

1 Estimation of airborne viral emission: quanta emission rate of SARS-CoV-2 for 2 infection risk assessment

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12 Abstract

13 Airborne transmission is a pathway of contagion that is still not sufficiently investigated despite the
14 evidence in the scientific literature of the role it can play in the context of an epidemic. While the
15 medical research area dedicates efforts to find cures and remedies to counteract the effects of a
16 virus, the engineering area is involved in providing risk assessments in indoor environments by
17 simulating the airborne transmission of the virus during an epidemic. To this end, virus air emission
18 data are needed. Unfortunately, this information is usually available only after the outbreak, based
19 on specific reverse engineering cases. In this work, a novel approach to estimate the viral load
20 emitted by a contagious subject on the basis of the viral load in the mouth, the type of respiratory
21 activity (e.g. breathing, speaking), respiratory physiological parameters (e.g. inhalation rate), and
22 activity level (e.g. resting, standing, light exercise) is proposed. The estimates of the proposed
23 approach are in good agreement with values of viral loads of well-known diseases from the
24 literature. The quanta emission rates of an asymptomatic SARS-CoV-2 infected subject, with a viral
25 load in the mouth of 10^8 copies mL^{-1} , were $10.5 \text{ quanta h}^{-1}$ and $320 \text{ quanta h}^{-1}$ for breathing and
26 speaking respiratory activities, respectively, at rest. In the case of light activity, the values would
27 increase to $33.9 \text{ quanta h}^{-1}$ and $1.03 \times 10^3 \text{ quanta h}^{-1}$, respectively.

28 The findings in terms of quanta emission rates were then adopted in infection risk models to
29 demonstrate its application by evaluating the number of people infected by an asymptomatic SARS-
30 CoV-2 subject in Italian indoor microenvironments before and after the introduction of virus
31 containment measures. The results obtained from the simulations clearly highlight that a key role is
32 played by proper ventilation in containment of the virus in indoor environments.
33

34 **Keywords:** SARS-CoV-2 (CoVID19); virus airborne transmission; indoor; ventilation; coronavirus;
35 viral load
36

37 1. Introduction

38 Expiratory human activities generate droplets, which can also carry viruses, through the atomization
39 processes occurring in the respiratory tract when sufficiently high speeds are reached (Chao et al.,
40 2009; Morawska, 2006). Indeed, during breathing, coughing, sneezing or laughing, toques of liquid
41 originating from different areas of the upper respiratory tract are drawn out from the surface, pulled
42 thin, and broken into columns of droplets of different sizes (Hickey and Mansour, 2019). The content
43 of infectious agents expelled by an infected person depends, among other factors, on the location
44 within the respiratory tract from which the droplets originated. In particular, air velocities high
45 enough for atomization are produced when the exhaled air is forced out through some parts of the

46 respiratory tract which have been greatly narrowed. The front of the mouth is the site of narrowing
47 and the most important site for atomization; since most droplets originate at the front of the mouth,
48 the concentration of an infectious agent in the mouth (sputum) is representative of the
49 concentration in the droplets emitted during the expiratory activities (Morawska, 2006). Thus,
50 knowledge of the size and origin of droplets is important to understand transport of the virus via
51 the aerosol route. Contrary to the findings of early investigations (Duguid, 1945; Jennison, 1942;
52 Wells, 1934), subsequent studies involving optical particle detection techniques capable of
53 measurements down to fractions of a micrometer suggested that the majority of these particles are
54 in the sub-micrometer size range (Papineni and Rosenthal, 1997). More recently, the growing
55 availability of higher temporal and spatial visualization methods using high-speed cameras (Tang et
56 al., 2011), particle image velocimetry (Chao et al., 2009) and, above all, increasingly accurate particle
57 counters (Morawska et al., 2009) allowed the detailed characterization and quantitation of droplets
58 expelled during various forms of human respiratory exhalation flows (e.g. breathing, whispering,
59 speaking, coughing). Therefore, in recent years a marked development has occurred both in the
60 techniques for detecting the viral load in the mouth and in the engineering area of the numerical
61 simulation of airborne transmission of the viral load emitted.

62 However, the problem of estimating the viral load emitted, which is fundamental for the simulation
63 of airborne transmission, has not yet been solved. This is a missing "transfer function" that would
64 allow the virology area, concerned with the viral load values in the mouth, to be connected with the
65 aerosol science and engineering areas, concerned with the spread and mitigation of contagious
66 particles.

67 A novel approach is here presented for estimating the viral load emitted by an infected individual.
68 This approach, based on the principle of conservation of mass, represents a tool to connect the
69 medical area, concerned with the concentration of the virus in the mouth, to the engineering area,
70 dedicated to the simulation of the virus dispersion in the environment. On the basis of the proposed
71 approach, the quanta emission rate data of SARS-CoV-2 were calculated as a function of different
72 respiratory activities, respiratory parameters, and activity levels.

73 The quanta emission rate data, starting from the recently documented viral load in sputum
74 (expressed in copies mL⁻¹), were then applied in an acknowledged infection risk model to investigate
75 the effectiveness of the containment measures implemented by the Italian government to reduce
76 the spread of SARS-CoV-2. In particular, airborne transmission of SARS-CoV-2 by an asymptomatic
77 subject within pharmacies, supermarkets, restaurants, banks, and post offices were simulated, and
78 the reduction in the average number of infected people from one contagious person, R_0 , was
79 estimated.

