital samples and samples relating to COVID-19 patients were analyzed. Controls, exhaled breath condensates, and experimental and sewage samples were excluded. Studies with no full-text available, experimental study designs, and reviews containing secondary data were excluded. Observational studies of study designs other than cross-sectional were excluded due to incomparability of exposures and measures of association. Studies whose design was not apparent from the abstract were assessed by full-text review.

Due to the urgency of this issue, records identified through other sources, such as preprint articles from the servers of Medrxiv and Biorxiv, were included for review even if not yet available as fully peer-reviewed published papers. When peer-reviewed versions became available during the review process, data from the published manuscript were used for the review tables.

2.2 | Data extraction

The following data were extracted: authors, publishing date, country, study design, type of hospital, location of sampling site within hospital; number, particle size, positivity, concentration and viability of airborne contamination; number, positivity, concentration, viability, location, and types of surfaces of surface-borne contamination; type of air sampling device, its height above the ground, sampling duration, flow rate, volume of air collected and distance to patients; type of surface swab, size of the sampled surface area, and collection time; type of room ventilation, presence of high-efficiency particulate air (HEPA) filters severity, and activity during sampling; identification methods, cycle thresholds and limits of detection (LoDs).

2.3 | Data analysis

To conduct a descriptive analysis, the locations of sampling sites within hospitals (Table S1), the types of surfaces examined for SARS-CoV-2 (Table S2), and the types of air sampling devices (Table S3) were categorized.

Droplet sizes of size-fractionated air samples were categorized in line with the definitions of the Centers for Disease Control and Prevention (CDC) and the Infectious Diseases Society of America (IDSA): Respirable particles of $<5\text{--}10\text{ }\mu\text{m}$ in size were referred to as aerosols, whereas inspirable particles of $>10\text{--}100\text{ }\mu\text{m}$ in size were classified as droplets.^{13,14} As for other pathogens, it has been reported for SARS-CoV-2 that virus-laden aerosols of different size deposit at distinct locations within the respiratory tract, resulting in different manifestations of respiratory tract infections.¹⁵ Aerosols were therefore subdivided into 2 fractions: coarse aerosols of $5\text{--}10\text{ }\mu\text{m}$ in size that can pass the larynx and have a higher probability to cause upper respiratory tract infections as well as fine aerosols $<5\text{ }\mu\text{m}$ that can reach the acinar airways of the lung and more readily cause lower respiratory tract infections.¹⁶ Size-fractionated air samples were treated as the amount of size fractions the air sampler divided them into.

Regarding the classification of AGPs, latest research suggests that a consensus exists about few clinical procedures that can be categorized as aerosol-generating, in spite of differences in AGP definitions between sources. As proposed in a recent systematic review, the following clinical procedures were categorized as AGPs due to a consensus in $\geq 90\%$ of the available literature: "autopsy, surgery or post-mortem procedures with high-speed devices, intubation and extubation procedures, bronchoscopy, sputum induction, manual ventilation, airway suctioning, cardiopulmonary resuscitation, tracheostomy, tracheostomy procedures, non-invasive ventilation, high-flow oxygen therapy, breaking closed ventilation systems, nebulized therapy, aerosol therapy, and high-frequency oscillatory ventilation".¹⁷ Oxygen supplementation via nasal cannula with unknown flow rate was treated as low-flow oxygen therapy and thus not considered an AGP.

Univariate analyses were performed on key factors for hospital SARS-CoV-2 contamination using IBM SPSS Statistics 27, investigating their association with air- and surface-borne sample positivity and concentration (Appendix Tables 1–4).

Key factors included type of hospital, location of sampling site within hospital; type of air sampling device, its height above the ground, sampling duration, flow rate, volume of air collected per sample, and distance to patients; types of surfaces examined for surface-borne contamination, type of surface swab, size of the sampled surface area, and collection time; type of room ventilation, presence of HEPA filters, ACH, humidity, temperature, presence, and type of AGPs; number of patients present per sample, patient masking, and COVID-19 severity; cycle thresholds and LoD. For patient masking, COVID-19 severity, and AGPs, samples from patient areas and the clinical area were analyzed as those are the hospital areas in which patients are treated.

Data were pooled and distributions tested for normality with the Kolmogorov-Smirnov test and Shapiro-Wilk test. For categorical factors, chi-square tests were used to calculate p -values. For metric factors, p -values were obtained from Mann-Whitney U and Kruskal-Wallis tests. Two-sided $p < 0.05$ was considered statistically significant. For sample sizes <30 , the exact p -value was calculated. Bonferroni corrections after chi-square tests were done as post hoc tests to control for multiple comparisons. Cramér's ϕ after chi-square tests and Pearson's r after Mann-Whitney U tests were calculated to assess effect sizes. Odds ratios (OR) and 95% confidence intervals (95% CI) were additionally calculated for univariate analyses of dichotomous factors.

To investigate interaction effects between the factors analyzed in univariate comparisons, a multivariate, pooled analysis was carried out in form of binary logistic regressions. The dependent variable comprised the detection of SARS-CoV-2 RNA in air or surface samples. Factors were eligible for inclusion if a significant association with air- or surface-borne SARS-CoV-2 contamination was demonstrated in univariate analyses. Air and surface samples were analyzed separately in two regressions. The maximum number of factors that together represented the greatest proportion of samples was each selected for the two models. Regressions were conducted by using standard maximum-likelihood procedures, and its coefficients were utilized to derive ORs and 95% CI. p -values were obtained from two-sided z tests.

2.4 | Methodology of quality assessment

The quality of evidence was assessed by two investigators independently, using the JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies with any discrepancies in item scores being resolved by discussion.¹⁸ Recent research suggests this is the optimum approach for reviewed studies.¹⁹ No study was excluded on the basis of a quality assessment. Quality scores are detailed in Table S4.

3 | RESULTS

In total, 7156 articles were identified after the removal of duplicates and 186 identified for full-text review. After applying criteria, 51 articles were included (Figure 1).^{20–70}

3.1 | Study characteristics

51 observational cross-sectional studies analyzed hospital samples for the presence of SARS-CoV-2 RNA. 32 of them sampled both air and surfaces and 19 studies sampled the air exclusively. In total, 6258 samples were collected, and SARS-CoV-2 RNA was detected in 1014 air and surface samples (16.20%) from 47 of 51 studies.

Most of included studies were carried out in Asia (32): China (15), Iran (5), Singapore (3), Hong Kong (2), South Korea (2), India (2),

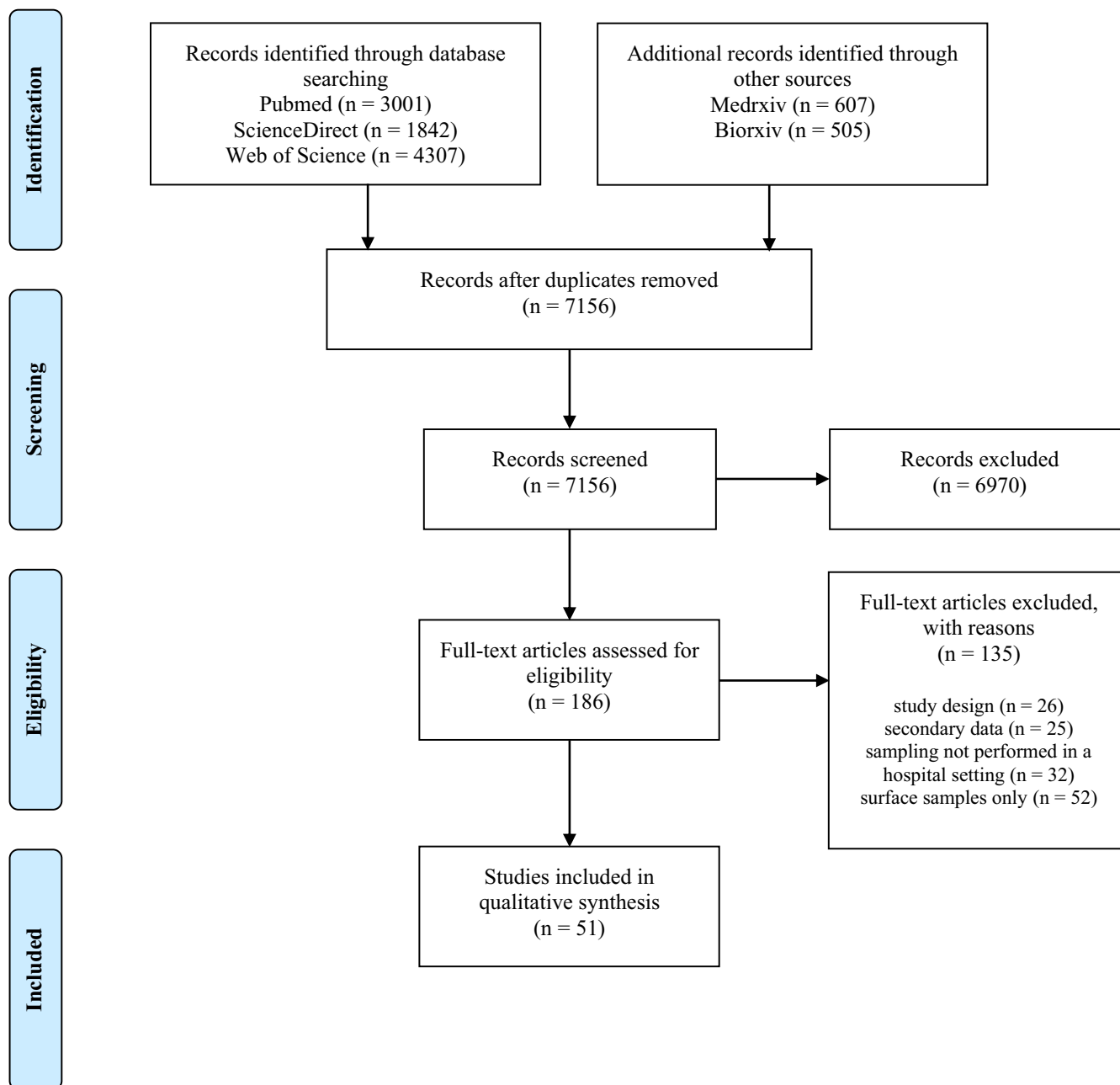


FIGURE 1 PRISMA flow diagram

Malaysia (1), Israel (1), and Kuwait (1). The remaining studies were conducted in North America (11): the United States (10), Mexico (1); and Europe (8): Italy (4), United Kingdom (1), Ireland (1), Greece (1), and Russia (1). 50 studies were peer-reviewed journal articles and one a preprint. Characteristics of reviewed studies are shown in Tables S5 and S6.

3.2 | Nature and extent of airborne SARS-CoV-2 contamination in hospitals

51 studies investigated the presence of SARS-CoV-2 RNA in hospital air. In total, 1850 air samples were collected and 302 of them

(16.32%) were positive for SARS-CoV-2 RNA in 35 studies. Viral concentrations were detailed in 26 of 35 studies detecting SARS-CoV-2 RNA in the air, making up 242 of 302 air samples (Table 1).

Airborne contamination was observed in all major hospital areas and almost every subdivision of them. Overall, patient areas were significantly more frequently (19.40% vs. 11.78%, $p < 0.001$; Appendix Table 1) and heavily contaminated than non-patient areas (4.36 Copies/L vs. 0.71 Copies/L; $p < 0.001$ and Ct 28.15 vs. Ct 31.29; $p = 0.010$, Appendix Table 2).

The highest prevalence of SARS-CoV-2 RNA in the air was reported from ICU patient rooms, significantly exceeding that of non-ICU patient rooms (27.61% vs. 16.90%; $p < 0.001$, Appendix Table 1). Viral concentrations, however, were lower in ICU patient rooms

TABLE 1 Detection rates and Concentrations of SARS-CoV-2 RNA in air samples according to sampling location within hospitals

	Detection rates			SARS-CoV-2 RNA concentrations ^a									
				In Copies/L of air				In Ct-values					
	n	N	%	n	μ	σ	M	IQR	n	μ	σ	M	IQR
Patient Areas	215	1104	19.47	75	5.18	13.39	1.40	3.41	83	28.15	6.72	28.10	11.31
ICU	90	335	26.87	28	1.58	2.32	1.26	1.38	47	27.22	6.28	26.70	8.40
ICU Patient Room (total)	90	326	27.61	28	1.58	2.32	1.26	1.38	47	27.22	6.28	26.70	8.40
ICU Patient Room at patient	85	305	27.87	23	1.10	2.29	0.51	1.38	47	27.22	6.28	26.70	8.40
ICU Patient Room near air outlets	5	21	23.81	5	3.80	N.A.	3.80	N.A.	-	-	-	-	-
ICU Bathroom	0	9	0.00	-	-	-	-	-	-	-	-	-	-
Non-ICU	124	765	16.21	46	7.46	16.67	1.72	4.82	36	29.35	7.17	29.50	12.46
Non-ICU Patient Room (total)	120	705	17.02	44	7.79	16.97	2.21	4.91	34	28.98	7.21	29.04	11.46
Non-ICU Patient Room at patient	118	694	17.00	42	8.13	17.31	2.45	5.18	34	28.98	7.21	29.04	11.46
Non-ICU Patient Room near air outlets	2	11	18.18	2	0.68	N.A.	0.68	N.A.	-	-	-	-	-
Non-ICU Bathroom	4	60	6.67	2	0.24	0.31	0.24	-	2	35.60	N.A.	35.60	N.A.
Operating Theater	1	4	25.00	1	1.16	-	1.16	-	-	-	-	-	-
Non-Patient Areas	87	746	11.66	52	0.72	1.72	0.01	0.29	30	31.29	4.36	31.10	5.22
Staff Area	23	218	10.55	21	0.02	0.05	0.01	0.02	1	38.83	-	-	-
Public Area	2	39	5.13	2	0.79	1.11	0.79	-	-	-	-	-	-
Clinical Area (total)	61	478	12.76	28	1.20	2.21	0.04	2.03	29	31.03	4.20	31.10	3.89
Clinical Area: Anterooms	0	39	0.00	-	-	-	-	-	-	-	-	-	-
Clinical Area: Corridors	29	137	21.17	14	2.21	2.79	1.30	3.67	15	33.30	3.56	31.10	6.70
Clinical Area: Corridors near air outlets	0	3	0.00	-	-	-	-	-	-	-	-	-	-
Clinical Area: Other	32	302	10.60	14	0.20	0.51	0.02	0.11	14	28.60	3.47	27.54	3.36
Clinical Area: Other near air outlets	0	3	0.00	-	-	-	-	-	-	-	-	-	-
Non-patient Bathroom	1	11	9.09	1	1.55	-	1.55	-	-	-	-	-	-
Total Air Samples	302	1850	16.32	127	3.35	10.55	0.51	2.41	113	28.98	6.32	29.60	10.17

n = number of air samples positive for SARS-CoV-2 RNA, N = total number of air samples, % = percent of air samples positive for SARS-CoV-2 RNA.

n = mean, σ = standard deviation, M = median, IQR = interquartile range, N.A. = not available.

^aConcentrations of 2 additional air samples from Non-ICU Patient Rooms were detailed in Copies/μl of viral transport media (10 and 74 Copies/μl).

when given in Copies/L (1.58 vs. 7.79; $p = 0.008$) and did not significantly differ from Non-ICU patient rooms in Ct-values (27.22 vs. 28.98; $p = 0.242$, Appendix Table 2). The second most frequently contaminated hospital area with more than 5 air samples was located in one of the overall lesser contaminated, non-patient areas: 21.17% of air samples from corridors adjacent to patient rooms were positive for SARS-CoV-2 RNA (Table 1).

In general, when SARS-CoV-2 RNA was detected within non-patient areas, those open to patients reported higher viral concentrations than those without patient access (staff area) or uninvolved in patient care (public area, Table 1). Yet, the same trend was not observed for the detection rates of SARS-CoV-2 RNA as they were not significantly lower in the staff area compared to the clinical area (10.55% vs. 12.76%; $p = 0.406$; Appendix Table 1).

