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Environmental circulation of airborne SARS-CoV-2 particles in intensive care rooms

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Abstract

Background:

Airborne transmission is a major concern in intensive care units (ICUs). This study aimed to identify the determinants of airborne and surface contamination in ICU rooms occupied by patients with COVID-19 associated respiratory failure.

Methods:

Observational study in a tertiary care hospital comprising six ICUs with diverse architectural layouts and HVAC systems. We modeled the dispersion of respiratory particles in five rooms using computational fluid dynamics (CFD). Air and surface samples were collected at predefined locations in 19 rooms occupied by 28 patients testing positive for SARS-CoV-2. Risk factors associated with environmental contamination were identified using classification tree analysis.

Results:

Measured HVAC airflow rates were substantially lower than programmed values in three ICUs. CFD simulations suggested that exhaled particles initially rose above the patient, accumulated beneath the ceiling, and subsequently dispersed in the room. SARS-CoV-2 was detected in 14/64 (22%) air samples and 60/134 (45%) surface samples. The most important determinants of environmental contamination were patient viral load, room characteristics, and mode of respiratory support. Environmental contamination was more frequent in rooms with low airflow rates and extraction vents located outside the room.

Conclusion:

In our ICUs, the main factors associated with environmental detection of SARS-CoV-2 particles were patient airway viral load, the flow rate and location of the exhaust ventilation system, and the use of mechanical ventilation. These results could help guide the renovation or construction of intensive care rooms.

Introduction

The global spread of Coronavirus Disease 2019 (COVID-19) was driven by the high transmissibility of the Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) [1]. The pandemic highlighted the importance of preventing airborne human-to-human transmission [2]. ICUs are characterized by high workload and staff density [3], placing healthcare workers at high risk of exposure to airborne pathogens [4]. Reducing airborne transmission involves behavioral strategies [5] and attention to respiratory support

techniques [6]. Experimental studies have documented the survival of airborne pathogens in different settings [7]. Hospital air management strategies include natural or pulsed ventilation, filtration, and disinfection [8]. In ICUs equipped with a heating, ventilation, and air conditioning (HVAC) system, recommendations from international engineering and infection prevention societies advocate at least for six air exchanges per hour [9] with positive pressure generally used in rooms intended to protect immunocompromised patients from nosocomial infection. Some rooms can be converted to negative pressure to accommodate patients with highly contagious airborne infections [9]. Since the start of the COVID-19 pandemic, the circulation of respiratory particles has been investigated in existing buildings including hospital rooms [10] and modeled using computational approaches [11]. The heterogeneity in architectural design, building age, maintenance, and HVAC control across hospitals requires real-world assessment of airborne particle circulation [12].

In our hospital, which comprises six ICUs, we sought to detect SARS-CoV-2 in the air and surfaces of rooms housing patients with acute respiratory failure due to COVID-19 and to determine the risk factors associated with positive airborne environmental samples.

Methods

Our ICUs, built in the 1980s, include mainly single-bed rooms equipped with HVAC systems. The ICUs (numbered I to VI) are units of 6 to 10 beds located on three different floors of the hospital. Each ICU consists of a nursing station of approximately 150 m² and rooms of 20 m². All rooms connect to a utility room and a visitor entrance vestibule via doors. A typical room is depicted in supplement paragraph (§) I-A and figures S1 to S4. The HVAC system is independent of the rest of the hospital in two units (I and VI) and shared with other medical units in four (II to V). The investigation was conducted between April 2021 and January 2023. Table 1 presents the periods as well as the number of rooms and patients studied for each type of assessment. The protocol was carried out in accordance with professional guidelines and the Belgian law. The study was not considered to involve human experimentation and collection of a written consent was waived. The protocol was approved by the Institutional Review Board of the University of Liège (Comité d'Ethique Hospitalo-Facultaire Universitaire de Liège, #707; 2022/104).

To estimate the impact of human activities, we assessed continuous values of carbon dioxide, temperature and relative humidity in three rooms of one unit (unit V) over 7 days (supplement § I-D). The recommended values across the world are 18 to 26°C for temperature, 30 to 60% for relative humidity [9] and 400 to 1,000 ppm for carbon dioxide [13].