80 **2. Materials and methods**

81 **2.1. Estimation of the quanta emission rate**

82 The approach proposed in the present work is based on the hypothesis that the droplets emitted
83 by the infected subject have the same viral load as the sputum. Therefore, if the concentration of
84 the virus in the sputum and the quantity of droplets emitted with dimensions less than 10 μm is
85 known, the viral load emitted can be determined through a mass balance. In particular, the viral
86 load emitted, expressed in terms of quanta emission rate (ER_q , quanta h⁻¹), was evaluated as:

$$87 \quad ER_q = c_v \cdot V_{br} \cdot N_{br} \cdot \int_0^{10\mu m} N_d(D) \cdot dV_d(D) \quad (1)$$

88 where c_v is the viral load in the sputum (RNA copies mL⁻¹), V_{br} is the volume of exhaled air per breath
89 (cm³; also known as tidal volume), N_{br} is the breathing rate (breath h⁻¹), N_d is the droplet number
90

91 concentration (part. cm⁻³), and $V_d(D)$ is the volume of a single droplet (mL) as a function of the
92 droplet diameter (D). Information about the viral load in terms of quanta is essential as the quantum
93 represents the “viral load” considered in engineering science: in other words, an infected individual
94 constantly generates a number of infectious quanta over time, where a “quantum” is defined as the
95 dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons.
96 The volume of the droplet (V_d) was determined on the basis of data obtained experimentally by
97 (Morawska et al., 2009): they measured the size distribution of droplets for different expiratory
98 activities (e.g. breathing, whispering, counting, speaking), recognizing that such droplets present
99 one or more modes occurring at different concentrations. In particular, in the study a particle size
100 distribution with four channels was considered with midpoint diameters of $D_1=0.8$, $D_2=1.8$, $D_3=3.5$,
101 and $D_4=5.5$ μm . As an example, speaking was recognized as producing additional particles in modes
102 near 3.5 and 5.5 μm . These two modes became even more pronounced during sustained
103 vocalization. Details of the aerosol concentrations at the four channels of the size distribution during
104 each expiratory activity are reported in Table 1. The midpoint diameters of each channel were used
105 to calculate the corresponding volume of the droplets.

106 **Table 1** - Droplet concentrations (N_i , part. cm⁻³) of the different size distribution channels during each
107 expiratory activity measured by (Morawska et al., 2009).

Expiratory activity	D_1 (0.80 μm)	D_2 (1.8 μm)	D_3 (3.5 μm)	D_4 (5.5 μm)
Whispered counting	0.236	0.068	0.007	0.011
Voiced counting	0.110	0.014	0.004	0.002
Speaking	0.751	0.139	0.139	0.059
Breathing	0.084	0.009	0.003	0.002

108
109 Based on the results obtained by (Morawska et al., 2009), equation (1) can be simplified as:

110
$$ER_{q,j} = c_v \cdot IR \cdot \sum_{i=1}^4 (N_{i,j} \cdot V_i) \quad (2)$$

111 where j indicates the different expiratory activities considered (namely whispered counting, voiced
112 counting, speaking, breathing) and IR (m³ h⁻¹) is the inhalation rate, i.e. the product of breathing
113 rate (N_{br}) and tidal volume (V_{br}), which is a function of the activity level of the infected subject. The
114 quanta emission rate from equation (2) can vary in a wide range depending on the virus
115 concentration in the mouth, the activity level, and the different types of expiration. Regarding the
116 inhalation rate effect, the quanta emission rate calculations are shown for three different activity
117 levels (resting, standing, and light exercise) in which the inhalation rates, averaged between males
118 and females, are equal to 0.36, 0.54, and 1.16 m³ h⁻¹, respectively (Adams, 1993; International
119 Commission on Radiological Protection, 1994).

120 **2.2. A demonstration application: the containment measures for the spread of SARS-CoV-2 in Italy**

121 The pandemic of a novel human coronavirus, now named Severe Acute Respiratory Syndrome
122 CoronaVirus 2 (SARS-CoV-2 throughout this manuscript), emerged in Wuhan (China) in late 2019
123 and then spread rapidly in the world ([https://www.who.int/emergencies/diseases/novel-](https://www.who.int/emergencies/diseases/novel-coronavirus-2019)
124 [coronavirus-2019](https://www.who.int/emergencies/diseases/novel-coronavirus-2019)). In Italy, an outbreak of SARS-CoV-2 infections was detected starting from 16
125 cases confirmed in Lombardy (a northern region of Italy) on 21 February. The Italian government
126 has issued government a decree dated 11 March 2020 concerning urgent measures to contain the
127 contagion throughout the country. This decree regulated the lockdown of the country to counteract
128 and contain the spread of the SARS-CoV-2 virus by suspending retail commercial activities, with the
129 exception of the sale of food and basic necessities. It represents the starting point of a system with
130 imposed constraints. Among the measures adopted for the containment of the virus in Italy, great
131 importance was placed on the safe distance of 1 m (also known as “droplet distance”). This distance