To better assess the airborne contamination arising during patient contact, researchers of one study wore personal air samplers. SARS-CoV-2 RNA was found in all 4 air samples, and the detailed concentrations were among the highest of all studies (5.37–48.22 Copies/L). A similar approach was chosen in another study, in which a portable air sampler was frequently re-positioned in close proximity to three bedridden COVID-19 patients. All air samples were likewise positive, with a mean concentration of Ct 31.10.

A total of 6 studies collected air samples near air outlets to examine the role of ventilation systems in airborne SARS-CoV-2 contamination, with 3 of them sampling in patient rooms. No differences in detection rates or RNA concentrations were observed between samples from the immediate patient environment and those near air outlets in patient rooms (21.88% vs. 20.32%; $p = 0.821$ and 4.64

Copies/L vs. 2.91 Copies/L; $p = 0.083$). In non-patient areas, none of the 6 air samples collected next to air outlets were SARS-CoV-2 RNA-positive (Table 1).

10 studies assessed whether airborne SARS-CoV-2 was viable. Two of these found significant evidence of viable virus in 7 out of 22 specimens from Non-ICU Patient rooms, with patients experiencing mild and unknown case progressions of COVID-19 and no aerosol-generating procedures present (Table 2). Each two air samples from which infectious virus was cultured were collected from 2 and 4.8 m away from the patients' heads. Mean concentration of viable SARS-CoV-2 recovered from the 4 air samples with known distances to patients were 1.13×10^4 TCID₅₀ per 100 μ l of purified vRNA, primers and hydrolysis probes for qRT-PCR.²¹ Mean concentrations of infectious SARS-CoV-2 from the remaining 3 air samples were 1.93×10^{-1} pfu/ml.

11 studies segregated air samples from patient and non-patient areas by droplet size into 14 different size fractions ranging from <0.25 μ m to >10.00 μ m (Table 3). SARS-CoV-2 RNA was detected in 87 of in total 548 size-fractionated air samples, which was similar to the overall detection rate of non-size-fractionated air samples (15.88% vs. 16.51%; $p = 0.735$). RNA concentrations were available for 54 of 87 size-fractionated air samples (Table 3). Detection rates for all 14 size fractions grouped by sampling location within hospitals are listed in Table S7.

The prevalence of virus-laden, fine aerosols was significantly higher than that of coarse aerosols or droplets (18.25% vs. 11.62%; $p = 0.049$), while RNA concentrations did not significantly differ in any

	Detection rates of viable SARS-CoV-2					
	In air samples			In surface samples		
	<i>n</i>	<i>N</i>	%	<i>n</i>	<i>N</i>	%
Patient Areas	7	82	8.54	9	94	9.57
ICU	0	9	0.00	1	15	6.67
ICU Patient Room	0	9	0.00	1	14	7.14
ICU Bathroom	–	–	–	0	1	0.00
Non-ICU	7	72	9.72	8	76	10.53
Non-ICU Patient Room	7	71	9.86	8	73	10.96
Non-ICU Bathroom	0	1	0.00	0	3	0.00
Operating Theater	0	1	0.00	0	3	0.00
Non-Patient Areas	0	16	0.00	0	69	0.00
Staff Area	0	1	0.00	0	14	0.00
Public Area	0	1	0.00	0	9	0.00
Clinical Area	0	13	0.00	0	39	0.00
Non-Patient Bathroom	0	1	0.00	0	7	0.00
Total Samples	7	98	7.14	9	163	5.52

Note: *n* = number of samples from which viable SARS-CoV-2 was recovered, % = Percent of samples from which viable SARS-CoV-2 was recovered.

N = total number of SARS-CoV-2 RNA-positive samples for which for which viral viability was established.

TABLE 2 Detection rates of viable SARS-CoV-2 in air and surface samples according to sampling location within hospitals

TABLE 3 Detection rates, concentrations of SARS-CoV-2 RNA and viral viability in size-fractionated air samples

Fine aerosols			Coarse aerosols and droplets				Size fractions that span across particle cut-off sizes					
Size ranges included	<0.25 μm			>4.00 μm				>2.50 μm				
	0.25–0.50 μm			>10.00 μm				2.50–10.00 μm				
	0.50–1.00 μm							≤ 10.00 μm				
	<1.00 μm											
1.00–2.50 μm												
≤ 2.50 μm												
1.00–4.00 μm												
<4.00 μm												
<4.35 μm												
Detection Rates		n ₁	N ₁	% ₁	n ₁	N ₁	% ₁	p	r	n ₁	N ₁	% ₁
		50	274	18.25	23	198	11.62	0.049	0.091	14	76	18.42
Viral Concentrations		n ₁	μ	σ	M	IQR	n ₁	μ	σ	M	IQR	
Copies/L of air		22	0.29	0.47	0.03	0.54	10	0.52	0.70	0.04	1.04	0.01
Ct-values		4	37.08	0.65	37.00	1.22	2	38.30	1.14	38.30	N.A.	0.01
Copies/μl of VTM		2	42.00	45.25	42.00	–	–	–	–	–	–	1.80
Viability		n ₂	N ₂	% ₂	n ₂	N ₂	% ₂	n ₂	N ₂	% ₂	n ₂	% ₂
		3	30	10.00	0	13	0.00	–	–	–	–	–

Note: n_1 = number of size-fractionated air samples positive for SARS-CoV-2 RNA, N_1 = total number of size-fractionated air samples, $\%_1$ = Percent of size-fractionated air samples positive for SARS-CoV-2 RNA. n_2 = number of SARS-CoV-2 RNA-positive size-fractionated air samples from which viable SARS-CoV-2 was recovered. N_2 = total number of SARS-CoV-2 RNA-positive size-fractionated air samples for which viral viability was established. $\%_2$ = Percent of SARS-CoV-2 RNA-positive size-fractionated air samples from which viable SARS-CoV-2 was recovered. N.A. = not available. p = p -value, Pearson's r , r = mean, σ = standard deviation, M = median, IQR = interquartile range, VTM = viral transport media.

TABLE 4 Binary Logistic Regressions for the detection of air- and surface-borne SARS-CoV-2 RNA in hospitals

Factor	Reference	OR _{air} (95% CI)	p-value	OR _{surface} (95% CI)	p-value
Makeshift Hospitals	Traditional construction	2.93 (1.41–6.06)	0.004	-	-
Patient Areas	Non-Patient Areas	1.79 (1.16–2.78)	0.009	1.83 (1.36–2.48)	<0.001
Patient Masking present	no Patient Masking listed	0.41 (0.25–0.70)	0.001	0.45 (0.34–0.61)	<0.001
AGPs present	no AGPs listed	2.56 (1.46–4.51)	0.001	1.95 (1.27–2.99)	0.002
Type of Room Ventilation			0.042		<0.001
Natural Ventilation	Mechanical Ventilation ^a	2.47 (0.92–6.67)	0.074	0.28 (0.14–0.56)	<0.001
Natural Ventilation and UV light air purification	Mechanical Ventilation ^a	0.84 (0.22–3.21)	0.800	0.72 (0.50–1.05)	0.085
Mechanical Ventilation with outdoor air supply	Mechanical Ventilation ^a	0.24 (0.03–1.89)	0.175	0.23 (0.13–0.41)	<0.001
Mechanical Ventilation and HEPA Filtration	Mechanical Ventilation ^a	– ^b	0.997	– ^b	0.997
Mechanical Ventilation and Air Purifiers	Mechanical Ventilation ^a	0.10 (0.01–0.73)	0.024	0.08 (0.02–0.35)	0.001
Negative Pressure Ventilation	Mechanical Ventilation ^a	0.88 (0.57–1.35)	0.560	1.09 (0.84–1.42)	0.504
Negative Pressure Ventilation and HEPA Filtration	Mechanical Ventilation ^a	– ^b	0.998	1.11 (0.24–5.09)	0.889
Negative Pressure Ventilation, HEPA Filtration, and Laminar Flow	Mechanical Ventilation ^a	– ^b	0.998	–	–
Laminar Flow Ventilation	Mechanical Ventilation ^a	0.07 (0.01–0.50)	0.008	– ^b	0.995
Type of Air Sampling Device/Method			<0.001	–	–
Cyclone	Other Device/Method	9.09 (0.95–87.47)	0.056	–	–
Laminar-flow water-based condensator	Other Device/Method	68.46 (6.70–699.79)	<0.001	–	–
Filter	Other Device/Method	15.19 (1.63–141.40)	0.017	–	–
Impinger	Other Device/Method	2.42 (0.23–25.75)	0.464	–	–
Impactor	Other Device/Method	11.59 (1.13–113.09)	0.039	–	–
Types of Surfaces			–		<0.001
Floor	Other Surfaces	–	–	2.62 (1.86–3.68)	<0.001
Medical Equipment	Other Surfaces	–	–	1.01 (0.73–1.41)	0.943
Personal Items	Other Surfaces	–	–	0.74 (0.42–1.30)	0.296
Bedside Surfaces	Other Surfaces	–	–	0.99 (0.73–1.34)	0.944
Air Outlets	Other Surfaces	–	–	2.08 (1.18–3.70)	0.012
Medical AGP Equipment	Other Surfaces	–	–	1.01 (0.41–2.47)	0.984
Bathroom Surfaces	Other Surfaces	–	–	0.67 (0.45–0.98)	0.041

OR = Odds Ratio, 95% CI = 95% confidence intervals.

^aNot further specified mechanical ventilation.

^bNo odds ratio with 95% confidence intervals could be calculated because no SARS-CoV-2 RNA was detected.

reported unit between the particle types (Table 3). Aerosols of <1 µm in size were particularly frequently contaminated with SARS-CoV-2 (Table S7). Both droplets and aerosols were collected from patient and non-patient areas of hospitals (Table S7). In contrast to droplets, however, only fine aerosols contained viable SARS-CoV-2 (Table 3).

3.3.1 | Sampling strategies to detect airborne SARS-CoV-2 contamination

A variety of different sampling strategies were utilized to detect SARS-CoV-2 RNA in hospital air. Sampling duration per sample,

volume of air collected per sample, and flow rates of air sampling devices ranged from 2 to 10 080 minutes, 50 to 80 000 L of air and 1.50 to 4000 L of air per minute, respectively. Air sampling devices could be categorized into 7 different types, sampling the air at heights ranging from 0.20 to 1.65 m above the ground. 2 identification methods, qRT-PCR and ddPCR, were used with qRT-PCR cycle thresholds defining a SARS-CoV-2 RNA-positive sample ranging from 35 to 45. Their LoDs span over 5 orders of magnitude, from 4.3×10^{-3} to 1.0×10^2 Copies/µl of viral transport media (VTM, Appendix Tables 1–4).

These differences in sampling strategies significantly affected reported airborne contamination, which altered the most when

TABLE 5 Detection rates of SARS-CoV-2 RNA in surface samples grouped by surface type and sampling location within hospitals

	Floor		Medical		Personal		Bedside		Air		Other		Medical AGP		Bathroom		Total	
	N	%	Equipment		Items		Surfaces		Outlets		Surfaces		Equipment		Surfaces		N	%
			N	%	N	%	N	%	N	%	N	%	N	%	N	%		
Patient Areas	162	47.53	213	30.99	244	21.31	796	18.84	64	35.94	957	14.32	34	23.53	340	18.10	2810	20.50
ICU Patient Room	19	63.16	92	38.04	-	-	59	28.82	15	53.33	224	9.38	14	7.14	-	-	423	22.22
ICU Bathroom	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	0.00	2	0.00
Non-ICU Patient Room	135	47.41	121	25.62	206	23.79	737	18.05	47	29.79	720	15.69	20	35.00	-	-	1986	20.69
Non-ICU Bathroom	8	12.50	-	-	38	7.89	-	-	2	50.00	-	-	-	-	338	18.64	386	17.62
Operating Theater	-	-	-	-	-	-	-	-	-	-	13	23.08	-	-	-	-	13	23.08
Non-Patient Areas	218	6.88	495	4.24	54	1.85	89	3.37	23	4.35	658	13.22	10	0.00	51	13.73	1598	8.51
Staff Area	53	0.00	7	14.29	-	-	-	-	1	0.00	194	9.79	-	-	-	-	255	7.84
Public Area	-	-	-	-	-	-	-	-	-	-	20	50.00	-	-	-	-	20	50.00
Clinical Area	161	9.32	488	4.10	54	1.85	89	3.37	22	9.09	444	13.06	10	0.00	-	-	1268	7.81
Non-Patient Bathroom	4	0.00	-	-	-	-	-	-	-	-	-	-	-	-	51	13.73	55	12.73
Total	380	24.21	708	12.29	298	17.79	885	17.29	87	28.74	1615	13.87	44	18.18	391	17.90	4408	16.15

Note: N = total number of surface samples, % = percent of surface samples positive for SARS-CoV-2 RNA, AGP = aerosol-generating procedures.

TABLE 6 SARS-CoV-2 RNA concentrations in surface samples grouped by surface type and location within hospitals

		Floor		Medical equipment		Personal items		Bedside surfaces	
		Copies/swab	Ct-value	Copies/swab	Ct-value	Copies/swab	Ct-value	Copies/swab	Ct-value
Patient	<i>n</i>	9	55	14	32	3	43	9	63
Areas	μ	5.5×10^4	34.30	1.4×10^6	33.94	1.8×10^3	38.36	3.0×10^4	34.24
	σ	2.2×10^4	4.10	5.0×10^6	6.49	1.5×10^3	2.38	2.0×10^4	6.06
	M	5.5×10^4	34.00	1.9×10^4	35.90	1.0×10^3	39.00	4.3×10^4	36.40
	IQR	N.A.	6.35	2.4×10^4	3.39	–	2.50	3.9×10^4	6.21
ICU	<i>n</i>	7	5	12	15	–	–	8	6
Patient	μ	6.6×10^4	31.91	1.6×10^6	31.97	–	–	3.3×10^4	25.13
Room	σ	N.A.	7.67	5.5×10^6	8.65	–	–	1.9×10^4	8.74
	M	6.6×10^4	28.81	2.8×10^4	36.45	–	–	4.3×10^4	20.52
	IQR	N.A.	14.67	2.5×10^4	19.06	–	–	2.9×10^4	17.09
Non-	<i>n</i>	2	49	2	17	–	43	1	57
ICU	μ	1.6×10^4	34.46	9.2×10^3	35.68	–	38.36	3.8×10^3	35.20
Patient	σ	N.A.	3.60	N.A.	3.02	–	2.38	–	4.90
Room	M	1.6×10^4	34.00	9.2×10^3	35.10	–	39.00	–	36.72
	IQR	–	5.61	–	3.85	–	2.50	–	5.37
Non-	<i>n</i>	–	1	–	–	3	–	–	–
ICU	μ	–	38.50	–	–	1.8×10^3	–	–	–
Bath-	σ	–	–	–	–	1.5×10^3	–	–	–
room	M	–	–	–	–	1.0×10^3	–	–	–
	IQR	–	–	–	–	–	–	–	–
Non-	<i>n</i>	7	7	8	7	–	–	–	–
Patient	μ	3.4×10^4	36.56	1.4×10^4	34.90	–	–	–	–
Areas	σ	3.9×10^4	2.46	1.5×10^4	5.82	–	–	–	–
	M	3.8×10^3	37.23	5.5×10^3	35.70	–	–	–	–
	IQR	7.2×10^4	4.00	3.1×10^4	3.02	–	–	–	–
Staff	<i>n</i>	–	–	–	1	–	–	–	–
Area	μ	–	–	–	22.20	–	–	–	–
	σ	–	–	–	–	–	–	–	–
	M	–	–	–	–	–	–	–	–
	IQR	–	–	–	–	–	–	–	–
Clinical	<i>n</i>	7	7	8	6	–	–	–	–
Area	μ	3.4×10^4	36.56	1.4×10^4	37.01	–	–	–	–
	σ	3.9×10^4	2.46	1.5×10^4	1.73	–	–	–	–
	M	3.8×10^3	37.23	5.5×10^3	36.90	–	–	–	–
	IQR	7.2×10^4	4.00	3.1×10^4	3.34	–	–	–	–
Total	<i>n</i>	16	62	22	39	3	43	9	63
	μ	4.6×10^4	34.56	8.8×10^5	34.11	1.8×10^3	38.36	3.0×10^4	34.24
	σ	3.1×10^4	4.00	4.0×10^6	6.31	1.5×10^3	2.38	2.0×10^4	6.06
	M	6.6×10^4	35.00	9.2×10^3	35.80	1.0×10^3	39.00	4.3×10^4	36.40
	IQR	5.9×10^4	6.01	2.5×10^4	3.98	–	2.50	3.9×10^4	6.21

Note: *n* = number of surface samples positive for SARS-CoV-2 RNA, μ = mean, σ = standard deviation, M = median, IQR = interquartile range, AGP = aerosol-generating procedures, N.A.: not available.