We assessed the HVAC characteristics of 21 rooms in five units (I, III, IV, V and VI) that seemed representative of all the rooms of the ICUs. We used the architectural blueprints and measured actual locations of the room furniture, of the aeration holes in the doors and the HVAC inlets and outlets (supplement § I-B). We obtained the programmed supply and return airflow and the mapping of the HVAC tubing from the technical department of the hospital. We assessed the actual airflow rates of the HVAC system with a anemometer (Testo 417, Testo, Forbach, France). Airflow measurements were

repeated five times at each location. The results were compared to the programmed values. After documenting that the flows we measured were substantially lower than those that were supposed to be delivered in units with a shared HVAC system (see results), we took advantage of a period of renovation of one unit (unit IV) to test the possibility to obtain the programmed flows while no patient was present. In this unit, the measurements were also made in the nursing station to estimate the air leak outside the rooms, and all measures were repeated after 24 hours to confirm the validity of the previous values. The procedures are detailed in the supplement § I-C. To introduce the characteristics of the rooms among the risk factors for environment contamination, we classified these into four groups (A,B,C,D), based on their architectural characteristics, the location of the HVAC outlet and the airflow rates of the HVAC system.

We simulated the spatial distribution of particles over time in five rooms, using computational fluid dynamics (CFD). The simulation was designed to estimate areas with a higher risk of particle concentration in the room. We then simulated several modifications of the HVAC system (supplement § II A and figure S7).

We selected patients tested positive to COVID-19 in a naso-pharyngeal (NP) sample, whatever their cause of admission. Clinical and lab data were collected prospectively, including severity scores, therapeutic characteristics and organ support at the time of sampling. We classified the respiratory support as “spontaneous breathing with low flow oxygen supply (less than 30 L/min) or non invasive ventilation” (LF), “spontaneous breathing with high flow oxygen supply” if receiving at least 30 L/min (HF), and “mechanical ventilation” (MV) through an endotracheal tube or a tracheostomy. This classification was empirical and based on the assumption that HF oxygen could induce a higher aerosolization in the room [14] than LF, while MV could induce less aerosolization thanks to the occlusion of the trachea by the cuff of the endotracheal tube [15]. Routine bronchial suctioning of intubated patients was performed using a closed system (Avanos Inc, Alpharetta, Georgia, USA).

We searched for viral RNA particles in the air and on the surfaces of 19 rooms. Air samples were performed with the MD8 AirPort air sampler device and the 47 mm Gelatine Filter (Sartorius, Göttingen, Germany) using an airflow rate of 50L/min over 20 minutes at different locations in the room. Surface samples were swabs of 15cmx15cm zones. We chose locations corresponding to usual locations of the nursing personnel and the visitors of the patients, and locations predicted for either a high or a low risk of particles in the air, based on the CFD modeling. The transport medium was an isotonic sodium chloride solution. The samples were sent to the routine microbiology lab of the hospital for SARS-CoV-2 reverse transcription quantitative polymerase chain reaction (RT-qPCR) using the Cobas® SARS-CoV2 kit on Cobas® 6800 (Roche). The samples were frozen at -20°C until analysis. Analyses were batched and performed within the week following sample collection. The results were reported as cycle threshold for the ORF and E Genes of the virus. The lower value of the cycle threshold of both tests was used for the statistical analyses.

The datasets used during the current study are available from the corresponding author upon reasonable request.

Statistical analysis

The capacity of CFD to predict positive PCR value in environment samples was assessed with sensitivity and specificity. We determined the main risk factors for a sample to be positive using a classification tree analysis (CTA) (supplement § III). The diagnostic power of the decision tree generated was assessed with a receiver operating characteristic (ROC). All quantitative values are presented as median (IQR) and qualitative ones as n (%).

Results

Room temperature was 26.2 [25.3–26.6]°C, relative humidity 24.3 [22.3–27.0]%, and carbon dioxide 657 ppm (daily peaks > 1000 ppm during care) (table S3, Figures S5-S6).