132 was actually indicated by the World Health Organization as sufficient to avoid transmission by air,
133 without any reference to the possibility of transmission over greater distances indoors
134 (<https://www.who.int/emergencies/diseases/novel-coronavirus-2019>). With this measure, along
135 with the opening of only primary commercial establishments (such as pharmacies, supermarkets,
136 banks, post offices) and the closure of restaurants, the Italian government has adopted the concept
137 of spacing (known as “social distancing”) to prevent the spread of the infection. Obviously, this limit
138 per se would have no influence on the reduction of airborne transmission of the infection in indoor
139 environments since this distance is compatible with the normal gathering of people in commercial
140 establishments. Actually, on an absolutely voluntary basis, and despite the continuous denials by
141 the government on the risk of indoor airborne transmission, commercial associations have changed
142 the methods of accessing their commercial spaces such as restaurants, pharmacies, supermarkets,
143 post offices, and banks; for example, by forcing customers to queue outside. It is clear that the best
144 choice in containing an epidemic is a total quarantine which, however, appears to have enormous
145 costs and social impacts, especially in Western countries.

146 To show the possible effect of the measures imposed by the Italian government (i.e. lockdown), the
147 infection risk in different indoor microenvironments for the exposed population due to the presence
148 of one contagious individual was simulated, adopting the infection risk model described in section
149 2.2.1. In particular, the risk expressed in terms of basic reproduction number (R_0) was derived from
150 the quanta concentration and the infection risk; indeed, R_0 represents the average number of
151 secondary infections produced by a typical case of an infection in a population where everyone is
152 susceptible (Rothman et al., 2008).

153 The indoor microenvironments considered here were a pharmacy, supermarket, restaurant, post
154 office, and bank whose dimensions are summarized in Table 2. Two different exposure scenarios
155 were simulated for each microenvironment: before lockdown (B) and after lockdown (A). In the
156 simulation of the scenario before lockdown, the microenvironments were run with no particular
157 recommendations; thus, people enter the microenvironments and queue indoors, often resulting in
158 overcrowded environments. Since most of the indoor microenvironments in Italy are not equipped
159 with mechanical ventilation systems, the simulations were performed considering two different
160 situations: natural ventilation (a typical value for an Italian building equal to 0.2 h^{-1} was adopted,
161 with reference to (d’Ambrosio Alfano et al., 2012; Stabile et al., 2017)) and mechanical ventilation
162 (calculated according the national standard, UNI 10339 (UNI, 1995), as a function of the crowding
163 index and the type of indoor microenvironment). The scenario after lockdown was tested
164 considering the typical solutions adopted (on a voluntary basis) by the owners of stores and offices
165 – reduced personnel, a reduced number of customers inside the microenvironment, customers
166 forced to queue outdoors, and doors kept open. The scenario after lockdown was also tested for
167 both natural ventilation and mechanical ventilation; in this case a slight increase in the air exchange
168 rate (AER) for natural ventilation (0.5 h^{-1}) was considered in order to take into account that the door
169 was always kept open. The restaurant was not tested in the scenario after lockdown since such
170 commercial activity was closed down as a consequence of the lockdown. For all the scenarios
171 considered in the simulations, the infected individual was considered to enter the
172 microenvironment as the first customer (alone or along with other individuals according to the
173 scenarios summarized in Table 2). All the scenarios were simulated taking into account that the virus
174 is able to remain viable in the air for up to 3 hours post aerosolization as recently detected by (van
175 Doremalen et al., 2020); thus, if the infected individual remained inside the environment for 10
176 minutes (e.g. pharmacy), the calculation of the quanta concentration, infection risk, and R_0 was
177 performed for up to 3 hours and 10 minutes (named “total exposure time” in Table 2). For
178 restaurants the calculation was performed for 3 hours considering that after 3 hours (i.e. two groups

179 remaining inside for 1 hour and 30 minutes one after the other) the microenvironment was left
 180 empty.

181 **Table 2 - Summary of the exposure scenarios tested for the different microenvironments under**
 182 **investigation: dimensions, ventilation conditions, number of workers and customers.**