Air outlets		Other surfaces		Medical AGP equipment		Bathroom surfaces		Total	
Copies/swab	Ct-value	Copies/swab	Ct-value	Copies/ swab	Ct-value	Copies/swab	Ct-value	Copies/swab	Ct-value
9	8	7	56	–	6	2	47	53	310
1.3×10^5	35.95	1.8×10^3	36.79	–	31.92	5.7×10^2	35.81	4.0×10^5	35.49
4.9×10^4	2.40	1.4×10^3	2.68	–	2.78	2.2×10^2	4.40	2.6×10^6	4.72
1.5×10^5	35.77	1.3×10^3	37.28	–	31.37	5.7×10^2	36.93	2.8×10^4	36.83
N.A.	3.85	2.7×10^3	3.39	–	3.37	–	3.87	6.3×10^4	4.63
8	–	3	3	–	1	–	–	38	30
1.5×10^5	–	3.4×10^3	35.56	–	37.03	–	–	5.6×10^5	31.12
N.A.	–	N.A.	0.87	–	–	–	–	3.1×10^6	8.29
1.5×10^5	–	3.4×10^3	35.50	–	–	–	–	4.3×10^4	35.76
N.A.	–	–	–	–	–	–	–	5.9×10^4	16.16
1	7	4	53	–	5	–	–	10	231
3.4×10^3	35.67	7.6×10^2	36.85	–	30.89	–	–	6.1×10^3	35.97
–	2.45	3.8×10^2	2.73	–	1.34	–	–	6.2×10^3	3.81
–	34.15	6.6×10^2	37.54	–	30.95	–	–	3.6×10^3	37.00
–	4.01	6.7×10^2	3.34	–	2.35	–	–	1.0×10^4	5.02
–	1	–	–	–	–	–	47	5	49
–	37.90	–	–	–	–	–	35.81	1.3×10^3	35.91
–	–	–	–	–	–	–	4.40	1.2×10^3	4.33
–	–	–	–	–	–	–	36.93	9.0×10^2	37.00
–	–	–	–	–	–	–	3.87	1.7×10^3	3.91
1	1	2	11	–	–	–	–	18	26
4.2×10^2	39.19	3.1×10^2	33.16	–	–	–	–	1.9×10^4	34.77
–	–	5.2×10^2	5.88	–	–	–	–	2.8×10^4	5.12
–	–	3.1×10^2	34.02	–	–	–	–	3.8×10^3	36.62
–	–	–	10.18	–	–	–	–	3.1×10^4	5.56
–	–	–	4	–	–	–	–	–	5
–	–	–	31.92	–	–	–	–	–	29.98
–	–	–	7.52	–	–	–	–	–	7.83
–	–	–	31.86	–	–	–	–	–	25.62
–	–	–	13.29	–	–	–	–	–	4.35
1	1	2	7	–	–	–	–	18	21
4.2×10^2	39.19	3.1×10^2	33.87	–	–	–	–	1.9×10^4	35.92
–	–	5.2×10^2	5.27	–	–	–	–	2.8×10^4	3.66
–	–	3.1×10^2	34.02	–	–	–	–	3.8×10^3	37.23
–	–	–	7.88	–	–	–	–	3.1×10^4	4.35
10	9	9	67	–	6	2	47	71	336
1.2×10^5	36.31	1.2×10^3	36.19	–	31.92	5.7×10^2	35.81	3.0×10^5	35.43
6.2×10^4	2.49	1.7×10^3	3.61	–	2.78	2.2×10^2	4.40	2.3×10^6	4.74
1.5×10^5	37.38	6.7×10^2	37.17	–	31.37	5.7×10^2	36.93	2.8×10^4	36.83
3.7×10^4	4.55	3.4×10^3	4.53	–	3.37	–	3.87	6.3×10^4	4.68

different types of air sampling devices were used. Impingers were associated with the lowest detection rates (4.56%, $p < 0.001$, Appendix Table 1) and together with impactors also with one of the two lowest concentrations of detected SARS-CoV-2 RNA (0.08 Copies/L and 0.06 Copies/L, $p < 0.001$, Appendix Table 2). A laminar-flow water-based condensator most commonly detected SARS-CoV-2 RNA in air samples (61.11%, $p < 0.001$, Appendix Table 1) at the highest viral concentrations (17.41 Copies/L, $p < 0.001$, Appendix Table 1). Multivariate analyses underlined these findings, showing that all types of air sampling devices, apart from impingers and cyclones, significantly more frequently detected airborne SARS-CoV-2 RNA than those categorized as other devices/methods, with the laminar-flow water-based condensator having by far the highest odds to identify airborne SARS-CoV-2 RNA ($OR_{air} = 68.46$ (6.70–699.79); $p < 0.001$, Table 4).

High and low flow rates of air samplers were not associated with significantly different detection rates for airborne contamination (Appendix Table 1). However, much higher viral concentrations were documented when sampling the air with higher flow rates (Appendix Table 2).

Another factor playing an important role in the detection of SARS-CoV-2 contamination in hospitals was the LoDs of the identification methods utilized. When SARS-CoV-2 was detected, significantly lower LoDs were reported (3.71 vs. 18.25 Copies/ μ L of VTM; $p < 0.001$; Appendix Table 4). The vast majority of specimens were identified as SARS-CoV-2 RNA-positive when the LoD was below 3.8×10^{-1} Copies/ μ L of VTM. Univariate comparisons demonstrated that the odds to collect a positive air sample notably increased below this threshold ($OR = 5.08$ (2.61–9.92), Appendix Table 1). Still, LoDs were detailed in only 13 studies, accounting for roughly one in five analyzed air samples, which is why LoDs were not included in the binary logistic regression model.

All other analyzed factors regarding sampling strategy, even though highly variable between and within studies, did not significantly differ between SARS-CoV-2 RNA-positive and SARS-CoV-2 RNA-negative air samples (Appendix Tables 1–4).

3.4 | Nature and extent of surface-borne SARS-CoV-2 contamination in hospitals

32 studies investigated surface-borne SARS-CoV-2 contamination, and 29 of them documented contaminated surfaces. In total, 712 of 4408 surface samples were positive for SARS-CoV-2 RNA (16.15%; Table 5). Viral concentrations were available for 407 samples from 19 studies and given in Copies/ cm^2 , Copies/ μ L of VTM, Copies/swab, and Ct-values. For better comparability, they were converted into the least number of units: RNA concentrations of 336 positive surface samples were expressed as Ct-values and those of 71 as Copies/swab (Table 6).

Surfaces from all major hospital areas were contaminated with SARS-CoV-2. Patient areas were significantly more frequently contaminated than non-patient areas (20.50% vs. 8.51%, $p < 0.001$;

Appendix Table 1). Among hospital areas with large samples sizes, ICU patient rooms were the most frequently contaminated (22.22%), followed by non-ICU patient rooms (20.69%; Table 5). Few samples were collected in operating theaters ($N = 13$) and the public area ($N = 20$), but very high detection rates observed (23.08% and 50.00%; Table 5). The types of surfaces to be the most commonly contaminated were air outlets (28.74%), the floor (24.21%), and medical equipment used in aerosol-generating procedures (18.18%, Table 5). Multivariate analyses underlined these findings, demonstrating that the odds for SARS-CoV-2 RNA-positive surfaces were significantly higher in patient areas compared to non-patient areas as well as on air outlets and the floor, compared to other surfaces (Table 4).

Viral concentrations of surface swabs were the highest in ICU patient rooms, significantly differing from non-ICU patient rooms (5.6×10^5 vs. 6.1×10^3 Copies/swab; $p < 0.001$ and Ct 31.12 vs. Ct 35.97; $p = 0.005$, Appendix Table 3). In general, surfaces sampled in the non-ICU did not show higher levels of SARS-CoV-2 contamination than those from non-patient areas. Therefore, depending on the amount of surface samples collected from the non-ICU per unit, differences in SARS-CoV-2 RNA concentration between patient and non-patient areas were either significant (4.0×10^5 vs. 1.9×10^4 Copies/swab; $p = 0.032$; Appendix Table 3) or not (Ct 35.49 vs. Ct 34.77; $p = 0.669$; Appendix Table 1). Air outlets and medical equipment used in aerosol-generating procedures were the most heavily contaminated types of surfaces (1.2×10^5 Copies/swab and 31.92 Ct; Table 6), each followed by the floor (4.6×10^4 Copies/swab and Ct 34.56; Table 6).

Six studies established the infectivity of their surface swabs, and two of them provided evidence for viable virus in 1 of 9 SARS-CoV-2 RNA-positive surface samples from ICU patient rooms and 8 of 17 positive surface samples from 3 non-ICU isolation rooms for invasively and non-invasively ventilated patients (Table 2). Viable SARS-CoV-2 was recovered from on a number of surfaces: two endotracheal tubes/nasal prongs, one Ambu mask/NIV mask (medical AGP equipment), on the floor one meter from a non-invasively ventilated patient, his bed rail, bedsheet, and bedside table (bedside contamination), his remote controller (other surfaces) as well as a facemask of a critically ill patient (medical equipment).

3.4.1 | Sampling strategies to detect surface-borne SARS-CoV-2 contamination

26 studies provided information on the methods used to sample hospital surfaces. In all of these, swabs were pre-moistened prior to sample collection. The media used for pre-moistening were predominantly viral transport media, with three studies utilizing cell culture media. Saline and phosphate-buffered saline were used as viral transport media, whereas hank's solution, hank's solution enriched with nucleic acid protective agents and Dulbecco's Modified Eagle's Medium (DMEM) were the cell culture media used. 14 studies additionally documented that their swabs were sterile, which

remained unknown for all other studies. In general, surfaces were sampled with 5 different types of swabs: gauze pads, foam swabs, cotton swabs, rayon swabs, and viscose swabs. However, for more than 50% of all surface samples, the material coating the swab, or the tip of the applicator was not detailed. Gauze pads most frequently detected surface-borne contamination, however, at the lowest concentrations. Conversely, cotton swabs rarely positive for SARS-CoV-2 RNA, reported the highest viral concentrations, significantly exceeding those reported from viscose swabs or gauze pads (Appendix Tables 1 and 3).

The size of the surface area sampled was detailed in 16 studies investigating surface-borne SARS-CoV-2 contamination in hospitals, ranging from 4 to 2500 cm². The vast majority of samples reflected SARS-CoV-2 contamination of surface areas of 100 cm² or less (1718 of 2240 samples). When SARS-CoV-2 RNA was detected on surfaces, the surface area sampled was significantly larger than in negative surface samples (793.95 cm² vs. 429.41 cm²; $p < 0.001$; Appendix Table 4).

Collection time of surface samples likewise varied between studies. 10 studies sampled surfaces before routine disinfection, 7 studies examined surfaces after disinfection, and 2 studies collected surface samples both before and after disinfection. Minimal surface-borne contamination existed right after and 1–2 hours after the last disinfection of surfaces (1.92% and 2.11%; Appendix Table 1). When samples were collected at exactly 4 or 4–7 hours after surface cleaning, significantly increased detection rates were reported (17.08% and 39.29%; Appendix Table 1). Nonetheless, in one patient room housing an isolated, mildly ill COVID-19 patient, no surface sample was positive for SARS-CoV-2 RNA, even though sample collection took place 9 hours after surface disinfection.

As for airborne contamination, the LoDs of the identification methods significantly influenced the detection of surface-borne SARS-CoV-2 contamination (Appendix Table 4). When the LoD was below 3.8×10^{-1} Copies/μl of VTM, the odds to detect contaminated surfaces increased 12-fold (Appendix Table 1).

3.5 | Impact of COVID-19 interventions on SARS-CoV-2 contamination in hospitals

A common COVID-19 intervention in hospitals was the introduction of patient masking, documented in 18 studies sampling air and in 10 studies examining surface contamination. When facemasks were worn by patients, prevalence of SARS-CoV-2 RNA across patient and clinical areas decreased from 18.77% to 11.13% ($p < 0.001$; Appendix Table 1) in the air and from 19.87% to 8.84% ($p < 0.001$; Appendix Table 1) on surfaces. Concentrations of positive air (Ct 37.09 vs. Ct 28.00; $p < 0.001$; Appendix Table 1) and surface samples (Ct 37.83 vs. Ct 33.73; $p < 0.001$; Appendix Table 3) given in Ct-values were significantly lower as well. However, this was not observed for RNA concentrations given in Copies/L of air (1.52 vs. 4.27 Copies/L; $p = 0.203$; Appendix Table 2). Binary logistic regression models confirmed that patient masking significantly decreased

the odds of air- and surface-borne contamination in hospitals ($OR_{air} = 0.41$ (0.25–0.70) and $OR_{surface} = 0.45$ (0.34–0.61); Table 4).

9 studies reported the type of facemask used for patient masking. In all but one of them, surgical masks were utilized. The remaining study described it ambiguously, referring to them as medical masks, without further specifying the type of medical mask given to patients.

3.6 | Impact of clinical procedures on SARS-CoV-2 contamination in hospitals

In 15 studies examining air- and 5 studies investigating surface-borne SARS-CoV-2 contamination, a number of clinical procedures were performed that could be classified as AGPs, including tracheotomy, tracheal intubation, non-invasive ventilation via venturi masks (NIV), manual ventilation, continuous positive airway pressure therapy (CPAP), biphasic positive airway pressure therapy (BiPAP), high-flow nasal cannula (HFNC), cardiopulmonary resuscitation, and nebulized therapy. AGPs produced a significant increase in SARS-CoV-2 detection rates in patient and adjacent clinical areas from 16.33% to 33.98% ($p < 0.001$; Appendix Table 1) for air and from 15.63% to 48.36% ($p < 0.001$; Appendix Table 1) for surfaces. Their presence furthermore led to significantly elevated concentrations of both air (Ct 26.06 vs. Ct 29.50; $p = 0.014$; Appendix Table 2) and surface-borne contamination (31.02 Ct vs. 36.05 Ct; $p < 0.001$; Appendix Table 3). Multivariate analyses similarly revealed that, when AGPs were performed, the odds to detect air- or surface-borne SARS-CoV-2 contamination were 2 to 2.5 times higher than when no such procedures were documented (Table 4).

3.7 | Impact of the built environment on SARS-CoV-2 contamination in hospitals

Sampling was conducted in two types of hospitals: newly built makeshift hospitals to care for COVID-19 patients and hospitals of traditional construction. Makeshift hospitals were associated with significantly elevated odds of SARS-CoV-2 presence in the air in both univariate (Appendix Tables 1 and 2) and multivariate analyses (Table 4), while surface contamination stayed in a similar range (Appendix Tables 1 and 3).

43 studies reported the types of ventilation present during air and 29 during surface sampling. Natural, mechanical, laminar flow, negative pressure, and the absence of ventilation were reported, in some areas with the addition of HEPA filters, air purifiers, or ultraviolet (UV) light. The highest detection rates for both air- and surface-borne contamination were seen in the presence of negative pressure ventilation (Appendix Tables 1–3). Low SARS-CoV-2 contamination was reported under laminar flow ventilation, negative pressure ventilation with laminar flow, negative pressure ventilation with laminar flow and HEPA filters as well as mechanical ventilation with either HEPA filters, air purifiers, or outdoor air supply (Appendix Tables 1–3).