The programmed supply airflow rate of the HVAC system (supplement § I-B-a) was higher than the return airflow rate in four units (II, II, IV and V) and equivalent in two (II and VI) (Table S1). The measured values of the supply and return airflow (supplement § I-B-b, table S2) were close to programmed values in units I and VI, distributed by an independent HVAC system, and substantially lower (about half as low) in units III to V. Units III, IV and V were classified group A (low airflow and return vent outside the room), and units II, VI and I in three separate groups (B,C,D) (supplement § I-B-c and table 2). In unit IV, the total S/R flow of the nursing station was 781/480 m^3/h, representing 52%/31% of the programmed values. In this unit, these values renew 1.6 times per hour the ambient air volume.

CFD simulations suggested particles initially rise toward the ceiling (Fig. 1), driven by the temperature gradient between the patient's body [16] and ambient air. The particles then disperse laterally beneath the ceiling before progressively depositing on horizontal surfaces. Accumulation zones were identified near the door leading to the nursing station, on work surfaces and medical equipment used by healthcare staff, and on the floor surrounding the patient's bed. Areas with the highest particle concentrations at caregiver breathing height were located close to the patient. Detailed simulation results and figures are provided in supplement § II-B and figures S8 to S11. Finally, simulations evaluating droplet reduction strategies suggested that positioning the air extraction outlet directly above the patient's head and adding a funnel-shaped plate provided the best compromise between efficacy and technical feasibility using conventional ventilation systems (supplement § II-C and figure S12). Additional pictures and videos (Advanced Simulator for Airborne Pathogen Propagation) of the CFD simulations can be reached at [17, 18].

Patients had been tested positive for SARS-CoV-2 NP-PCR on day 1 [0–1] before environment sampling, at a median cycle threshold (Ct) of 19 [15–25]. Nineteen of 28 had been admitted because of COVID-19 pneumonia. On the day of environmental sampling, 21 patients were bedridden and 7 were seated, 14

patients were treated with LF oxygen (< = 15 L/min) or NIV through a facial mask, 7 with HF oxygen (> = 30 L/min), and 7 with mechanical ventilation through an oro-tracheal tube or tracheostomy. The individual characteristics of the patients are displayed in table S4. Air (n = 64) and surface (n = 134) samples were positive in 14/64 (22%) and 60/134 (45%) cases, and their Ct values for SARS-CoV-2 PCR were 37 [36–38] and 37 [35–38]. The sensitivity and specificity of CFD simulation to predict the presence of virus in the surface samples were 0.50 and 0.76. To predict the presence of virus in the air, these values were 0.57 and 1.00. When surface and air samples were combined, these were 0.52 and 0.82.

The risk factors for environmental contamination identified by the CTA, in descending order of importance (variable importance = VI, range from 0 to 100), are as follows: COVID-19 NP-PCR value (VI = 100), room classification - location and HVAC functioning (VI = 26), patient respiratory support mode (VI = 23), sampling type - air or surface (VI = 14), and patient position – seated or bedridden (VI = 8). Figure 2 shows the main decision nodes and terminal nodes obtained. The color code indicates the proportion of positive (blue) or negative (red) samples in the environment. Patient PCR, HVAC configuration and operation, and patient respiratory support account for 4, 1, and 2 decision nodes, respectively. Variables associated with a higher risk of environmental contamination are a low value of patient PCR Ct, an HVAC system with low airflow and an exhaust vent outside the room, and mechanical ventilation support.

The receiver operating characteristic (ROC) of the CTA (figure S13) shows a good discriminative ability in the training and a moderate performance in the test dataset. Both curves remain above the diagonal line, indicating performance better than chance.

Discussion

By analyzing room architecture, ventilation, and viral presence, we found that: 1) the HVAC system flow rates differed significantly from their programmed values when the circuit was common with others units of the hospital and were insufficient to renew the air in the rooms during nursing care periods; 2) the virus was present in the air and on surfaces, as predicted by numerical simulations; and 3) the main risk factors for the presence of the virus in the patient's room were the viral load in their airways, the operating mode of the HVAC system, and the mode of respiratory assistance. Our simulations suggest that positioning the exhaust vent of the HVAC above the patient's head could reduce the risk of particle spreading within the room.