		Pharmacy	Supermarket	Restaurant	Post office	Bank
Dimensions	Floor area (A, m ²)	25	600	100	100	50
	Height (h, m)	3	3	3	3	3
	Volume (V, m ³)	75	1800	300	300	150
Exposure scenario before lockdown (B)	Number of workers	5 (always present)	10 (always present)	4 (just the waiters, always present)	8 (always present)	4 (always present)
	Number and activity of the customers	<ul style="list-style-type: none"> - 1 new customer per min entering the pharmacy, - every customer remains 10 min inside (including waiting time), - thus, 10 customers are simultaneously present 	<ul style="list-style-type: none"> - 1 new customer every 30 s entering the supermarket, - every customer remains 30 min inside, - thus, 60 customers are simultaneously present 	<ul style="list-style-type: none"> - 80 costumers every 1.5 hours, - restaurant working for 3 hours (evening), - thus, 80 customers are simultaneously present for a total number of 160 customers per evening. 	<ul style="list-style-type: none"> - 1 new customer every 30 s entering the post office, - every customer remains 15 min inside (including waiting time), - thus, 30 customers are simultaneously present 	<ul style="list-style-type: none"> - 1 new customer per min entering the bank, - every customer remains 15 min inside (including waiting time), - thus, 15 customers are simultaneously present
	Air exchange rate (AER, h ⁻¹) for natural ventilation (NV)	0.2	0.2	0.2	0.2	0.2
	Air exchange rate (AER, h ⁻¹) for mechanical ventilation (MV)	2.2	1.1	9.6	2.4	2.4
	Total exposure time	3 hours and 10 minutes	3 hours and 30 minutes	3 hours	3 hours and 15 minutes	3 hours and 15 minutes
Exposure scenario after lockdown (A)	Number of workers	3 (always present)	10 (always present)	-	4 (always present)	4 (always present)
	Number and activity of the costumers	<ul style="list-style-type: none"> - 2 new customers every five min entering the pharmacy, - every customer remains 5 min inside, - people forced to queue outside the pharmacy, - thus, 2 customers are simultaneously present 	<ul style="list-style-type: none"> - 1 new customer per min entering the supermarket, - every customer remains 10 min inside, - people forced to queue outside the supermarket, - thus, 10 customers are simultaneously present 	-	<ul style="list-style-type: none"> - 4 new customers every five min entering the post office, - every customer remains 10 min inside, - people forced to queue outside the post office, - thus, 4 customers are simultaneously present 	<ul style="list-style-type: none"> - 4 new customers every five min entering the bank, - every customer remains 10 min inside, - people forced to queue outside the bank, - thus, 4 customers are simultaneously present
	Air exchange rate (AER, h ⁻¹) for natural ventilation (NV)	0.5	0.2	-	0.5	0.5
	Air exchange rate (AER, h ⁻¹) for mechanical ventilation (MV)	2.2	1.1	-	2.4	2.4
	Total exposure time	3 hours and 5 minutes	3 hours and 10 minutes	3 hours	3 hours and 10 minutes	3 hours and 10 minutes

183 2.2.1. The infection risk model

184 The simulation of airborne transmission of SARS-CoV-2 was performed adopting the infection risk
185 assessment typically implemented to evaluate the transmission dynamics of infectious diseases and
186 to predict the risk of these diseases to the public. The model considered here to quantify the
187 airborne transmitted infection risk was carried out by Gammaitoni and Nucci (Gammaitoni and
188 Nucci, 1997) which represents an upgrade of an earlier model provided by Wells-Riley (Riley et al.,
189 1978). This model was successfully adopted in previous papers estimating the infection risk due to
190 other diseases (e.g. influenza, SARS, tuberculosis, rhinovirus) in different indoor microenvironments
191 such as airplanes (Wagner et al., 2009), cars (Knibbs et al., 2011), and hospitals. The Gammaitoni
192 and Nucci model is based on the rate of change in quanta levels through time; in particular, the
193 differential equations for the change of quanta in a control volume as well as the initial conditions
194 (here not reported for the sake of brevity) allowed to evaluate the quanta concentration in an
195 indoor environment at the time t , $n(t)$, as:

$$196 \quad n(t) = \frac{ER_q \cdot I}{AER \cdot V} + \left(n_0 + \frac{ER_q \cdot I}{AER} \right) \cdot \frac{e^{-AER \cdot t}}{V} \quad (\text{quanta m}^{-3}) \quad (3)$$

197 where AER (h^{-1}) represents the air exchange rate of the space investigated, n_0 represents the initial
198 number of quanta in the space, I is the number of infectious subjects, V is the volume of the indoor
199 environment considered, and ER_q is the abovementioned quanta emission rate (quanta h^{-1})
200 characteristic of the specific disease/virus under investigation.

201 The equation was derived considering the following simplifying assumptions: the quanta emission
202 rate is considered to be constant, the latent period of the disease is longer than the time scale of
203 the model, and the droplets are instantaneously and evenly distributed in the room (Gammaitoni
204 and Nucci, 1997). The latter represents a key assumption for the application of the model as it
205 considers that the air is well-mixed within the modelled space. The authors highlight that in
206 epidemic modeling, where the target is the spread of the disease in the community, it is impossible
207 to specify the geometries, the ventilation, and the locations of the infectious sources in each
208 microenvironment. Therefore, adopting the well-mixed assumption is generally more reasonable
209 than hypothesizing about specific environments and scenarios because the results must be
210 interpreted on a statistical basis (Sze To and Chao, 2010).

211 To determine the infection risk (R , %) as a function of the exposure time (t) of susceptible people,
212 the quanta concentration was integrated over time through the Wells–Riley equation (Riley et al.,
213 1978) as:

$$214 \quad R = \left(1 - e^{-IR \int_0^T n(t) dt} \right) \quad (\%) \quad (4)$$