Binary logistic regressions demonstrated that when mechanical ventilation was accompanied with air purifiers ($OR_{air} = 0.10$ (0.01–0.73) and $OR_{surface} = 0.08$ (0.02–0.35); Table 4) or supplied exclusively with outdoor air ($OR_{surface} = 0.23$ (0.13–0.41); Table 4), SARS-CoV-2 RNA was detected significantly less frequently than under not further specified mechanical ventilation. When sampling was conducted in the presence of laminar flow ventilation, significantly decreased airborne ($OR_{air} = 0.07$ (0.01–0.50); Table 4) and no surface-borne SARS-CoV-2 RNA (0/160 = 0.00%; $p < 0.001$; Appendix Table 1) were documented. Natural ventilation also decreased surface- ($OR_{surface} = 0.28$ (0.14–0.56); Table 4) but not airborne contamination ($OR_{air} = 2.47$ (0.92–6.67); Table 4). When HEPA filters were present, infrequent SARS-CoV-2 contamination was observed on surfaces (2/90 = 2.22%; $p < 0.001$; Appendix Table 1) and none found in the air (0/148 = 0.00%; Appendix Table 1).

ACH were examined in patient rooms, ranging from 2.5 to 240–360. Those with already elevated ACH of 12 to 15 ACH or 12 air supplies and 16 air discharges per hour were associated with remarkably high detection rates of air- and surface-borne contamination (Appendix Table 1). However, with more than 16 ACH, detection rates of air- and surface-borne contamination significantly decreased, and very low RNA concentrations were observed (Appendix Tables 1–3). Evidence of SARS-CoV-2 contamination in the presence of such high ACH was too scarce to perform statistical tests.

Temperature (in °C) and relative humidity (in %) were known in 10 studies, however, often given as means for hospital areas. No significant difference in relative humidity was observed between positive or negative air or surface samples (Appendix Table 4). While temperatures did statistically differ between positive and negative samples, these differences were negligible (1.05°C for air samples and 0.32°C for surfaces; Appendix Table 4).

3.8 | Impact of patient-related factors on SARS-CoV-2 contamination in hospitals

COVID-19 severity was assessed in 553 patients from 35 studies during air sampling and in 243 patients from 25 studies carrying out surface sampling. SARS-CoV-2 contamination was observed in the presence of suspected, asymptomatic, mild, moderate, severe, critical, prolonged PCR-positive (>30 days), seroconverted patients, and a PCR-negative patient recovering from COVID-19. No significant difference was identified for the detection rates of air- or surface-borne contamination between asymptomatic, mild and moderate cases of COVID-19 or severe and critical ones (15.34% vs. 16.63%; $p = 0.550$ and 18.42% vs. 17.94%; $p = 0.750$; Appendix Table 1). While viral concentrations did not significantly vary between air samples from patients of diverging COVID-19 severities (Appendix Table 2), surface samples collected next to severe or critical COVID-19 patients were significantly heavier contaminated with SARS-CoV-2 than those next to asymptomatic, mild or moderately ill COVID-19 patients (4.5×10^5 Copies/swab vs. 4.8×10^3 Copies/swab; $p < 0.001$ and Ct 33.60 vs. Ct 36.98; $p < 0.001$; Appendix Table 3).

The number of patients of any COVID-19 severity present per sample in patient rooms was detailed in 41 studies. The mean number of patients per sample was slightly, but significantly higher when airborne SARS-CoV-2 RNA was detected compared to when air samples were negative for SARS-CoV-2 RNA (1.69 vs. 1.16 patients/sample; $p < 0.001$; Appendix Table 4). This might indicate that even small increases in the number of patients per room can elevate the prevalence of SARS-CoV-2 RNA in hospital air.

Respiratory activities of patients during sampling were rarely documented, known for 115 air samples from 7 studies. One study investigated if 5 prolonged PCR-positive patients with hospital-acquired COVID-19 contaminated the air during normal breathing, with and without wearing facemasks. When no facemasks were worn, airborne contamination was found in close vicinity to 2 patients in 2 of 11 air samples. Another study similarly reported that all 3 air samples collected in the patient room of a patient breathing normally and all 15 air samples from patients' rooms with patients breathing, speaking, and coughing were positive for SARS-CoV-2 RNA. Detection rates of airborne SARS-CoV-2 RNA were high in a study reporting the absence of coughing during air sampling in patient rooms (16/23 = 69.57%). However, no airborne contamination was detected in the 4 remaining studies, in which patients reportedly breathed deeply and normally, spoke, coughed, or sneezed.

Exact distances to patients were detailed for 749 air samples in 32 studies, with air sampling being carried out between 0.01 m and 7.62 m away from patients. Detection rates of airborne SARS-CoV-2 were significantly higher in the immediate patient environment (< 2 m) than ≥ 2 m away (20.85% vs. 14.49%; $p = 0.031$; Appendix Table 1). Nonetheless, airborne contamination was observed 40 times in 13 studies at or beyond the social distance of 2 m and, in another study, in 2 of 3 air samples collected more than 1.83 m away from patients. Additionally, 28 of 168 air samples (16.67%) from anterooms and corridors were positive for SARS-CoV-2 RNA, for which exact distances to patients were not documented.

Viral concentrations were significantly lower ≥ 2 m away from patients than in close vicinity in Ct-values (27.60 vs. 31.11; $p = 0.026$; Appendix Table 2), which was not the case for concentrations given in Copies/L of air (1.65 vs. 10.65; $p = 0.124$; Appendix Table 2).

When distances were analyzed by the meter, it was found that once the distance to patients was further increased above the 2 m threshold, there was no additional drop-off in viral concentrations or detection rates of airborne SARS-CoV-2 (Appendix Tables 1 and 2).

For surface-borne contamination, exact distances to patients were documented for a total of 23 samples. Of these, 10 were positive for SARS-CoV-2 RNA, both within and more than 2 m away from COVID-19 patients.

4 | DISCUSSION

Findings in our review indicate that SARS-CoV-2 can be frequently detected in hospital air since one in six air samples were

contaminated with SARS-CoV-2. Airborne SARS-CoV-2 RNA was detected throughout the hospital, regularly beyond the social distance of 2 m from patients, even extending up to 7.62 m away from the nearest patients. The nature of air contamination revealed the existence of patient-generated, size-fractionated, and infectious aerosols and that among size-fractionated air samples only fine aerosols contained viable SARS-CoV-2. The prevalence of virus-laden, fine aerosols in hospitals was also significantly higher than that of coarse aerosols or droplets, with a peak in size ranges $<1 \mu\text{m}$. In line with previously published studies, these findings suggest that aerosols can both dominate particle exposure during close patient or staff contacts and remain suspended in the air over longer distances, underpinning the short- and long-range aerosol transmission potential of SARS-CoV-2.⁷¹⁻⁷³

Moreover, SARS-CoV-2 RNA was found in the presence of suspected, asymptomatic, mild, moderate, severe, critical, seroconverted, prolonged-PCR-positive and recovering COVID-19 patients. Differences in the severity of COVID-19 were not significantly associated with changes in the prevalence of hospital contamination. Asymptomatic patients tend not to contaminate hospital air via coughing or sneezing but through normal breathing and speech, which predominantly generate fine aerosols.⁷⁴⁻⁷⁶ Two reviewed studies investigating if normal breathing by COVID-19 patients alone led to the presence of SARS-CoV-2 RNA in hospital air detected airborne SARS-CoV-2 RNA, one of them in close proximity to two patients who themselves nosocomially acquired COVID-19.^{20,64} These findings collectively indicate that normal breathing and speech by COVID-19 patients represent a serious hazard of in-hospital SARS-CoV-2 transmission, which is in accordance with the conclusions of a recent review.⁷⁷

In general, levels of airborne contamination varied considerably between sampling sites, which can be attributed to the observed variance in the extent patients emit particles.^{43,44} Another contributing factor is that patient viral loads in sputum are time dependent and differ up to $8 \log_{10}$ Copies/ml between patients.^{78,79} This nature of airborne contamination reflects the possibility of superspreaders within hospitals, which have dominated the transmission dynamics of COVID-19 outside of hospitals.⁸⁰ Evidence of an outbreak in a non-COVID-19 hospital due to a single case of COVID-19 had profound consequences, as it resulted in 27 infected HCPs and 21 nosocomially infected patients, many of which sharing identical viral sequences without contact to each other.⁸¹

The most frequent and intense contamination of surfaces was found on air outlets (28.74% and 1.2×10^5 Copies/swab), located either at the ceiling or far above head height. Such high deposition rates on surfaces that are hard to reach are unlikely to be the result of frequent touching or contamination through large droplets. A study exclusively investigating the SARS-CoV-2 contamination of hospital surfaces reported that air outlets were positive for SARS-CoV-2 RNA up to 56m away from patients, stressing the potential for the virus to be propelled through the air, even facilitated through ventilation systems.⁸² Indeed, long-range aerosol spread has been verified via whole-genome sequencing in a superspreading event, in

which people were infected over distances up to 8m in a facility with recirculated air.⁸³

The review was unable to determine the extent of recirculated air present during sampling. Few unventilated spaces were studied and associated with significantly elevated detection rates of SARS-CoV-2 RNA in the air. Very low detection rates were observed in the presence of laminar flow ventilation in combination with and without negative pressure or HEPA filters. An alternative to such sophisticated ventilation systems with similar effects on airborne SARS-CoV-2 contamination proved to be mechanical ventilation with either HEPA filters, air purifiers, or strict fresh-air supply, which could be more readily utilized throughout the hospital.

The presence of negative pressure ventilation alone is not sufficient to provide protection to patients and staff. Patient rooms with negative pressure relative to adjacent anterooms or corridors but without laminar airflow or HEPA filtration were associated with SARS-CoV-2 contamination rates more similar to those from areas with not further specified mechanical ventilation. Multivariate analysis via binary logistic regression confirmed these findings, showing that the odds to detect airborne SARS-CoV-2 in hospital areas with negative pressure ventilation were not significantly lower than for those with not further specified mechanical ventilation. It is well known that the effectiveness of negative pressure ventilation can be compromised during the daily workflow in hospitals, for example, by constant door openings, affecting the pressure gradients intended to reduce contamination.⁸⁴

In our review, patient rooms with 12 to 15 ACH or 12 air supplies and 16 air discharges per hour were similarly associated with surprisingly high detection rates of air- and surface-borne contamination. When the number of ACH was increased to more than 16, significant reductions in the prevalence of air- and surface-borne SARS-CoV-2 RNA and very low viral concentrations were observed, regardless of the type of ventilation. Even though infrequent SARS-CoV-2 contamination was reported at few selected ACH below 16, increasing the number of ACH in patient rooms to more than 16 would be the safest approach. In addition, when HEPA filters were utilized, regardless of the type of ventilation, number of ACH or hospital area, minimal surface-borne and no airborne SARS-CoV-2 RNA was detected. These results suggest that the type of ventilation used, the presence of effective air filtration, purification or sufficient fresh-air supply, and more than 16 ACH are crucial in ensuring appropriate dilution for infection prevention purposes. Continuous maintenance and design of hospital ventilation systems are also pivotal in keeping the number of ACH above the proposed threshold.⁸⁴

Aerosol-generating procedures significantly increased SARS-CoV-2 contamination. These included tracheotomy, tracheal intubation, several forms of non-invasive oxygen supplementation (NIV, CPAP, BiPAP, HFNC, and manual ventilation), cardiopulmonary resuscitation, and nebulized therapy. During and after these procedures, detection rates and viral concentrations of both air- and surface-borne SARS-CoV-2 contamination heavily increased in patient and adjacent clinical areas. Binary logistic regressions likewise revealed that the odds of SARS-CoV-2 persistence increased 2.5-fold for the

air and twofold for surfaces. Furthermore, viable virus was recovered from medical equipment used in AGPs and all but one of the remaining surface samples with viable SARS-CoV-2 were collected from the vicinity of an isolated, non-invasively ventilated patient. These findings provide further evidence of higher risk of infection with SARS-CoV-2 for hospital staff caring for non-invasively ventilated patients, as well as reinforcing the need for surface cleaning to be carried out within twenty minutes following AGPs performed on COVID-19 patients.^{85,86} A systematic review similarly concluded that tracheal intubation, tracheotomy, manual and non-invasive ventilation significantly elevated the HCP's risk of infection with SARS-CoV, the predecessor of SARS-CoV-2.⁸⁷

In our view, hazards of SARS-CoV-2 transmission routes involving fomites should be considered due to the presence of viable virus on surfaces in two reviewed studies. Viral concentrations on surfaces were highly variable, ranging from the around the lowest possible levels of detection to very high (maximum: 1.90×10^7 Copies/swab). Such high SARS-CoV-2 RNA concentrations on hospital surfaces are possible, since they constitute the sum of all exhaled particles which evaporate and settle on surfaces over periods of time together with particles transmitted through direct contact. This could explain why the floor, especially in patient areas, was very commonly heavily contaminated with SARS-CoV-2. Reviewed articles also suggest that SARS-CoV-2 contamination can arise from the resuspension of virus-laden aerosols by the cleaning of floors or staff movement.^{22,23} It is not always likely to resuspend particles of a respirable size by that, but fomites can be transmitted to the hands, mouth, nose, or eyes.⁸⁸ Even though SARS-CoV-2 can remain viable on different types of surfaces for up to a week, presenting an important hazard for surface-mediated transmission, it is also an enveloped virus and easily affected by most cleaning agents that destroy its envelope.^{25,89} Therefore, effective surface cleaning and audit as well as adequate hand hygiene after contact with surrounding surfaces are crucial to prevent in-hospital SARS-CoV-2 spread.⁹⁰

The outlined potential transmission routes of SARS-CoV-2 are thought to complement each other as aerodynamic characteristics of droplets depend on inertia, the formation of respiratory gas clouds and alter gradually with droplet size, which in itself is heavily dependent on ambient conditions, such as relative humidity and temperature.⁹¹⁻⁹⁴ Inhalable droplets $>10-100 \mu\text{m}$, which would quickly descend to the floor in a room with no airflow present, can under the right circumstances behave like aerosols and thus transmit SARS-CoV-2 the same way in the indoor environments of hospitals.⁹⁵ Relative contributions of transmission modes have not been fully established yet; however, evidence is growing. One study modeled that, without precautions, the inhalation of particles $<10 \mu\text{m}$ would contribute a mean of 57% to the HCP's probability of infection with COVID-19, while droplet or fomite transmission would make up 35% or 8%, respectively.⁹⁶ Another study found aerosol transmission to generally be the main transmission mode.⁹⁷ Similarly, short- and long-range aerosol transmission were found to be the dominant mode of transmission in a

serious cruise ship outbreak, even if very high exchange rates with no recirculated air were assumed.⁹⁸

Infection prevention and control are based on three key determinants: microbiology, epidemiology, and behavioral sciences.⁹⁹ Our review confirmed that facemasks are a suitable epidemiological intervention because patient masking with surgical facemasks significantly decreased the prevalence of air- and surface-borne SARS-CoV-2 contamination in hospitals in univariate and multivariate analyses. Furthermore, viable virus was recovered from the facemask of a critically ill patient in one study, indicating its ability to block viable SARS-CoV-2 from being released by exhalation. The effectiveness of facemasks in infection prevention has already been demonstrated as a number of hospitals outbreaks were contained with the introduction of universal masking for staff and patients.¹⁰⁰⁻¹⁰² Still, residual SARS-CoV-2 infections in spite of patient masking are possible.^{103,104} Also, a reduction in viral concentration of SARS-CoV-2 RNA in the air was observed for one, but not both units of concentration, which can be attributed to the possibility of imperfect sealing of surgical masks.¹⁰⁵ Therefore, double masking or the use of tight-fitting FFP respirators can increase its preventative effect.^{106,107} Facemasks can also be worn during AGPs such as HFNC, which has shown to reduce aerosol particle concentrations in the air around the patient.¹⁰⁸ Additionally, mask removal should be treated with caution as one reviewed study reported it to be the most plausible reason for contaminated air in staff areas.²³ Apparently, considerable rates of self-contamination are possible when doffing PPE.¹⁰⁹

The air and surface contamination with SARS-CoV-2 presented in our review was not limited to specific hospital areas or close contact with COVID-19 patients. Those insights emphasize the importance of involving all patients and HCPs in protective measures regardless of hospital area or occupancy to reduce risks of viral spread. Evidence shows that more than 3/4 of positively tested HCPs in a major hospital outbreak were not devoted to COVID-19 units, with infrequent contact to those infected.¹⁰¹ Whole-genome sequencing of hospital outbreaks identified that HCP to HCP-, patient to HCP-, HCP to patient-, patient to patient- as well as community-associated transmission, all from both asymptomatic and symptomatic individuals, propagate SARS-CoV-2 in hospitals.^{102,110-115} They further revealed that the majority of patients with hospital-associated COVID-19 tested negative multiple times during their hospital stay before testing positive, stressing the importance of COVID-19 surveillance among hospitalized patients.⁶ In fact, a longitudinal sero-epidemiological analysis showed that when precautions did not include contacts with asymptomatic patients, significantly elevated seroconversion rates among hospital staff were found.¹¹⁶

5 | LIMITATIONS

This review is limited by the range of patient, location, and sampling-specific information provided in included articles, and in some cases by incomplete information about those factors. The prevalence of hospital SARS-CoV-2 contamination might be underestimated, mainly because small volumes of air with respect to the volume of air present in

sampling sites were analyzed and more sensitive identification methods were infrequently used. Viral concentrations were not detailed for all samples positive for SARS-CoV-2 RNA and it is further possible that those reported at times do not sufficiently represent real concentrations of SARS-CoV-2 RNA in hospital air, due to the possibility of viral destruction, dehydration, re-aerosolisation, or retention in sampling devices during sampling.^{117,118} Exhaled breath condensates that could better reflect concentrations of airborne SARS-CoV-2 RNA during close and prolonged patient contact were also not analyzed in this review.