ICU rooms are at high risk of contagion [14] because patients carry a large inoculum, the atmosphere is confined, and care is extensive and invasive due to the severity of organ dysfunction. This study makes it possible to formulate hypotheses aimed at reducing contact between infectious particles and individuals entering the room. Since particles tend to accumulate above the patient’s head, near the door, and on work surfaces, avoiding prolonged presence in these areas could reduce the risk of contamination. Similarly, the risk could be reduced by locating HVAC return vent as close as possible to the patient's head and HVAC distribution independent of other hospital structures during renovations of existing

facilities or the construction of new ones. These findings could be used to anticipate the risk in other airborne diseases and the specific protection of immunocompromised patients.

Our method is original in that we were able to combine the search for viral particles in patients in real-world settings with measurements that allow us to perform simulations using actual data from our patients and rooms. The simulation method we used is based on known models [18] and incorporates droplet size criteria [8]. The method we used to establish risk factors account for the multiplicity of risks and the non-linear distribution of the variables we had to study [19].

Our observation of viral particles in 22% and 45% of air and surface samples in these rooms is consistent with other studies [20] and were correlated with CFD simulations. CFD simulations made it possible to determine areas at increased risk of viral particle contamination. Such simulations could be used to guide the architectural design of intensive care rooms.

The patient's PCR value is logically the main risk factor for environmental contamination because the patient is the source of the virus. The role of HVAC could be highlighted because our department is equipped with a series of ICUs whose rooms and HVAC distribution systems differ. The best ventilated rooms are in ICUs with air distribution separate from the rest of the medical units. The fact that ventilation values in some units are much lower than those programmed by the building maintenance departments suggests that the design of such rooms should be reviewed during hospital renovations. The simulations we performed, based on our real-world measurements, suggest that simply modifying the location of the air exhaust vent could improve the risk at a lower cost.

Our study has limitations. First, the relatively small number of samples may have reduced the chances of finding certain risk factors. Second, particle distribution predictions were based on theoretical airflow rates that proved to differ significantly from those measured in practice. Finally, we demonstrated the presence of viral RNA in the samples, which may not reflect viable virus.

Conclusion

In our ICUs, the main risk factors for viral presence in the patient's room were the viral load in their airways, the flow rate and location of the exhaust ventilation system, and the use of mechanical ventilation. These results could help guide the renovation or construction of intensive care rooms, with the aim of protecting healthcare workers in a high-risk environment.

Abbreviations

ASAPP: Advanced Simulator for Airborne Pathogen Propagation

CFD: Computational Fluid Dynamic

COVID-19: Coronavirus Disease 2019

Ct : Cycle threshold

CTA: Classification Tree Analysis

HEPA: High-Efficiency Particulate Air

HF: High Flow

HVAC : Heating, Ventilation and Air-Conditioning

ICU: Intensive Care Unit

LIR: Inter-quartile Range

LF: Low Flow

MV: Mechanical Ventilation

NIV: Non-Invasive Ventilation

NP PCR: Naso-Pharyngeal Polymerase Chain Reaction

RNA: RiboNucleic Acid

ROC : Receiver Operating Characteristic

RT-qPCR: Reverse Transcription-quantitative Polymerase Chain Reaction

SARS-CoV-2: Severe Acute Respiratory Syndrome Coronavirus 2

§ : paragraph

Declarations

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Conflict of interest statement

Name entities:

Innoviris (Brussels Public Organisation for Research and Innovation)

Specifications/Comments:

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Tables

Tables are available in the Supplementary Files section.