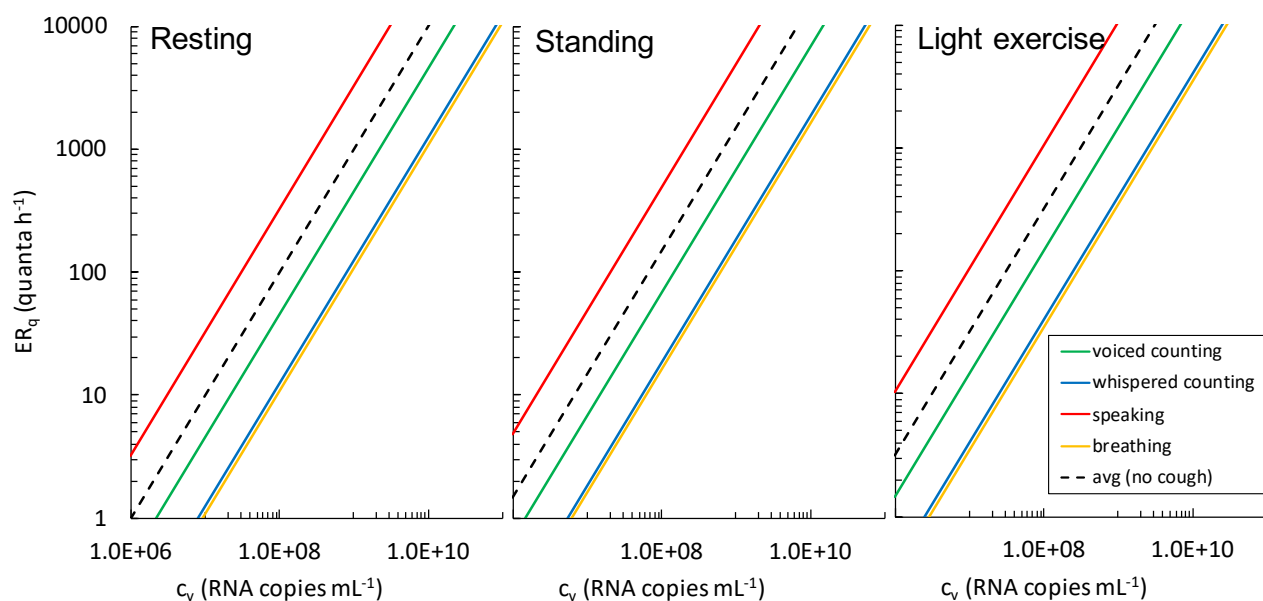
215 where IR is the inhalation rate of the exposed subject (which is, once again, affected by the subject's
216 activity level) and T is the total time of exposure (h). From the infection risk R , the number of
217 susceptible people infected after the exposure time can be easily determined by multiplying it by
218 the number of exposed individuals. In fact, equations (3) and (4) were adopted to evaluate the
219 infection risk of different exposure scenarios of Italian microenvironments hereinafter reported.
220 The quanta emission rate used in the simulation of the scenario represents the average value
221 obtained from the four expiratory activities (whispered counting, voiced counting, speaking, and
222 breathing); the data are reported and discussed in the result sections.

223 3. Results and discussions

224 3.1. The quanta emission rate

225 As discussed in the Materials and methods section, the quanta emission rate, ER_q , depends on
226 several parameters. In Figure 1 the ER_q (quanta h^{-1}) trends are reported as a function of the viral
227 load in the sputum (c_v , RNA copies mL^{-1}) for different expiratory activities (whispered counting,
228 voiced counting, speaking, breathing) and different activity levels (resting, standing, light exercise).
229 To represent the large variabilities (over several orders of magnitude) of ER_q as a function of c_v , the
230 graph is reported on a bi-logarithmic scale.

231 To benchmark the proposed approach for the estimation of the quanta emission rate, we
232 considered the case of seasonal influenza for which more data are available in terms of both viral
233 load in sputum and quanta emission rate. As an example, (Hirose et al., 2016) found an average
234 value of RNA concentration in sputum for influenza equal to 2.38×10^7 copies mL^{-1} . Thus, applying
235 the findings of the proposed approach in the case of a standing subject, a corresponding ER_q varying
236 between 3.7 (breathing) and 114 quanta h^{-1} (speaking) is estimated: this value is in good agreement
237 with the quanta emission rates for influenza found in the scientific literature, from 2 to 128
238 quanta h^{-1} with a most frequent value of 67 quanta h^{-1} (Knibbs et al., 2012). Such variability in the
239 quanta emission rates for influenza is due both to the method used to calculate it (Rudnick and
240 Milton, 2003) and, especially, the viral load of the subject and the type of respiratory activity, which
241 is typically not reported and discussed.
242



243 **Figure 1** - ER_q (quanta h^{-1}) trends as a function of the viral load in sputum (c_v , RNA copies mL^{-1}) for different
244 respiratory activities (whispered counting, voiced counting, speaking, breathing) and different activity
245 levels (resting, standing, light exercise). The average (avg) value of the respiratory activities considered was
246 also reported.
247

248 With reference to SARS-CoV-2 infection, researchers have recently found values for the viral load in
249 the mouth between 10^2 and 10^{11} copies mL^{-1} , also variable in the same patient during the course of
250 the disease (Pan et al., 2020; To et al., 2020; Woelfel et al., 2020). (Rothe et al., 2020) reported a
251 case of SARS-CoV-2 infection acquired outside Asia in which transmission appears to have occurred
252 during the incubation period in the index patient. A high viral load of 10^8 copies mL^{-1} was found,
253 confirming that asymptomatic persons are potential sources of SARS-CoV-2 infection; this may
254 warrant a reassessment of the transmission dynamics of the current outbreak. Table 3 lists the

255 quanta emission rates (ER_q) for a SARS-CoV-2 infected asymptomatic subject as a function of activity
256 level (resting, standing, and light exercise) and respiratory activity (voiced counting, whispered
257 counting, speaking, breathing). The data confirm the huge variations in the quanta emission rate,
258 with the lowest value being for breathing during resting activity ($10.5 \text{ quanta h}^{-1}$) and the highest
259 value being for speaking during light activity (more than $1000 \text{ quanta h}^{-1}$).