In reviewed studies, the viability of specimens was rarely established and not all hospital areas were equally represented. Difficulties in demonstrating viral replication arose due to low concentrations in recovered samples and SARS-CoV-2 being outgrown by other cell populations during culture.^{22,29} This highlights the importance of the existing evidence of infectious fomites as well as patient-generated, size-fractionated, infectious airborne particles, underlines the need for a validation of these findings utilizing the same methodology and indicates that the presence of viable virus in hospitals is probably understated. Two studies could not demonstrate a significant increase of SARS-CoV-2 in the supernatant of all of the air and surface samples for which intact virions or the presence of viral proteins were observed, suggesting that failure to recover viable virus does not definitively rule out its presence.^{20,22,119}

6 | CONCLUSIONS

Our review demonstrates that SARS-CoV-2 contamination, widely found in the air and on surfaces in patient and non-patient areas of hospitals, presents a notable hazard of hospital-associated COVID-19.

Multivariate analyses identified patient areas ($OR_{air} = 1.79$ (1.16–2.78) and $OR_{surface} = 1.83$ (1.36–2.48)) and aerosol-generating procedures ($OR_{air} = 2.56$ (1.46–4.51) and $OR_{surface} = 1.95$ (1.27–2.99)) to promote, whereas patient masking ($OR_{air} = 0.41$ (0.25–0.70) and $OR_{surface} = 0.45$ (0.34–0.61)) decreased both air- and surface-borne SARS-CoV-2 contamination. Further, the type of ventilation used, the presence of effective air filtration, purification or sufficient fresh-air supply as well as more than 16 ACH are crucial in ensuring appropriate dilution for infection prevention and control.

The nature and extent of hospital contamination indicate that SARS-CoV-2 is likely dispersed conjointly through several transmission routes, including short- and long-range aerosol, droplet, and fomite transmission. Without appropriate behavioral compliance to safety protocols that address all air- and surface-mediated transmission routes of SARS-CoV-2, the hidden hazards of SARS-CoV-2 transmission in hospitals will not be controlled.

7 | DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

AUTHOR CONTRIBUTIONS

Noach Leon Ribaric involved in conceptualization, investigation, methodology, data curation, formal analysis, visualization, validation, writing-original draft, and writing-review and editing. **Charles Vincent** involved in conceptualization, supervision, methodology, validation, visualization, writing-original draft, and writing-review and editing. **Günther Jonitz**, **Achim Hellinger** involved in conceptualization, supervision, validation, and writing-review and editing. **Goran Ribaric** involved in conceptualization, investigation, methodology, data curation, formal analysis, project administration, visualization, validation, writing-original draft, and writing-review and editing.

ETHICS APPROVAL AND PATIENT CONSENT STATEMENT

No ethical approval or patient consent was needed since this is a review article.

PERMISSION TO REPRODUCE MATERIAL FROM OTHER SOURCES

No material was reproduced from other sources that required permission.

ORCID

Noach Leon Ribaric  <https://orcid.org/0000-0002-5234-2788>

Charles Vincent  <https://orcid.org/0000-0003-0270-0222>

Günther Jonitz  <https://orcid.org/0000-0001-8067-1776>

Achim Hellinger  <https://orcid.org/0000-0002-1089-4496>

Goran Ribaric  <https://orcid.org/0000-0002-2292-3004>

REFERENCES

1. Suetens C, Latour K, Kärki T, et al. Prevalence of healthcare-associated infections, estimated incidence and composite antimicrobial resistance index in acute care hospitals and long-term care facilities: results from two European point prevalence surveys, 2016 to 2017. *Euro Surveill*. 2018;23(46):1800516.
2. OECD/European Union. Health at a Glance: Europe 2020: State of Health in the EU Cycle, OECD Publishing, Paris. 2020. doi:10.1787/82129230-en
3. Read JM, Green CA, Harrison EM, et al. Hospital-acquired SARS-CoV-2 infection in the UK's first COVID-19 pandemic wave. *Lancet*. 2021;398(10305):1037–8.
4. Carter B, Collins JT, Barlow-Pay F, et al. Nosocomial COVID-19 infection: examining the risk of mortality. The COPE-Nosocomial Study (COVID in Older PEople). *J Hosp Infect*. 2020;106(2):376–384.
5. Rickman HM, Rampling T, Shaw K, et al. Nosocomial transmission of Coronavirus Disease 2019: A Retrospective Study of 66 Hospital-acquired Cases in a London Teaching Hospital. *Clin Infect Dis*. 2021;72(4):690–693.
6. Lumley SF, Constantinides B, Sanderson N, et al. Epidemiological data and genome sequencing reveals that nosocomial transmission of SARS-CoV-2 is underestimated and mostly mediated by a small number of highly infectious individuals. *J Infect*. 2021;83(4):473–82.

7. Brehm TT, van der Meirschen M, Hennigs A, et al. Comparison of clinical characteristics and disease outcome of COVID-19 and seasonal influenza. *Sci Rep*. 2021;11(1):5803.
8. Karan A, Klompas M, Tucker R, Baker M, Vaidya V, Rhee C. The risk of SARS-CoV-2 transmission from patients with undiagnosed Covid-19 to roommates in a large academic medical center. *Clin Infect Dis*. Published online June 18, 2021. doi:10.1093/cid/ciab564
9. Council Recommendation of 9 June 2009 on Patient Safety, Including the Prevention and Control of Healthcare Associated Infections (2009/C 151/01). Accessed September 17, 2021. <https://op.europa.eu/en/publicationdetail/-/publication/8ae80abf-31cd-4577-b0be-4f2fe108f6f9/language-en>
10. European Centre for Disease Prevention and Control. Infection prevention and control and preparedness for COVID-19 in health-care settings – Sixth update. ECDC: Stockholm; 2021. Accessed September 17, 2021. https://www.ecdc.europa.eu/sites/default/files/documents/Infection-prevention-and-control-in-healthcare-settings-COVID-19_6th_update_9_Feb_2021.pdf
11. WHO. Guidelines on core components of infection prevention and control programmes at the national and acute health care facility level, Geneva; 2016. Accessed September 17, 2021. <https://apps.who.int/iris/handle/10665/251730>
12. <https://www.prisma-statement.org/> Accessed September 17, 2021
13. <https://www.cdc.gov/coronavirus/2019-ncov/science/science-briefs/masking-science-sars-cov2.html> Accessed September 17, 2021
14. <https://www.nap.edu/read/13027/chapter/4#30> Accessed September 17, 2021
15. Madas BG, Furi P, Farkas Á, et al. Deposition distribution of the new coronavirus (SARS-CoV-2) in the human airways upon exposure to cough-generated droplets and aerosol particles. *Sci Rep*. 2020;10(1):22430.
16. Milton DK. A Rosetta stone for understanding infectious drops and aerosols. *J Pediatric Infect Dis Soc*. 2020;9(4):413-415.
17. Jackson T, Deibert D, Wyatt G, et al. Classification of aerosol-generating procedures: a rapid systematic review. *BMJ Open Respir Res*. 2020;7(1):e000730.
18. Moola S, Munn Z, Tufanaru C, et al. Chapter 7: Systematic reviews of etiology and risk. In: Aromataris E, Munn Z (Eds). *JBI Manual for Evidence Synthesis*. JBI, 2020. Accessed September 17, 2021. <https://www.synthesismanual.jbi.global>
19. Ma LL, Wang YY, Yang ZH, Huang D, Weng H, Zeng XT. Methodological quality (risk of bias) assessment tools for primary and secondary medical studies: what are they and which is better. *Mil Med Res*. 2020;7(1):7.
20. Santarpia JL, Herrera VL, Rivera DN, et al. The size and culturability of patient-generated SARS-CoV-2 aerosol. *J Expo Sci Environ Epidemiol*. Published online August 18, 2021. doi:10.1038/s41370-021-00376-8
21. Lednicky JA, Lauzardo M, Fan ZH, et al. Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. *Int J Infect Dis*. 2020;100:476-482.
22. Santarpia JL, Rivera DN, Herrera VL, et al. Aerosol and surface contamination of SARS-CoV-2 observed in quarantine and isolation care. *Sci Rep*. 2020;10(1):12732.
23. Liu Y, Ning Z, Chen Y, et al. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. *Nature*. 2020;582(7813):557-560.
24. Guo ZD, Wang ZY, Zhang SF, et al. Aerosol and surface distribution of severe acute respiratory syndrome coronavirus 2 in hospital wards, Wuhan, China, 2020. *Emerg Infect Dis*. 2020;26(7):1583-1591.
25. Zhou J, Otter JA, Price JR, 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*. 2021;73(7):e1870–e1877. doi:10.1093/cid/ciaa905
26. Razzini K, Castrica M, Menchetti L, et al. SARS-CoV-2 RNA detection in the air and on surfaces in the COVID-19 ward of a hospital in Milan, Italy. *Sci Total Environ*. 2020;742:140540.
27. Lei H, Ye F, Liu X, et al. SARS-CoV-2 environmental contamination associated with persistently infected COVID-19 patients. *Influenza Other Respir Viruses*. 2020;14(6):688-699.
28. Kenarkoohi A, Noorimotlagh Z, Falahi S, et al. Hospital indoor air quality monitoring for the detection of SARS-CoV-2 (COVID-19) virus. *Sci Total Environ*. 2020;748:141324.
29. Lednicky JA, Shankar SN, Elbadry MA, et al. Collection of SARS-CoV-2 virus from the air of a clinic within a university student health care center and analyses of the viral genomic sequence. *Aerosol Air Qual Res*. 2020;20(6):1167-1171.
30. Ge XY, Pu Y, Liao CH, et al. Evaluation of the exposure risk of SARS-CoV-2 in different hospital environment. *Sustain Cities Soc*. 2020;61:102413.
31. Tan L, Ma B, Lai X, et al. Air and surface contamination by SARS-CoV-2 virus in a tertiary hospital in Wuhan, China. *Int J Infect Dis*. 2020;99:3-7.
32. Chia PY, Coleman KK, Tan YK, et al. Detection of air and surface contamination by SARS-CoV-2 in hospital rooms of infected patients. *Nat Commun*. 2020;11(1):2800.
33. Ding Z, Qian H, Xu B, et al. Toilets dominate environmental detection of severe acute respiratory syndrome coronavirus 2 in a hospital. *Sci Total Environ*. 2021;753:141710.
34. Cheng VCC, Wong SC, Chen JHK, 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(5):493-498.
35. Cheng VCC, Wong SC, Chan VW, et al. Air and environmental sampling for SARS-CoV-2 around hospitalized patients with coronavirus disease 2019 (COVID-19). *Infect Control Hosp Epidemiol*. 2020;41(11):1258-1265.
36. Faridi S, Niazi S, Sadeghi K, et al. A field indoor air measurement of SARS-CoV-2 in the patient rooms of the largest hospital in Iran. *Sci Total Environ*. 2020;725:138401.
37. Ong SWX, Tan YK, Chia PY, 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(16):1610-1612.
38. 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(8):910-914.
39. Lane MA, Brownsword EA, Morgan JS, et al. Bioaerosol sampling of a ventilated patient with COVID-19. *Am J Infect Control*. 2020;48(12):1540-1542.
40. Ahn JY, An S, Sohn Y, et al. Environmental contamination in the isolation rooms of COVID-19 patients with severe pneumonia requiring mechanical ventilation or high-flow oxygen therapy. *J Hosp Infect*. 2020;106(3):570-576.
41. Li YH, Fan YZ, Jiang L, Wang HB. Aerosol and environmental surface monitoring for SARS-CoV-2 RNA in a designated hospital for severe COVID-19 patients. *Epidemiol Infect*. 2020;148:e154.
42. Wei L, Lin J, Duan X, et al. Asymptomatic COVID-19 patients can contaminate their surroundings: an environment sampling study. *mSphere*. 2020;5(3):e00442-e520.
43. Ma J, Qi X, Chen H, et al. Coronavirus disease 2019 patients in earlier stages exhaled millions of severe acute respiratory syndrome coronavirus 2 per hour. *Clin Infect Dis*. 2021;72(10):e652-e654.
44. Zhou L, Yao M, Zhang X, et al. Breath-, air- and surface-borne SARS-CoV-2 in hospitals. *J Aerosol Sci*. 2021;152:105693.
45. Jerry J, O'Regan E, O'Sullivan L, Lynch M, Brady D. Do established infection prevention and control measures prevent spread