Figures

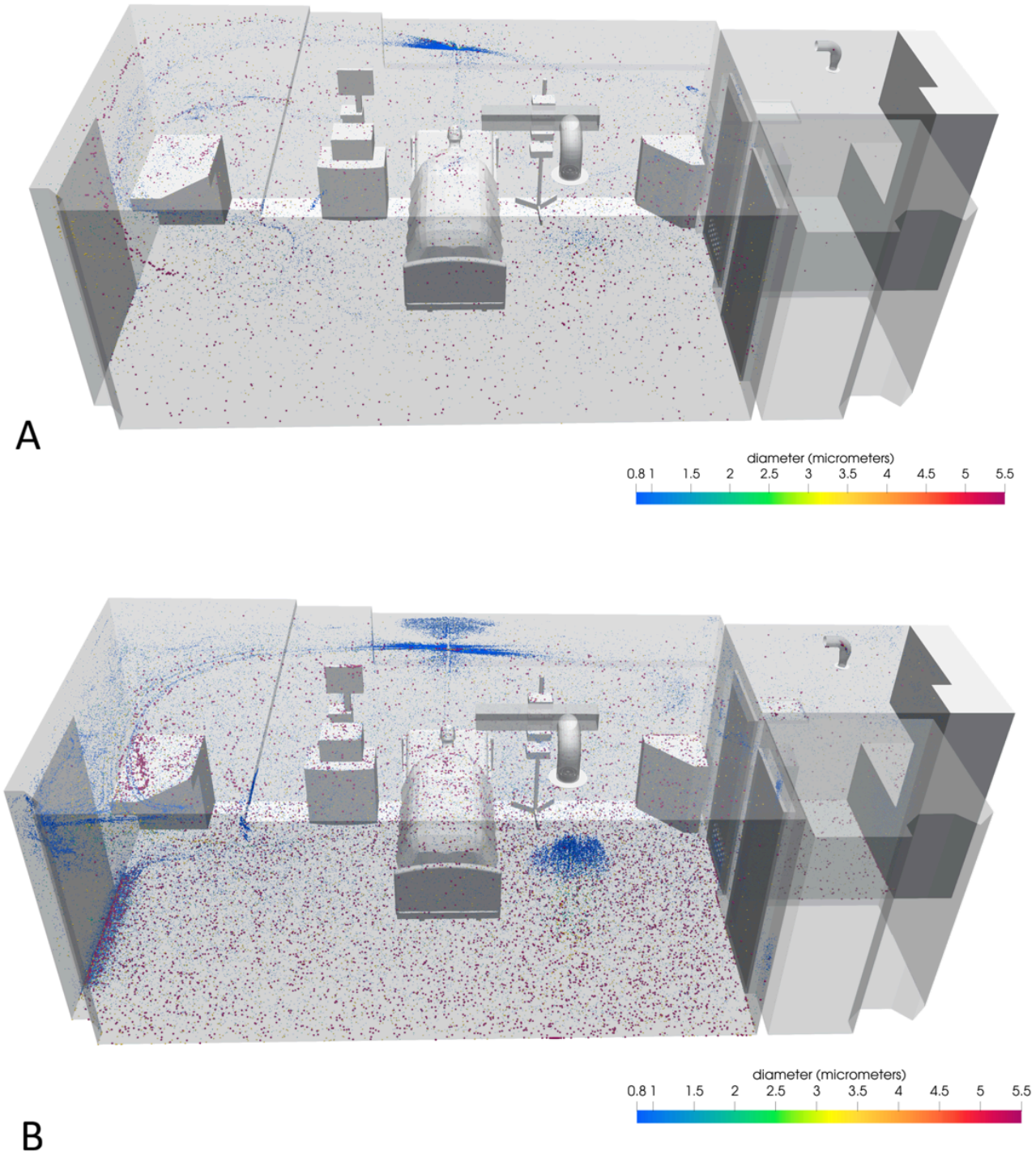


Figure 1

CFD simulation of the propagation of exhaled droplets at 30 minutes (1A) and 3 hours (1B)

Legend: 3D representation of the simulation of exhaled droplets after 30 minutes (1A) and 3 hours (1B). The furniture position reflects reality. The position of the ventilation system and doors follow the architectural plans. CFD = Computational Fluid Dynamic. The color of simulated particles range from

blue (diameter 1.8 μM) to red (diameter 5.5μM). The figure shows that small particles initially (1A) get out of the mouth of the patient, rise toward the ceiling and concentrate above the patient's head. Larger particles then disperse to different parts of the furniture and the floor (1B).