260 **Table 3** – Quanta emission rates (ER_q) for a SARS-CoV-2 infected asymptomatic subject ($c_v=10^8 \text{ copies mL}^{-1}$)
261 as a function of the activity level and respiratory activity.

Activity level	Respiratory activity				
	Voiced counting	Whispered counting	Speaking	Breathing	Avg
Resting	49.9	12.1	320	10.5	98.1
Standing	74.8	18.1	480	15.7	147
Light exercise	161	39.1	1.03×10^3	33.9	317

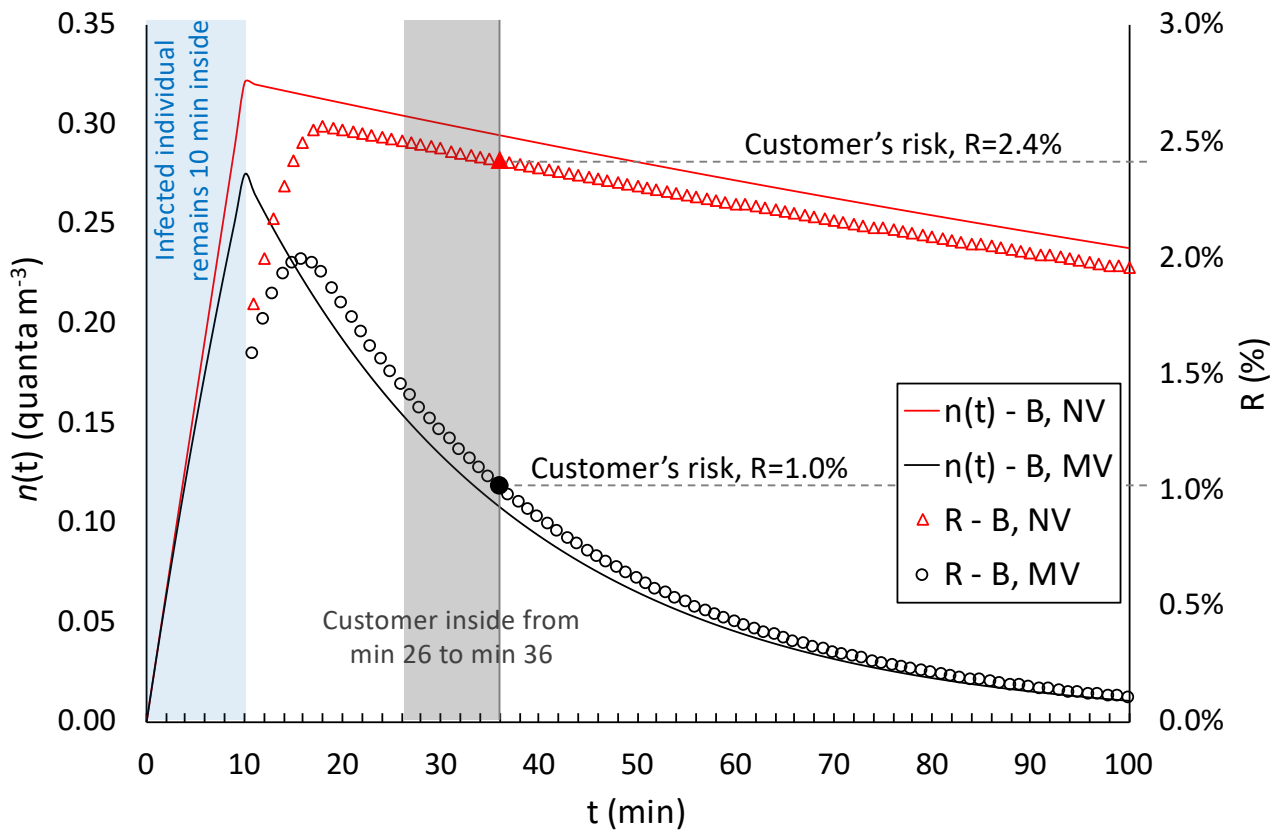
262 3.2. Results of the demonstration application

263 In this section, the results of the simulations performed for the microenvironments and exposure
264 scenarios described in section 2.2 and summarized in Table 2 are reported.