- of SARS-CoV-2 to the hospital environment beyond the patient room. *J Hosp Infect.* 2020;105(4):589-592.
46. Chen GM, Ji JJ, Jiang S, et al. Detecting environmental contamination of acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in isolation wards and fever clinics. *Biomed Environ Sci.* 2020;33(12):943-947.
 47. Mouchtouri VA, Koureas M, Kyritsi M, et al. Environmental contamination of SARS-CoV-2 on surfaces, air-conditioner and ventilation systems. *Int J Hyg Environ Health.* 2020;230:113599. doi:10.1016/j.ijheh.2020.113599
 48. Jin T, Li J, Yang J, et al. SARS-CoV-2 presented in the air of an intensive care unit (ICU). *Sustain Cities Soc.* 2021;65:102446.
 49. Feng B, Xu K, Gu S, et al. Multi-route transmission potential of SARS-CoV-2 in healthcare facilities. *J Hazard Mater.* 2021;402:123771.
 50. Ben-Shmuel A, Brosh-Nissimov T, Glinert I, et al. Detection and infectivity potential of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) environmental contamination in isolation units and quarantine facilities. *Clin Microbiol Infect.* 2020;26(12):1658-1662.
 51. Binder RA, Alarja NA, Robie ER, et al. Environmental and aerosolized severe acute respiratory syndrome coronavirus 2 among hospitalized coronavirus disease 2019 patients. *J Infect Dis.* 2020;222(11):1798-1806.
 52. Kim UJ, Lee SY, Lee JY, et al. Air and environmental contamination caused by COVID-19 patients: a multi-Center study. *J Korean Med Sci.* 2020;35(37):e332.
 53. Hu J, Lei C, Chen Z, et al. Distribution of Airborne SARS-CoV-2 and possible aerosol transmission in Wuhan hospitals, China. *Natl Sci Rev.* 2020;7(12):1865-1867.
 54. Masoumbeigi H, Ghanizadeh G, Yousefi Arfaei R, et al. Investigation of hospital indoor air quality for the presence of SARS-Cov-2. *J Environ Health Sci Eng.* Published online September 30, 2021. doi:10.1007/s40201-020-00543-3
 55. Wei L, Huang W, Lu X, et al. Contamination of SARS-CoV-2 in patient surroundings and on personal protective equipment in a non-ICU isolation ward for COVID-19 patients with prolonged PCR positive status. *Antimicrob Resist Infect Control.* 2020;9(1):167.
 56. Declementi M, Godono A, Mansour I, et al. Assessment of air and surfaces contamination in a COVID-19 non-Intensive Care Unit. *Med Lav.* 2020;111(5):372-378.
 57. López JH, Romo ÁS, Molina DC, et al. Detection of Sars-Cov-2 in the air of two hospitals in Hermosillo, Sonora, México, utilizing a low-cost environmental monitoring system. *Int J Infect Dis.* 2021;102:478-482.
 58. Moharir SC, Sharath Chandra T & Goel A et al. Detection of SARS-CoV-2 in the air from hospitals and closed rooms occupied by COVID-19 patients. *medRxiv.* 2021. doi:10.1101/2020.12.30.20248890
 59. Pochtovyi AA, Bacalin VV, Kuznetsova NA, et al. SARS-CoV-2 aerosol and surface contamination in health care settings: The Moscow Pilot Study. *Aerosol Air Qual Res.* 2021;21(4):200604. doi:10.4209/aaqr.200604
 60. Ong SWX, Tan YK, Coleman KK, et al. Lack of viable severe acute respiratory coronavirus virus 2 (SARS-CoV-2) among PCR-positive air samples from hospital rooms and community isolation facilities. *Infect Control Hosp Epidemiol.* 2021;42(11):1327-32. doi:10.1017/ice.2021.8
 61. Nor NSM, Yip CW, Ibrahim N, et al. Particulate matter (PM_{2.5}) as a potential SARS-CoV-2 carrier. *Sci Rep.* 2021;11(1):2508.
 62. Yarahmadi R, Bokharaei-Salim F, Soleimani-Alyar S, et al. Occupational exposure of health care personnel to SARS-CoV-2 particles in the intensive care unit of Tehran hospital. *Int J Environ Sci Technol.* Published online February 02, 2021. doi:10.1007/s13762-020-03095-z
 63. Munoz-Price LS, Rivera F, Ledebor N. Air contamination of households versus hospital inpatient rooms occupied by severe acute respiratory coronavirus virus 2 (SARS-CoV-2)-positive patients. *Infect Control Hosp Epidemiol.* Published online February 04, 2021. doi:10.1017/ice.2021.45
 64. Di Carlo P, Falasca K, Ucciferri C, et al. Normal breathing releases SARS-CoV-2 into the air. *J Med Microbiol.* 2021;70(3):1328.
 65. Stern RA, Koutrakis P, Martins MAG, et al. Characterization of hospital airborne SARS-CoV-2. *Respir Res.* 2021;22(1):73.
 66. Stern RA, Al-Hemoud A, Alahmad B, et al. Levels and particle size distribution of airborne SARS-CoV-2 at a healthcare facility in Kuwait. *Sci Total Environ.* 2021;782:146799. doi:10.1016/j.scitotenv.2021.146799
 67. Hemati S, Mobini GR, Heidari M, et al. Simultaneous monitoring of SARS-CoV-2, bacteria, and fungi in indoor air of hospital: a study on Hajar Hospital in Shahrekord, Iran. *Environ Sci Pollut Res Int.* 2021;28(32):43792-43802.
 68. Dubey A, Kotnala G, Mandal TK, et al. Evidence of the presence of SARS-CoV-2 virus in atmospheric air and surfaces of a dedicated COVID hospital. *J Med Virol.* 2021;93(9):5339-5349.
 69. Barbieri P, Zupin L, Licen S, et al. Molecular detection of SARS-CoV-2 from indoor air samples in environmental monitoring needs adequate temporal coverage and infectivity assessment. *Environ Res.* 2021;198:111200.
 70. Barksdale AN, Zeger WG, Santarpia JL, et al. Implementation of a COVID-19 cohort area resulted in no surface or air contamination in surrounding areas in one academic emergency department. *Am J Emerg Med.* 2021;47:253-257.
 71. Chen W, Zhang N, Wei J, Yen H-L, Li Y. Short-range airborne route dominates exposure of respiratory infection during close contact. *Build Environ.* 2020;176:106850.
 72. Li Y. Hypothesis: SARS-CoV-2 transmission is predominated by the short-range airborne route and exacerbated by poor ventilation. *Indoor Air.* 2021;31(4):921-925.
 73. Liu L, Li Y, Nielsen PV, Wei J, Jensen RL. Short-range airborne transmission of expiratory droplets between two people. *Indoor Air.* 2017;27(2):452-462.
 74. Asadi S, Wexler AS, Cappa CD, Barreda S, Bouvier NM, Ristenpart WD. Aerosol emission and superemission during human speech increase with voice loudness. *Sci Rep.* 2019;9(1):2348.
 75. Mürbe D, Kriegel M, Lange J, Schumann L, Hartmann A, Fleischer M. Aerosol emission of adolescents voices during speaking, singing and shouting. *PLoS One.* 2021;16(2):e0246819.
 76. Mürbe D, Kriegel M, Lange J, Rotheudt H, Fleischer M. Aerosol emission in professional singing of classical music. *Sci Rep.* 2021;11(1):14861.
 77. Stadnytskyi V, Anfinrud P, Bax A. Breathing, speaking, coughing or sneezing: What drives transmission of SARS-CoV-2. *J Intern Med.* 2021;290(5):1010-27. doi:10.1111/joim.13326
 78. To KK, Tsang OT, Leung WS, et al. Temporal profiles of viral load in posterior oropharyngeal saliva samples and serum antibody responses during infection by SARS-CoV-2: an observational cohort study. *Lancet Infect Dis.* 2020;20(5):565-574.
 79. Wölfel R, Corman VM, Guggemos W, et al. Virological assessment of hospitalized patients with COVID-2019. *Nature.* 2020;581(7809):465-469.
 80. Lewis D. Superspreading drives the COVID pandemic - and could help to tame it. *Nature.* 2021;590(7847):544-546.
 81. Borges V, Isidro J, Macedo F, et al. Nosocomial outbreak of SARS-CoV-2 in a "Non-COVID-19" Hospital Ward: virus genome sequencing as a key tool to understand cryptic transmission. *Viruses.* 2021;13(4):604.
 82. Nissen K, Krambrich J, Akaberi D, et al. Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards. *Sci Rep.* 2020;10(1):19589.
 83. Günther T, Czech-Sioli M, Indenbirken D, et al. SARS-CoV-2 outbreak investigation in a German meat processing plant. *EMBO Mol Med.* 2020;12(12):e13296.

84. Eames I, Tang JW, Li Y, Wilson P. Airborne transmission of disease in hospitals. *J R Soc Interface*. 2009;6(Suppl 6):S697-702.
85. Schünemann HJ, Khabsa J, Solo K, et al. Ventilation techniques and risk for transmission of coronavirus disease, including COVID-19: A living systematic review of multiple streams of evidence. *Ann Intern Med*. 2020;173(3):204-216.
86. <https://www.gov.uk/government/publications/wuhan-novel-coronavirus-infection-prevention-and-control> Accessed September 17, 2021
87. 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(4):e35797.
88. National Academies of Sciences, Engineering, and Medicine. Rapid Expert Consultations on the COVID-19 Pandemic: March 14, 2020–April 8, 2020. Washington (DC): National Academies Press. doi:10.17226/25784
89. Rawlinson S, Ciric L, Cloutman-Green E. COVID-19 pandemic - let's not forget surfaces. *J Hosp Infect*. 2020;105(4):790-791.
90. https://www.who.int/gpsc/5may/tools/who_guidelines-handhygiene_summary.pdf. Accessed September 17, 2021.
91. Bahl P, Doolan C, de Silva C, Chughtai AA, Bourouiba L, MacIntyre CR. Airborne or droplet precautions for health workers treating COVID-19. *J Infect Dis*. Published online April 16, 2020. doi:10.1093/infdis/jiaa189
92. Prather KA, Wang CC, Schooley RT. Reducing transmission of SARS-CoV-2. *Science*. 2020;368(6498):1422-1424.
93. Bourouiba L. Turbulent gas clouds and respiratory pathogen emissions: potential implications for reducing transmission of COVID-19. *JAMA*. 2020;323(18):1837-1838.
94. Tsuda A, Henry FS, Butler JP. Particle transport and deposition: basic physics of particle kinetics. *Compr Physiol*. 2013;3(4):1437-1471.
95. Tellier R, Li Y, Cowling BJ, Tang JW. Recognition of aerosol transmission of infectious agents: a commentary. *BMC Infect Dis*. 2019;19(1):101.
96. Jones RM. Relative contributions of transmission routes for COVID-19 among healthcare personnel providing patient care. *J Occup Environ Hyg*. 2020;17(9):408-415.
97. Zhang R, Li Y, Zhang AL, Wang Y, Molina MJ. Identifying airborne transmission as the dominant route for the spread of COVID-19. *Proc Natl Acad Sci USA*. 2020;117(26):14857-14863.
98. Azimi P, Keshavarz Z, Cedeno Laurent JG, Stephens B, Allen JG. Mechanistic transmission modeling of COVID-19 on the Diamond Princess cruise ship demonstrates the importance of aerosol transmission. *Proc Natl Acad Sci USA*. 2021;118(8):e2015482118.
99. Pittet D. The Lowbury lecture: behaviour in infection control. *J Hosp Infect*. 2004;58(1):1-13.
100. Contejean A, Leporrier J, Canouë E, et al. Comparing dynamics and determinants of severe acute respiratory syndrome Coronavirus 2 transmissions among healthcare workers of adult and pediatric settings in central Paris. *Clin Infect Dis*. 2021;72(2):257-264.
101. Thompson ER, Williams FS, Giacin PA, et al. Universal masking to control healthcare-associated transmission of severe acute respiratory coronavirus virus 2 (SARS-CoV-2). *Infect Control Hosp Epidemiol*. Published online March 29, 2021. doi:10.1017/ice.2021.127
102. Paltansing S, Sikkema RS, de Man SJ, Koopmans MPG, Oude Munnink BB, de Man P. Transmission of SARS-CoV-2 among healthcare workers and patients in a teaching hospital in the Netherlands confirmed by whole-genome sequencing. *J Hosp Infect*. 2021;110:178-183.
103. Klompas M, Baker MA, Griesbach D, et al. Transmission of SARS-CoV-2 from asymptomatic and presymptomatic individuals in healthcare settings despite medical masks and eye protection. *Clin Infect Dis*. 2021;73(9):1693-5. doi:10.1093/cid/ciab218
104. Goldberg L, Levinsky Y, Marcus N, et al. SARS-CoV-2 infection among health care workers despite the use of surgical masks and physical distancing-the role of airborne transmission. *Open Forum Infect Dis*. 2021;8(3):ofab036.
105. Cappa CD, Asadi S, Barreda S, Wexler AS, Bouvier NM, Ristenpart WD. Expiratory aerosol particle escape from surgical masks due to imperfect sealing. *Sci Rep*. 2021;11(1):12110.
106. Brooks JT, Beezhold DH, Noti JD, et al. Maximizing Fit for cloth and medical procedure masks to improve performance and reduce SARS-CoV-2 transmission and exposure, 2021. *MMWR Morb Mortal Wkly Rep*. 2021;70(7):254-257.
107. Lee SA, Hwang DC, Li HY, Tsai CF, Chen CW, Chen JK. Particle size-selective assessment of protection of European standard FFP respirators and surgical masks against particles-tested with human subjects. *J Healthc Eng*. 2016;2016:8572493.
108. Li J, Fink JB, Elshafei AA, et al. Placing a mask on COVID-19 patients during high-flow nasal cannula therapy reduces aerosol particle dispersion. *ERJ Open Res*. 2021;7(1):00519-2020.
109. Chughtai AA, Chen X, Macintyre CR. Risk of self-contamination during doffing of personal protective equipment. *Am J Infect Control*. 2018;46(12):1329-1334.
110. Lucey M, Macori G, Mullane N, et al. Whole-genome sequencing to track severe acute respiratory syndrome Coronavirus 2 (SARS-CoV-2) transmission in nosocomial outbreaks. *Clin Infect Dis*. 2021;72(11):e727-e735.
111. Ellingford JM, George R, McDermott JH, et al. Genomic and healthcare dynamics of nosocomial SARS-CoV-2 transmission. *Elife*. 2021;10:e65453.
112. Braun KM, Moreno GK, Buys A, et al. Viral sequencing reveals US healthcare personnel rarely become infected with SARS-CoV-2 through patient contact. *Clin Infect Dis*. 2021;73(6):e1329-e1336. doi:10.1093/cid/ciab281
113. Sikkema RS, Pas SD, Nieuwenhuijse DF, et al. COVID-19 in healthcare workers in three hospitals in the south of the Netherlands: a cross-sectional study. *Lancet Infect Dis*. 2020;20(11):1273-1280.
114. Meredith LW, Hamilton WL, Warne B, et al. Rapid implementation of SARS-CoV-2 sequencing to investigate cases of health-care associated COVID-19: a prospective genomic surveillance study. *Lancet Infect Dis*. 2020;20(11):1263-1271.
115. Francis RV, Billam H & Clarke M et al. The impact of real-time whole genome sequencing in controlling healthcare-associated SARS-CoV-2 outbreaks. *medRxiv*. 2021. doi:10.1101/2021.04.15.21253894
116. Brehm TT, Schwing D, Lampalzer S, et al. Seroprevalence of SARS-CoV-2 antibodies among hospital workers in a German tertiary care center: A sequential follow-up study. *Int J Hyg Environ Health*. 2021;232:113671.
117. Pan M, Lednicky JA, Wu CY. Collection, particle sizing and detection of airborne viruses. *J Appl Microbiol*. 2019;127(6):1596-1611.
118. Verreault D, Moineau S, Duchaine C. Methods for sampling of airborne viruses. *Microbiol Mol Biol Rev*. 2008;72(3):413-444.
119. Tang JW, Bahnfleth WP, Bluyssen PM, et al. Dismantling myths on the airborne transmission of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2). *J Hosp Infect*. 2021;110:89-96.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

How to cite this article: Ribaric NL, Vincent C, Jonitz G, Hellinger A, Ribaric G. Hidden hazards of SARS-CoV-2 transmission in hospitals: A systematic review. *Indoor Air*. 2022;32:e12968. doi:10.1111/ina.12968

TABLE A1 Association of categorical factors with detection rates of air- and surface-borne SARS-CoV-2 contamination

Detection rates of airborne SARS-CoV-2 RNA					Detection rates of surface-borne SARS-CoV-2 RNA				
N	%	p	φ _c	OR (95% CI)	N	%	p	φ _c	OR (95% CI)
COVID-19 Severity		0.550	0.018				0.750	0.006	
asymptomatic/mild/moderate	626	15.34		Reference	1683	18.42			Reference
severe/critical	517	16.63		1.10 (0.80–1.51)	1098	17.94			0.97 (0.80–1.18)
Patient Masking		<0.001	0.096				<0.001	0.147	
Patient Masking present	485	11.13		0.54 (0.39–0.75)	1335	8.84			0.39 (0.32–0.49)
no Patient Masking listed	1060	18.77		Reference	2225	19.87			Reference
Aerosol-generating procedures (AGPs)		<0.001	0.115				<0.001	0.145	
AGPs present	103	33.98		2.64 (1.72–4.06)	117	47.86			4.96 (3.41–7.20)
no AGPs listed	1476	16.33		Reference	3961	15.63			Reference
Types of AGPs		–	–	–			0.127	0.188	–
Non-invasive oxygen supplementation	95	33.68	–		94	52.13	0.345*		
Tracheotomy	3	33.33	–		13	23.08	0.345*		
Cardiopulmonary Resuscitation	1	100.00	–		10	40.00	>0.999*		
Tracheal Intubation	1	100.00	–		–	–	–		
Nebulized Therapy	3	0.00	–		–	–	–		
Types of Room Ventilation		<0.001	0.279	–			<0.001	0.245	–
None	15	73.33	<0.001*		–	–	–		
UV light air purification	18	0.00	>0.999*		81	16.05	>0.999*		
Natural Ventilation	114	17.54	>0.999*		318	3.14	<0.001*		
Natural Ventilation and UV light air purification	60	8.33	>0.999*		555	9.19	<0.001*		
Not further specified Mechanical Ventilation	856	17.41	>0.999*		1297	20.51	<0.001*		
Mechanical Ventilation with outdoor air supply	65	1.54	0.025*		307	4.56	<0.001*		
Mechanical Ventilation and HEPA Filtration	108	0.00	<0.001*		75	0.00	0.002*		
Mechanical Ventilator and Air Purifiers	25	4.00	>0.999*		68	2.94	0.054*		
Laminar Flow Ventilation	58	1.72	0.070*		160	0.00	<0.001*		
Negative Pressure Ventilation	246	29.27	<0.001*		1176	26.02	<0.001*		