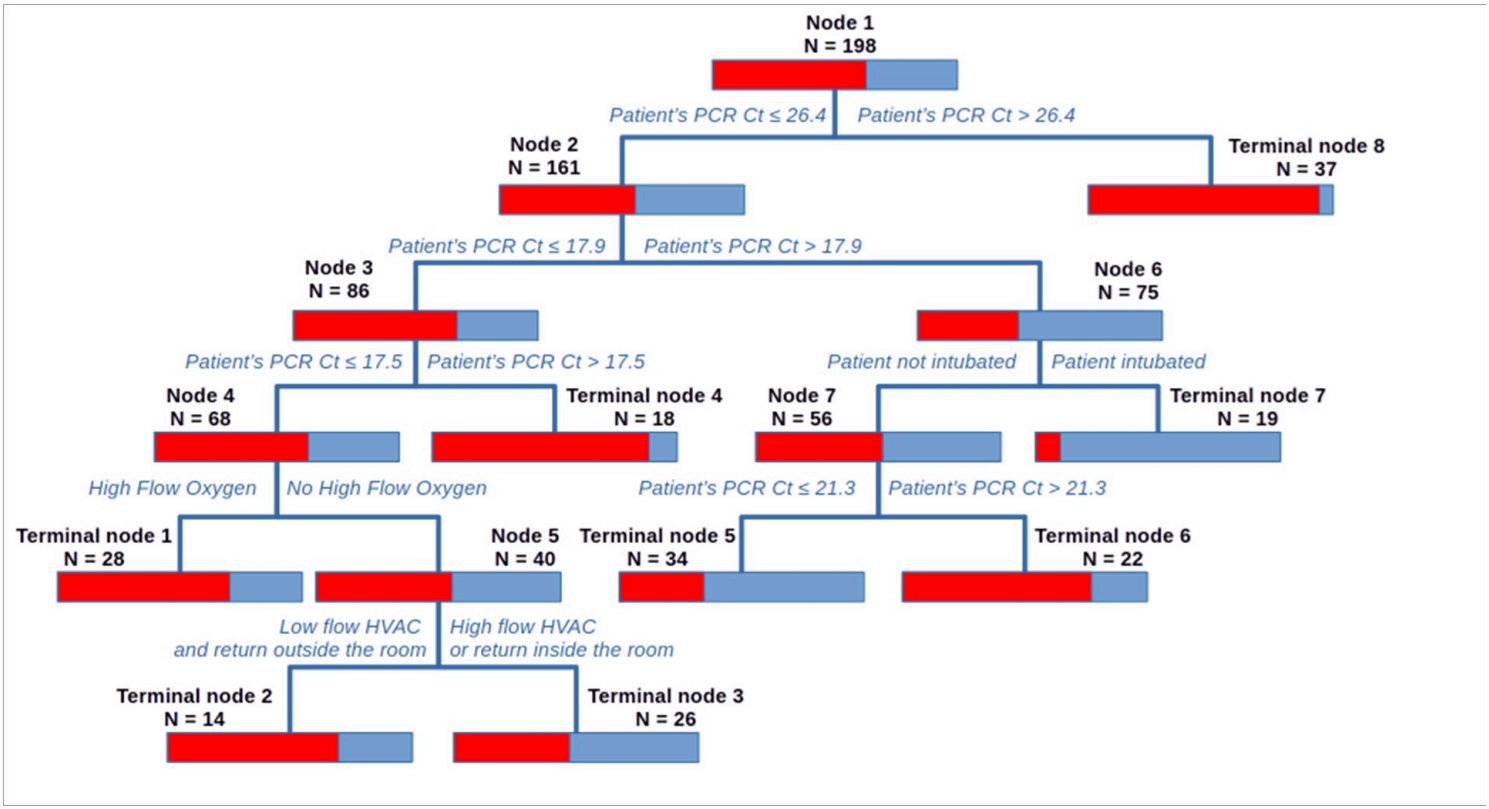


Figure 2

Classification tree analysis of the risk of collecting a positive sample to SARS-CoV-2 in the air or surfaces of the patient's room

Legend: Decision and terminal nodes derived from the classification tree analysis. The color code indicates the proportion of positive (blue) or negative (red) samples in the environment. See text for interpretation

Supplementary Files

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- Tables.docx