265 3.2.1. Infection risk and R_0 for different indoor environments and exposure scenarios

266 As an illustrative example, Figure 2 shows the quanta concentration ($n(t)$) and infection risk (R)
267 trends as a function of time for two different exposure scenarios simulated for the pharmacy, i.e.
268 before lockdown (B) in natural (NV) and mechanical ventilation (MV) conditions. The trends clearly
269 highlight that the presence of the infected individual remaining inside for 10 minutes leads to an
270 increase in the quanta concentration in the volume: in particular, a higher peak of quanta
271 concentration was recognized, as expected, for reduced ventilation (NV) with respect to the
272 mechanical ventilation (MV). People entering the pharmacy after the infected individual are
273 exposed to a certain quanta concentration during their 10-min time, and the resulting risk for their
274 exposure (evaluated through equation (4)) is just a function of the quanta concentration trend. For
275 example, people entering the microenvironment around the quanta concentration peak are at a
276 higher risk than people entering the pharmacy later. Figure 2 shows an example of a customer
277 entering at min 26 and leaving at min 36: the risk for this 10-min exposure is 2.4% in natural
278 ventilation conditions and 1.0% in mechanical ventilation conditions. During the entire exposure
279 time of such a scenario (3 hours and 10 minutes), 179 customers (after the infected individual) enter
280 the pharmacy and each of them receive their own risk. In particular, the average risk of the 179
281 customers is 2.0% for NV conditions and 0.4% for MV conditions, then leading to a R_0 (among the
282 customers) of 3.52 and 0.68, to which must be added the R_0 of the five pharmacists exposed for the
283 entire period. Similar trends, not shown here graphically for the sake of brevity, were obtained for
284 all the scenarios investigated, then leading to the evaluation of the R_0 for each of them as described
285 in the methodology section.

286



287
 288 **Figure 2** - Details of application of the proposed approach in the calculation of quanta concentrations, $n(t)$,
 289 and infection risks, R , in the pharmacy environment for the exposure scenarios before lockdown (B) in
 290 natural (NV) and mechanical ventilation (MV) conditions. The graph shows the entry of the infected
 291 individual (first 10 minutes) and the risk for a customer entering the microenvironment at min 26 and
 292 remaining inside for 10 minutes. The trends are shown for up to 100 minutes to highlight the peaks of the
 293 $n(t)$ and R values.

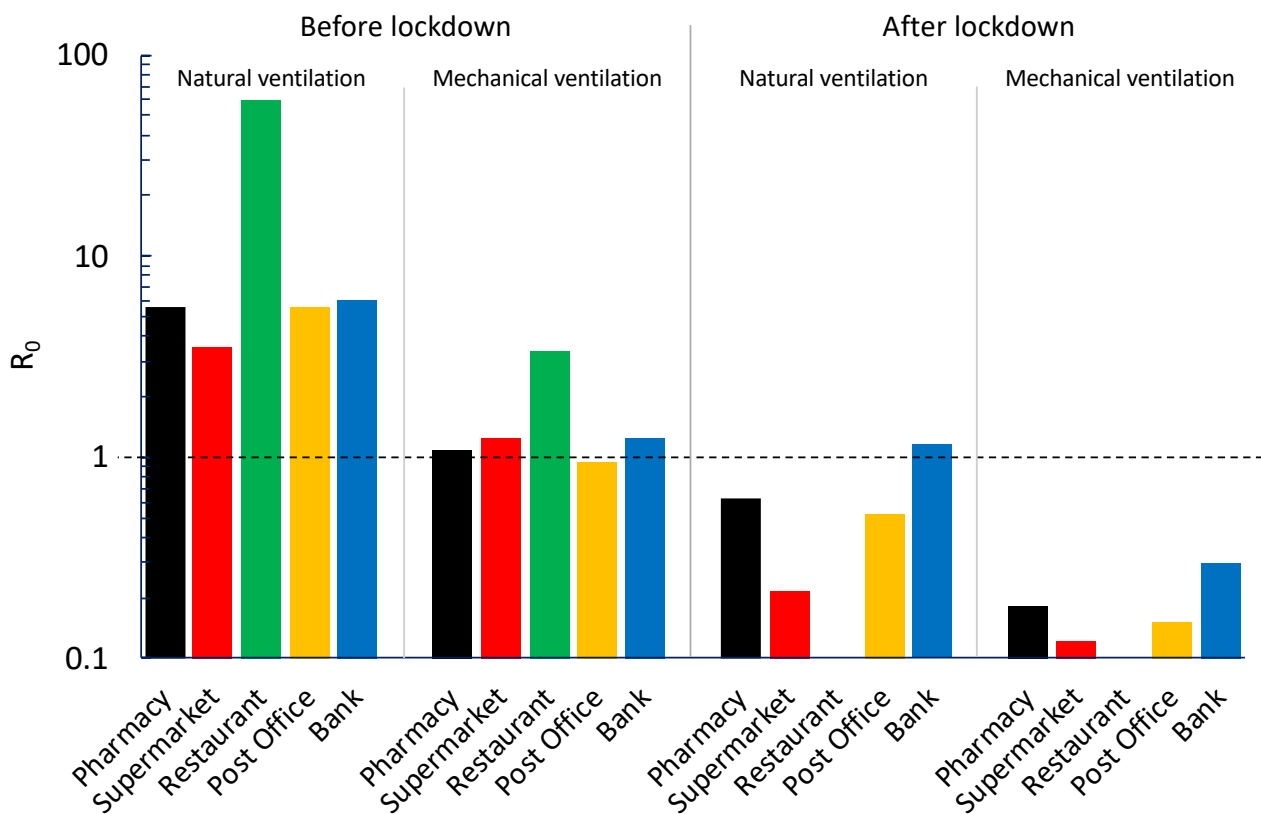
294 Figure 3 shows the reproduction number (R_0) data calculated for all the exposure scenarios and
 295 microenvironments under investigation (summarized in Table 2). The R_0 data were calculated for an
 296 asymptomatic SARS-CoV-2 infected subject ($c_v=1 \times 10^8$ copies mL^{-1}) while standing; in particular, the
 297 average ER_q value among the different respiratory activities was considered (147 quanta h^{-1} , Table
 298 **3**). The exposed subjects were also considered to be standing ($IR=0.54$ m^3 h^{-1}). The graph clearly
 299 highlights some critical exposure scenarios and microenvironments. Indeed, in all the
 300 microenvironments, a $R_0 > 1$ was estimated for all the exposure scenarios before lockdown (B) when
 301 the ventilation relied only upon the building being airtight (i.e. natural ventilation conditions): R_0
 302 was equal to 5.55, 3.51, 59.3, 5.59, and 6.04 for pharmacy, supermarket, restaurant, post office,
 303 and bank, respectively. The huge value for the restaurant is obviously due to the simultaneous co-
 304 presence of many people (80 customers and 4 waiters) and to the long exposure time (1 h and
 305 30 min in the current simulations). This situation is obviously improved if mechanical ventilation
 306 systems are adopted, but the R_0 is still higher than 1 ($R_0=3.40$). Similar results are obviously expected
 307 for all the indoor environments characterized by high crowding indexes and long-lasting exposures
 308 such as schools, swimming pools, gyms – venues that, in fact, were also concomitantly locked down
 309 by the government. Actually, adopting mechanical ventilation solutions that purportedly provide an
 310 adequate indoor air quality (i.e. providing AER values suggested by the standards (UNI, 1995)) did
 311 not satisfactorily reduce the R_0 in the other microenvironments investigated. Indeed, the R_0 values
 312 obtained from the simulations performed for the pharmacy, supermarket, post office, and bank
 313 equipped with mechanical ventilation systems in the conditions before lockdown, with mechanical
 314 ventilation in operation, were still > 1 .