(Continues)

TABLE A1 (Continued)

Detection rates of airborne SARS-CoV-2 RNA					Detection rates of surface-borne SARS-CoV-2 RNA					
	N	%	p	φ _c	OR (95% CI)	N	%	p	φ _c	OR (95% CI)
Negative Pressure Ventilation and HEPA Filtration	18	0.00	>0.999*			15	13.33	>0.999*		
Negative Pressure, HEPA Filtration and Laminar Flow	22	0.00	>0.999*			-	-	-		
HEPA Filtration										
HEPA Filters present	148	0.00			-	90	2.22	<0.001	0.058	0.11 (0.03–0.46)
no HEPA Filters listed	1457	17.84		0.140		3962	16.71			Reference
Air Changes per Hour (ACH) in Patient Rooms										
>16 ACH	82	2.44			0.13 (0.03–0.53)	179	7.82			0.28 (0.16–0.48)
≤ 16 ACH	433	16.40			Reference	1281	23.58			Reference
Exact ACH in Patient Rooms										
2.5 ACH	29	0.00	0.558*	0.549	-	34	5.88	0.429*	0.459	-
2–6 ACH	3	100.00	<0.001*			12	25.00	>0.999*		
6 ACH	20	30.00	0.929*			-	-	-		
8 air supplies and 12 air discharges/hour	40	5.00	>0.999*			68	11.76	0.910*		
12 ACH	108	25.93	0.003*			789	17.24	<0.001*		
12–15 ACH	23	69.57	<0.001*			107	72.90	<0.001*		
12 air supplies and 16 air discharges/hour	38	34.21	0.006*			69	46.38	<0.001*		
14 ACH	160	1.88	<0.001*			100	7.00	0.004*		
15 ACH	12	0.00	>0.999*			102	35.29	0.009*		
>16 ACH	2	50.00	>0.999*			19	73.68	<0.001*		
20 ACH	22	0.00	>0.999*			-	-	-		
240–360 ACH	58	1.72	0.097*			160	0.00	<0.001*		
Sampling Distance to Patients				0.079					-	-
<2 m	470	20.85			Reference	13	61.54			
≥ 2 m	276	14.49			0.64 (0.43–0.96)	9	11.11			
Sampling Distance to Patients by the meter										
0.01–0.99 m	210	5.24	<0.001*	0.320	-	7	100.00	-	-	-

TABLE A1 (Continued)

	Detection rates of airborne SARS-CoV-2 RNA					Detection rates of surface-borne SARS-CoV-2 RNA				
	N	%	p	φ_c	OR (95% CI)	N	%	p	φ_c	OR (95% CI)
1.00–1.99 m	259	33.20	<0.001*			6	16.67	-		
>1.00 m (not included in categories </≥2 m)	-	-	-			1	100.00	-		
<1.83 m	1	100.00	0.786*			-	-	-		
2.00–2.99 m	136	13.24	>0.999*			1	0.00	-		
3.00–3.99 m	83	15.66	>0.999*			1	0.00	-		
4.00–4.99 m	10	30.00	>0.999*			-	-	-		
5.00 m	11	0.00	>0.999*			-	-	-		
6.10 m	1	100.00	0.786*			-	-	-		
7.62 m	18	16.67	>0.999*			-	-	-		
size ranges ≥2 m	17	11.76	>0.999*			7	14.29	-		
>1.83 m (not included in categories </≥2 m)	3	66.67	0.786*			-	-	-		
Limit of Detection			<0.001	0.250				<0.001	0.347	
<0.38 Copies/μl	269	28.25			5.08 (2.61–9.92)	553	29.11			12.10 (7.22–20.30)
≥ 0.38 Copies/μl	153	7.19			Reference	518	3.28			Reference
Type of Hospital			<0.001	0.085				0.947	0.001	
Makeshift Hospitals	148	27.03			2.04 (1.38–2.99)	307	16.29			1.01 (0.74–1.38)
Traditional Construction	1702	15.39			Reference	4101	16.14			Reference
General Hospital Areas			<0.001	0.104				<0.001	0.157	
Patient Areas	1104	19.47			Reference	2810	20.50			Reference
Non-Patient Areas	746	11.66			0.55 (0.42–0.71)	1598	8.51			0.36 (0.30–0.44)
Major Hospital Areas										
ICU	335	26.87	<0.001	0.124	Reference	425	22.12	0.366	0.017	Reference
Non-ICU	765	16.21			0.53 (0.39–0.72)	2372	20.19			0.89 (0.69–1.14)
Clinical Area	478	12.76	0.406	0.031	Reference	1268	7.81	0.985	0.001	Reference
Staff Area	218	10.55			0.81 (0.48–1.34)	255	7.84			1.01 (0.61–1.66)
Subdivisions of Hospital Areas			0.821	0.007				-	-	-
at patient in Patient Rooms	999	20.32			Reference	-	-			
near an air outlet in Patient Rooms	32	21.88			1.10 (0.47–2.57)	-	-			

(Continues)

TABLE A1 (Continued)

	Detection rates of airborne SARS-CoV-2 RNA					Detection rates of surface-borne SARS-CoV-2 RNA				
	N	%	p	ϕ_c	OR (95% CI)	N	%	p	ϕ_c	OR (95% CI)
Air Sampling Flow Rate			0.725	0.008				-	-	-
Low Flow Rate (≤ 10 L/min)	846	16.55			1.05 (0.81–1.35)	-	-			
High Flow Rate (>10 L/min)	929	15.93			Reference	-	-			
Type of air sampling device/ method			<0.001	0.280	-	-	-	-	-	-
Cyclone	594	13.80	0.455*			-	-			
Laminar-flow water-based condensator	18	61.11	<0.001 *			-	-			
Filter	497	29.98	<0.001 *			-	-			
Impinger	329	4.56	<0.001 *			-	-			
Impactor	235	14.89	>0.999 *			-	-			
Other	177	5.65	<0.001 *			-	-			
Type of surface swab			-	-	-			<0.001	0.476	-
gauze pads	-	-				143	66.43	<0.001 *		
foam swabs	-	-				245	22.86	<0.001 *		
cotton swabs	-	-				1131	7.34	<0.001 *		
rayon swabs	-	-				143	2.10	<0.001 *		
viscose swabs	-	-				116	10.34	>0.999 *		
Surface Sample Collection Time			-	-	-			<0.001	0.220	-
Before routine cleaning	-	-				1865	9.49	<0.001 *		
Directly after routine cleaning	-	-				52	1.92	0.389*		
1–2 hours after routine cleaning	-	-				95	2.11	0.052*		
4 hours after routine cleaning	-	-				363	17.08	0.003*		
4–7 hours after routine cleaning	-	-				112	39.29	<0.001 *		
6 hours after routine cleaning	-	-				13	0.00	>0.999 *		
After routine cleaning, exact time unknown	-	-				16	0.00	>0.999 *		

Note: N = Total number of samples, % = percent positive for SARS-CoV-2 RNA, p = p -value, ϕ_c = Cramer's phi, OR = odds ratio, (95% CI) = 95% confidence intervals.
*Bonferroni Corrections.

TABLE A2 Association of categorical factors with concentrations of airborne SARS-CoV-2 contamination

	Airborne SARS-CoV-2 RNA in Copies/L of air						Airborne SARS-CoV-2 RNA in Ct-values					
	n	μ	σ	M	IQR	p	r	n	μ	σ	M	IQR
COVID-19 Severity							0.915	0.011				
asymptomatic/mild/moderate	63	5.74	14.53	0.93	4.07			26	27.08	6.75	26.71	9.11
severe/critical	25	1.86	2.33	1.40	2.09			51	27.56	6.31	27.50	8.50
Patient Masking							0.203	0.142				
Patient Masking present	30	1.52	2.25	0.99	1.38			11	37.09	3.74	37.49	2.85
no Patient Masking listed	50	4.27	15.05	0.35	1.08			101	28.00	5.85	28.69	8.50
Aerosol-generating procedures (AGPs)							-	-				
AGPs present	3	0.41	0.65	0.04	-			26	26.06	5.13	27.19	10.40
no AGPs listed	100	4.21	11.75	1.06	3.63			84	29.50	6.23	29.76	12.36
Type of AGPs							-	-				
Non-invasive oxygen supplementation	1	0.03	-	-	-			26	26.06	5.13	27.19	10.40
Tracheotomy	1	1.16	-	-	-			-	-	-	-	-
Tracheal Intubation	-	-	-	-	-			-	-	-	-	-
Cardiopulmonary Resuscitation	1	0.04	-	-	-			-	-	-	-	-
Nebulized Therapy	-	-	-	-	-			-	-	-	-	-
Types of Room Ventilation							<0.001	-				
None	10	0.01	0.01	0.01	0.02			-	-	-	-	-
UV light air purification	-	-	-	-	-			-	-	-	-	-
Natural Ventilation	16	0.02	0.05	0.01	0.02			-	-	-	-	-
Natural Ventilation and UV light air purification	4	46.00	33.98	37.00	62.00			-	-	-	-	-
Not further specified Mechanical Ventilation	51	0.84	1.14	0.40	1.38			68	27.22	5.66	27.51	7.45
Mechanical Ventilation with outdoor air supply	-	-	-	-	-			1	37.80	-	-	-
Mechanical Ventilation and HEPA Filtration	-	-	-	-	-			-	-	-	-	-
Mechanical Ventilation and Air Purifiers	-	-	-	-	-			-	-	-	-	-
Laminar Flow Ventilation	-	-	-	-	-			1	41.50	-	-	-
Negative Pressure Ventilation	42	4.39	7.79	2.45	4.53			15	24.35	4.18	22.60	4.10

(Continues)

TABLE A2 (Continued)

	Airborne SARS-CoV-2 RNA in Copies/L of air							Airborne SARS-CoV-2 RNA in Ct-values						
	<i>n</i>	μ	σ	<i>M</i>	<i>IQR</i>	<i>p</i>	<i>r</i>	<i>n</i>	μ	σ	<i>M</i>	<i>IQR</i>	<i>p</i>	<i>r</i>
Negative Pressure Ventilation and HEPA Filtration	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Negative Pressure Ventilation, HEPA Filtration, and Laminar Flow	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HEPA Filtration	-	-	-	-	-	-	-	-	-	-	-	-	-	-
HEPA Filters present	-	-	-	-	-	-	-	-	-	-	-	-	-	-
no HEPA Filters listed	123	3.35	10.69	0.47	2.41			85	27.00	5.80	26.87	8.15		
Air Changes per Hour (ACH) in Patient Rooms														
>16 ACH	51	7.12	15.82	2.42	3.29			3	37.70	1.28	37.40			
≤ 16 ACH	1	0.03	-	-	-			1	41.50	-	-	-		
Exact ACH in Patient Rooms						0.001	-						-	-
2.5 ACH	-	-	-	-	-			-	-	-	-	-		
2–6 ACH	3	0.51	N.A.	0.51	-			-	-	-	-	-		
6 ACH	4	46.00	33.98	37.00	62.00			-	-	-	-	-		
8 air supplies and 12 air discharges/hour	2	0.68	N.A.	0.68	-			-	-	-	-	-		
12 ACH	13	0.98	0.78	0.92	1.10			-	-	-	-	-		
12–15 ACH	16	8.32	11.40	4.48	5.10			-	-	-	-	-		
12 air supplies and 16 air discharges/hour	13	2.32	1.22	1.40	2.40			-	-	-	-	-		
14 ACH	-	-	-	-	-			3	37.70	1.28	37.40			
15 ACH	-	-	-	-	-			-	-	-	-	-		
>16 ACH	1	0.03	-	-	-			-	-	-	-	-		
20 ACH	-	-	-	-	-			-	-	-	-	-		
240–360 ACH	-	-	-	-	-			1	41.50	-	-	-		
Sampling Distance to Patients						0.124	0.224						0.026	0.274
<2 m	29	1.65	1.28	1.40	1.54			50	27.60	7.19	27.19	10.72		
≥ 2 m	17	10.65	24.13	0.60	5.82			16	31.11	4.10	30.51	2.33		
Sampling Distance to Patients by the meter						0.215	0.212						0.108	0.213

	Airborne SARS-CoV-2 RNA in Copies/L of air						Airborne SARS-CoV-2 RNA in Ct-values							
	<i>n</i>	μ	σ	<i>M</i>	<i>IQR</i>	<i>p</i>	<i>r</i>	<i>n</i>	μ	σ	<i>M</i>	<i>IQR</i>	<i>p</i>	<i>r</i>
0.01–0.99 m	3	0.61	0.52	0.75	–			4	36.04	8.74	37.13	16.65		
1.00–1.99 m	25	1.68	1.23	1.40	1.45			46	28.86	6.66	26.79	9.56		
>1.00 m (not included in categories </≥2 m)	–	–	–	–	–			–	–	–	–	–		
<1.83 m	1	4.07	–	–	–			–	–	–	–	–		
2.00–2.99 m	9	14.20	31.47	0.68	14.95			4	36.15	2.99	36.70	5.61		
3.00–3.99 m	2	0.44	0.61	0.44	–			11	29.40	3.00	30.20	2.49		
4.00–4.99 m	3	20.17	22.04	16.00	–			–	–	–	–	–		
5.00 m	–	–	–	–	–			–	–	–	–	–		
6.10 m	–	–	–	–	–			1	29.82	–	–	–		
7.62 m	3	0.02	0.02	0.01	–			–	–	–	–	–		
size ranges ≥2 m	–	–	–	–	–			–	–	–	–	–		
>1.83 m (not included in categories </≥2 m)	2	2.45	0.04	2.45	–			–	–	–	–	–		
Limit of Detection						0.028	0.240						–	–
<0.38 Copies/μl	72	5.28	13.65	1.40	3.94			1	36.00	–	–	–		
≥ 0.38 Copies/μl	11	0.04	0.06	0.01	0.04			–	–	–	–	–		
Type of Hospital						<0.001	0.315						–	–
Makeshift Hospitals	40	0.81	1.27	0.02	1.40			–	–	–	–	–		
Traditional Construction	87	4.52	12.57	0.91	2.96			113	28.98	6.32	29.60	10.17		
General Hospital Areas						<0.001	0.517						0.010	0.242
Patient Areas	75	5.18	13.39	1.40	3.41			83	28.15	6.72	28.10	11.31		
Non-Patient Areas	52	0.72	1.72	0.01	0.29			30	31.29	4.36	31.10	5.22		
Major Hospital Areas						0.015	0.283						0.154	0.157
ICU	28	1.58	2.32	1.26	1.38			47	27.22	6.28	26.70	8.40		
Non-ICU	46	7.46	16.67	1.72	4.82			36	29.35	7.17	29.50	12.46		
Clinical Area	28	1.20	2.21	0.04	2.03	0.002	0.451	29	31.03	4.20	31.10	3.89		
Staff Area	21	0.02	0.05	0.01	0.02			1	38.83	–	–	–		
Subdivisions of Hospital Areas						0.306	0.121						–	–

TABLE A2 (Continued)

	Airborne SARS-CoV-2 RNA in Copies/L of air						Airborne SARS-CoV-2 RNA in Ct-values							
	<i>n</i>	μ	σ	<i>M</i>	IQR	<i>p</i>	<i>r</i>	<i>n</i>	μ	σ	<i>M</i>	IQR	<i>p</i>	<i>r</i>
near an air outlet in Patient Rooms	7	2.91	1.52	3.80	2.12			-	-	-	-	-		
Air Sampling Flow Rate						<0.001	0.538						0.001	0.322
Low Flow Rate (≤ 10 L/min)	68	4.12	14.23	0.02	0.89			23	33.34	4.85	31.00	8.44		
High Flow Rate (>10 L/min)	45	2.88	2.58	2.36	3.01			90	27.87	6.19	27.76	9.02		
Type of air sampling device/ method						<0.001	-						<0.001	0.427
Cyclone	39	1.48	1.43	1.34	1.03			10	38.22	2.85	37.45	3.44		
Laminar-flow water-based condensator	11	17.30	29.41	1.43	29.61			-	-	-	-	-		
Filter	38	4.30	8.26	2.45	5.44			102	27.99	5.78	28.60	8.50		
Impinger	3	0.08	0.12	0.02	-			-	-	-	-	-		
Impactor	34	0.06	0.15	0.01	0.03			-	-	-	-	-		
Other	2	6.16	7.13	6.16	-			-	-	-	-	-		

Note: *n* = number of samples positive for SARS-CoV-2 RNA, μ = mean, σ = standard deviation, *M* = median, IQR = interquartile range, *p* = *p*-value, *r* = Pearson's *r*.

TABLE A3 Association of categorical factors with concentrations of surface-borne SARS-CoV-2 contamination

	Surface-borne SARS-CoV-2 RNA in Copies/swab							Surface-borne SARS-CoV-2 RNA in Ct-values						
	n	μ	σ	M	IQR	p	r	n	μ	σ	M	IQR	p	r
COVID-19 Severity														
Asymptomatic/mild/moderate	15	4.8 × 10 ³	5.4 × 10 ³	3.4 × 10 ³	8.5 × 10 ³	<0.001	0.660	177	36.98	3.82	37.99	3.08	<0.001	0.442
Severe/critical	48	4.5 × 10 ⁵	2.7 × 10 ⁶	4.3 × 10 ⁴	4.5 × 10 ⁴			140	33.60	5.09	34.01	5.57		
Patient Masking														
Patient Masking present	66	3.3 × 10 ⁵	2.3 × 10 ⁶	2.8 × 10 ⁴	6.3 × 10 ⁴	-	-	31	37.83	2.33	37.15	1.91	<0.001	0.305
No Patient Masking listed	4	2.3 × 10 ³	1.6 × 10 ³	2.3 × 10 ³	2.8 × 10 ³			205	33.73	4.95	35.00	5.19		
Aerosol-generating procedures (AGPs)														
AGPs present	-	-	-	-	-			35	31.02	4.62	31.97	4.02		
no AGPs listed	71	3.0 × 10 ⁵	2.3 × 10 ⁶	2.8 × 10 ⁴	6.3 × 10 ⁴			296	36.05	4.37	37.16	4.16		
Types of AGPs														
Non-invasive oxygen supplementation	-	-	-	-	-			35	31.02	4.62	31.97	4.02		
Tracheotomy	-	-	-	-	-			-	-	-	-	-		
Cardiopulmonary Resuscitation	-	-	-	-	-			-	-	-	-	-		
Tracheal Intubation	-	-	-	-	-			-	-	-	-	-		
Nebulized Therapy	-	-	-	-	-			-	-	-	-	-		
Types of Room Ventilation														
None	-	-	-	-	-	<0.001	0.575	-	-	-	-	-	0.337	-
UV light air purification	-	-	-	-	-			-	-	-	-	-		
Natural Ventilation	8	5.0 × 10 ²	1.8 × 10 ²	5.0 × 10 ²	2.5 × 10 ²			2	36.90	1.70	36.90	-		
Natural Ventilation and UV light air purification	-	-	-	-	-			-	-	-	-	-		
Not further specified Mechanical Ventilation	54	4.0 × 10 ⁵	2.6 × 10 ⁶	3.4 × 10 ⁵	5.7 × 10 ⁴			102	35.02	5.97	37.27	5.89		
Mechanical Ventilation with outdoor air supply	4	5.5 × 10 ²	1.7 × 10 ²	5.4 × 10 ²	3.0 × 10 ²			14	37.21	1.36	37.47	1.82		
Mechanical Ventilation and HEPA Filtration	-	-	-	-	-			-	-	-	-	-		
Mechanical Ventilation & Air Purifiers	-	-	-	-	-			2	26.90	5.37	26.90	-		
Laminar Flow Ventilation	-	-	-	-	-			-	-	-	-	-		
Negative Pressure Ventilation	1	1.3 × 10 ³	-	-	-			172	35.67	4.44	37.00	5.62		

(Continues)

TABLE A3 (Continued)

Surface-borne SARS-CoV-2 RNA in Copies/swab														Surface-borne SARS-CoV-2 RNA in Ct-values					
	<i>n</i>	μ	σ	M	IQR	<i>p</i>	<i>r</i>	<i>n</i>	μ	σ	M	IQR	<i>p</i>	<i>r</i>					
Negative Pressure Ventilation and HEPA Filtration	-	-	-	-	-	-	-	-	-	-	-	-	-	-					
Negative Pressure Ventilation, HEPA Filtration, and Laminar Flow	-	-	-	-	-	-	-	-	-	-	-	-	-	-					
HEPA Filtration	-	-	-	-	-	-	-	-	-	-	-	-	-	-					
HEPA Filters present	-	-	-	-	-	-	-	-	-	-	-	-	-	-					
no HEPA Filters listed	67	3.2×10^5	2.3×10^5	2.8×10^6	2.8×10^4	6.3×10^4		292	35.47	4.99	37.00	4.96							
Air Changes per Hour (ACH) in Patient Rooms																			
>16 ACH	-	-	-	-	-	-	-	-	-	-	-	-	-	-					
≤ 16 ACH	41	5.5×10^4	5.2×10^4	4.3×10^4	4.3×10^4	5.0×10^4		157	36.69	3.07	37.54	4.24							
Exact ACH in Patient Rooms							0.217						<0.001	-					
2.5 ACH	2	5.4×102	1.8×102	5.4×102	-			2	36.51	0.42	36.51	-							
2–6 ACH	-	-	-	-	-	-		3	38.83	2.07	39.76	-							
6 ACH	-	-	-	-	-	-		-	-	-	-	-							
8 air supplies and 12 air discharges/hour	6	9.1×10^3	6.3×10^4	9.2×10^3	1.3×10^4			-	-	-	-	-							
12 ACH	1	1.3×10^3	-	-	-			31	33.59	2.78	33.09	4.40							
12–15 ACH	-	-	-	-	-			78	38.60	1.66	38.97	2.39							
12 air supplies and 16 air discharges/hour	32	6.9×10^4	5.0×10^4	4.3×10^4	1.0×10^5			-	-	-	-	-							
14 ACH	-	-	-	-	-			7	37.76	0.84	38.00	1.60							
15 ACH	-	-	-	-	-			36	34.86	2.87	35.50	4.00							
>16 ACH	-	-	-	-	-			-	-	-	-	-							
20 ACH	-	-	-	-	-			-	-	-	-	-							
240–360 ACH	-	-	-	-	-			-	-	-	-	-							
Sampling Distance to Patients						-	-						-	-					
<2 m	-	-	-	-	-			8	30.24	6.23	29.60	6.50							
≥ 2 m	-	-	-	-	-			1	31.97	-	-	-							
Sampling Distance to Patients by the meter						-	-						-	-					

TABLE A3 (Continued)

	Surface-borne SARS-CoV-2 RNA in Copies/swab							Surface-borne SARS-CoV-2 RNA in Ct-values						
	<i>n</i>	μ	σ	M	IQR	<i>p</i>	<i>r</i>	<i>n</i>	μ	σ	M	IQR	<i>p</i>	<i>r</i>
0.01–0.99 m	–	–	–	–	–	–	–	8	30.24	6.23	29.60	6.50	–	–
1.00–1.99 m	–	–	–	–	–	–	–	–	–	–	–	–	–	–
>1.00 m (not included in categories </≥2 m)	–	–	–	–	–	–	–	1	41.20	–	–	–	–	–
<1.83 m	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2.00–2.99 m	–	–	–	–	–	–	–	–	–	–	–	–	–	–
3.00–3.99 m	–	–	–	–	–	–	–	–	–	–	–	–	–	–
4.00–4.99 m	–	–	–	–	–	–	–	–	–	–	–	–	–	–
5.00 m	–	–	–	–	–	–	–	–	–	–	–	–	–	–
6.10 m	–	–	–	–	–	–	–	–	–	–	–	–	–	–
7.62 m	–	–	–	–	–	–	–	–	–	–	–	–	–	–
size ranges ≥2 m	–	–	–	–	–	–	–	1	31.97	–	–	–	–	–
>1.83 m (not included in categories </≥2 m)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Limit of Detection													0.040	0.199
<0.38 Copies/μl	50	5.2 × 10 ⁴	4.9 × 10 ⁴	3.4 × 10 ⁴	5.2 × 10 ⁴	<0.001	0.591	98	38.45	1.88	38.92	2.40	–	–
≥ 0.38 Copies/μl	8	5.0 × 10 ²	1.8 × 10 ²	5.0 × 10 ²	2.5 × 10 ²			9	37.25	1.70	38.00	3.15	–	–
Type of Hospital													–	–
Makeshift Hospitals	50	5.2 × 10 ⁴	4.9 × 10 ⁴	3.4 × 10 ⁴	5.2 × 10 ⁴			–	–	–	–	–	–	–
Traditional Construction	21	9.1 × 10 ⁵	4.1 × 10 ⁶	7.2 × 10 ²	2.1 × 10 ³			336	35.43	4.74	36.83	4.68	–	–
General Hospital Areas						0.032	0.255						0.669	0.023
Patient Areas	53	4.0 × 10 ⁵	2.6 × 10 ⁶	2.8 × 10 ⁴	6.3 × 10 ⁴			310	35.49	4.72	36.83	4.63	–	–
Non-Patient Areas	18	1.9 × 10 ⁴	2.8 × 10 ⁴	3.8 × 10 ³	3.1 × 10 ⁴			26	34.77	5.12	36.62	5.56	–	–
Major Hospital Areas						<0.001	0.546						0.005	0.173
ICU Patient Room	38	5.6 × 10 ⁵	3.1 × 10 ⁶	4.3 × 10 ⁴	5.9 × 10 ⁴			30	31.12	8.29	35.76	16.16	–	–
Non-ICU Patient Room	10	6.1 × 10 ³	6.2 × 10 ³	3.6 × 10 ³	1.0 × 10 ⁴			231	35.97	3.81	37.00	5.02	–	–
Clinical Area	18	1.9 × 10 ⁴	2.8 × 10 ⁴	3.8 × 10 ³	3.1 × 10 ⁴	–	–	21	35.92	3.66	37.23	4.35	0.250	0.236
Staff Area	–	–	–	–	–			5	29.98	7.83	25.62	4.35	–	–
Type of surface swab													<0.001	–
Gauze pads	–	–	–	–	–			95	38.61	1.64	38.92	2.39	–	–
Foam swabs	–	–	–	–	–			–	–	–	–	–	–	–

(Continues)

TABLE A3 (Continued)

	Surface-borne SARS-CoV-2 RNA in Copies/swab						Surface-borne SARS-CoV-2 RNA in Ct-values							
	n	μ	σ	M	IQR	p	r	n	μ	σ	M	IQR	p	r
Cotton swabs	12	5.2 × 10 ²	1.7 × 10 ²	5.0 × 10 ²	2.8 × 10 ²			62	34.48	2.81	34.51	4.73		
Rayon swabs	-	-	-	-	-			3	23.77	6.63	23.10	-		
Viscose swabs	-	-	-	-	-			12	38.77	1.18	38.63	1.96		
Surface Sample Collection Time							0.524						-	-
Before routine cleaning	7	1.4 × 10 ³	1.4 × 10 ³	7.2 × 10 ²	1.1 × 10 ³			45	33.54	7.56	36.21	7.27		
Directly after routine cleaning	-	-	-	-	-			-	-	-	-	-		
1-2 hours after routine cleaning	-	-	-	-	-			-	-	-	-	-		
4 hours after routine cleaning	50	5.2 × 10 ⁴	4.9 × 10 ⁴	3.4 × 10 ⁴	5.2 × 10 ⁴			-	-	-	-	-		
4-7 hours after routine cleaning	-	-	-	-	-			-	-	-	-	-		
9 hours after routine cleaning	-	-	-	-	-			-	-	-	-	-		
After routine cleaning, exact time unknown	-	-	-	-	-			-	-	-	-	-		

Note: number of samples positive for SARS-CoV-2 RNA, μ = mean, σ = standard deviation, *M* = median, IQR = interquartile range, *p* = *p*-value, *r* = Pearson's *r*.

TABLE A4 Association of metric factors with SARS-CoV-2 contamination

Airborne SARS-CoV-2 contamination							Surface-borne SARS-CoV-2 contamination						
<i>n</i>	μ	σ	<i>M</i>	<i>IQR</i>	<i>p</i>	<i>r</i>	<i>n</i>	μ	σ	<i>M</i>	<i>IQR</i>	<i>p</i>	<i>r</i>
Patients/sample (Patient Rooms)					<0.001	0.169						-	-
SARS-CoV-2 RNA detected	150	1.69	2.32	1.00	1.00		-	-	-	-	-		
SARS-CoV-2 RNA not detected	728	1.16	1.70	1.00	0.75		-	-	-	-	-		
Temperature in °C					<0.001	0.203						0.001	0.121
SARS-CoV-2 RNA detected	42	23.11	2.81	22.50	3.00		78	22.62	0.83	23.00	0.41		
SARS-CoV-2 RNA not detected	268	24.16	2.53	24.00	1.89		620	22.94	1.35	23.00	1.51		
Relative Humidity in %					0.474	0.041						0.170	0.052
SARS-CoV-2 RNA detected	42	45.20	11.65	50.00	16.00		78	53.29	8.12	56.00	0.10		
SARS-CoV-2 RNA not detected	268	42.46	13.33	45.00	25.28		620	51.71	10.71	56.00	2.72		
Volume/sample in L of air					0.363	0.022						-	-
SARS-CoV-2 RNA detected	302	4232.87	8537.13	1002.00	3182.50		-	-	-	-	-		
SARS-CoV-2 RNA not detected	1488	4376.13	5723.78	1002.00	8160.00		-	-	-	-	-		
Sampling minutes/ sample					0.249	0.027						-	-
SARS-CoV-2 RNA detected	288	41795	1083.73	60.00	210.00		-	-	-	-	-		
SARS-CoV-2 RNA not detected	1471	452.76	941.17	40.00	210.00		-	-	-	-	-		
Flow Rate in L of air/ min					0.266	0.026						-	-
SARS-CoV-2 RNA detected	288	84.01	344.73	14.00	46.00		-	-	-	-	-		
SARS-CoV-2 RNA not detected	1487	82.76	163.35	14.00	76.50		-	-	-	-	-		

(Continues)

TABLE A4 (Continued)

Airborne SARS-CoV-2 contamination							Surface-borne SARS-CoV-2 contamination							
	<i>n</i>	μ	σ	<i>M</i>	IQR	<i>p</i>	<i>r</i>	<i>n</i>	μ	σ	<i>M</i>	IQR	<i>p</i>	<i>r</i>
Sampling height in m						0.793	0.008						-	-
SARS-CoV-2 RNA detected	132	1.29	0.25	1.50	0.40			-	-	-	-	-		
SARS-CoV-2 RNA not detected	815	1.30	0.23	1.30	0.30			-	-	-	-	-		
Surface area sampled in cm ²						-	-						<0.001	0.113
SARS-CoV-2 RNA detected	-	-	-	-	-			308	793.95	1108.47	25.00	2475.00		
SARS-CoV-2 RNA not detected	-	-	-	-	-			1932	429.41	831.47	25.00	90.75		
Cycle thresholds						0.464	0.020						0.507	0.018
SARS-CoV-2 RNA detected	122	39.90	1.22	40.00	0.80			510	40.07	1.83	40.00	1.20		
SARS-CoV-2 RNA not detected	1209	40.14	2.12	40.00	0.40			2471	39.74	2.79	40.00	3.00		
LoD in Copies/ μ l of VTM						<0.001	0.478						<0.001	0.187
SARS-CoV-2 RNA detected	87	3.71	18.30	0.20	0.30			178	9.81	29.39	0.37	0.17		
SARS-CoV-2 RNA not detected	335	18.25	38.24	0.20	0.80			893	56.19	49.56	100.00	99.80		