315 The new regulations and methods of accessing the indoor environments that were applied in the
 316 conditions after lockdown (i.e. queuing outside, limited time spent in the environments, lower
 317 crowding index) were very effective; indeed, the R_0 values were reduced by roughly 80%–90% (for
 318 both natural and mechanical ventilation conditions) with respect to the corresponding pre-
 319 lockdown scenarios.

320 As an example, for the natural ventilation scenario, the only critical microenvironment was the bank,
 321 since the R_0 was >1 ; this was due to a crowding index that was higher than the post-office, which
 322 had a larger floor area but same number of customers. In contrast, all the R_0 values for indoor
 323 environments equipped with mechanical ventilation systems were much lower than 1 (0.18, 0.12,
 324 0.15, and 0.30 for pharmacy, supermarket, post office, and bank, respectively). Therefore, if in a
 325 single day the infected individual visited different environments, the resulting R_0 would be lower
 326 than 1 only if all the microenvironments were equipped with mechanical ventilation systems. Once
 327 again, these results highlight the importance of proper ventilation of indoor environments and are
 328 in line with the scientific literature that recognizes the importance of ventilation strategies in
 329 reducing indoor-generated pollution (Stabile et al., 2017)(Stabile et al., 2019).

330 The values obtained with this approach could vary significantly as a function of (i) the activity levels
 331 of both the infected subject and the exposed subjects; and (ii) the viral load in the sputum of the
 332 infected subject; therefore, in future studies, more specific exposure scenarios could be simulated
 333 on the basis of the findings proposed and discussed in this study.

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335

336 **Figure 3** - R_0 calculated for all the exposure scenarios (natural ventilation, mechanical ventilation; before
 337 lockdown, after lockdown) and microenvironments (pharmacy, supermarket, restaurant, post office, bank)
 338 under investigation considering an asymptomatic SARS-CoV-2 infected subject ($c_v=1 \times 10^8$ copies mL^{-1}) while
 339 standing ($IR=0.54 m^3 h^{-1}$; $ER_q=147$ quanta h^{-1}) and the exposed population, also standing.

340 **4. Conclusions**

341 The present study proposed the first approach aimed at filling the gap of knowledge still present in
342 the scientific literature about evaluating the viral load emitted by infected individuals. This
343 information could provide key information for engineers and indoor air quality experts to simulate
344 airborne dispersion of diseases in indoor environments. To this end, we have proposed an approach
345 to estimate the quanta emission rate (expressed in quanta h⁻¹) on the basis of the emitted viral load
346 from the mouth (expressed in RNA copies in mL⁻¹), typically available from virologic analyses. Such
347 approach also takes into account the effect of different parameters (including inhalation rate, type
348 of respiratory activity, and activity level) on the quanta emission rate. The suitability of the findings
349 was checked and confirmed as it was able to predict the values of quanta emission rates of previous
350 well-known diseases in accordance with the scientific literature. The proposed approach is of great
351 relevance as it represents an essential tool to be applied in enclosed space and it is able to support
352 air quality experts and epidemiologists in the management of indoor environments during an
353 epidemic just knowing its viral load, without waiting for the end of the outbreak.

354 For this purpose, it has been applied to the Italian case which, at the time of writing, represents the
355 country with the highest number of deaths from SARS-CoV-2 in the world, highlighting the great
356 importance of ventilation in indoor microenvironments to reduce the spread of the infection.

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