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Bronchoscopy is a procedure for viewing the inside of the respiratory tract for diagnostic or therapeutic purposes. The bronchoscope is inserted into the airways most often through the patient's nose and sometimes mouth. Bronchoscopy departments in hospital environments are among those most at risk of transmission of airborne infectious diseases. Bronchoscopies stimulate the cough reflex in patients. This cough represents the main aerosol generation process. The aerosols produced can contain pathogenic microorganisms such as mycobacteria, viruses and even moulds. These microorganisms can remain in the air for quite a long time. The main objective of this study was to measure the concentrations of the total and biological particles during bronchoscopy examinations, and to propose, using computational fluid dynamic, corrective measures.

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EVALUATION OF BIOAEROSOL EXPOSURES DURING HOSPITAL BRONCHOSCOPY EXAMINATIONS

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ABSTRACT

1 During hospital bronchoscopy examinations, aerosols emitted from the patient's during
2 coughing can be found suspended in the ambient air. The aerosols can contain pathogenic
3 microorganisms. Depending on their size, these microorganisms can remain in the air for a
4 long time. The objective of this study was to measure the sizes and concentrations of the
5 biological and non-biological particles produced during bronchoscopy examinations, and to
6 propose preventive or corrective measures.

7 Two bronchoscopy rooms were studied. An aerodynamic particle sizer (UV-APS)
8 was used to establish the concentrations of the particles present and their size distributions.
9 This instrument determines the aerodynamic diameter of the aerosols and can distinguish
10 fluorescent (bioaerosols) and non-fluorescent particles. Reference concentrations were
11 measured before the start of the examinations (morning background concentrations). They
12 were used as comparison levels for the concentrations measured during and at the end of the
13 bronchoscopies. In parallel, computational fluid dynamics (CFD) made it possible to isolate
14 and understand different factors that can affect the concentration levels in bronchoscopy
15 rooms.

16 The concentrations of the non-fluorescent and fluorescent particles (bioaerosols) were
17 significantly higher ($p \leq 0.05$) during the bronchoscopy examinations than the reference
18 concentrations. For the investigated factors, the bioaerosol concentrations were significantly
19 higher during bronchoscope insertion tasks. The time required at the end of the day for the
20 bioaerosols to reach the morning reference concentrations was about fifteen minutes. The
21 average particle sizes were 2.9 µm for the fluorescent particles (bioaerosols) and 0.9 µm for
22 the non-fluorescent particles. Our models based on computational fluid dynamics (CFD)
23 enabled us to observe the behaviour of aerosols for the different rooms.

24

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INTRODUCTION

Bronchoscopy is a procedure for viewing the inside of the respiratory tract for diagnostic purposes (e.g., lung diseases such as cancer or tuberculosis, congenital lung deformation, suspected tumour, obstruction, secretion, bleeding, foreign body in the respiratory tract, abnormalities) or therapeutic purposes (e.g., extraction of a foreign body and excessive secretions from the lungs)[1] The instrument (bronchoscope) is inserted into the airways most often through the patient's nose and sometimes mouth, or occasionally via a tracheostomy.[1] The bronchoscope consists of a flexible tube containing optical fibres that transmit the image to an eyepiece or a video camera. It can be equipped with an aspiration device. All the bronchoscopies performed in this project used this type of bronchoscope.

Bronchoscopy departments in hospital environments are among those most at risk of transmission of airborne infectious diseases.[1-5] Hospital studies show a strong association between ventilation, air currents in the buildings, and the transmission and propagation of airborne pathogenic biological agents causing infectious diseases such as mumps, pneumonia, tuberculosis, influenza, chickenpox, smallpox, SARS, etc.[1,3,6-9]

Bronchoscopies and endotracheal intubations stimulate the cough reflex in patients.[6,10] This cough during intubation possibly represents the main aerosol generation process when bronchoscopy examinations are performed. According to Malasky et al. (1990), coughing would generate droplets between 5 to 10 µm in size. Liquid aerosols dry quickly to produce droplet nuclei which, according to Yassi and Bryce, would be between 0.1 and 10 µm in the case of coughing and sneezing.[11,12] The phenomenon of drying of the liquid particles begins immediately after they are expelled. The drying times for 100 and 50 µm droplets in air with a relative humidity of 50% are 1.3 and 0.3 seconds respectively.[13] Most viruses and bacteria that cause respiratory diseases in humans are found on droplet nuclei of approximately 5 µm.[6,11,12] It is the size of the particles that determines whether they can be inhaled and retained in the respiratory tract.[14]

The size of the particles is also what determines the sedimentation distance from the source.[12] According to Lenhart et al. (2004), it is incorrect to define a limit distance of one or two metres as being the space in which a health worker should not enter in order not to be exposed to respiratory infections. Large infectious droplets (bigger than 20 microns) are rapidly deposited and are generally not inhaled into the lungs because they are trapped by the cilia and the mucus in the nose and mouth.[11] However, they can be deposited in the pharynx if

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57 the health worker is near the infectious patient.[11] The inhalation of a single microdroplet
58 containing fewer than three tuberculous bacilli can lead to an infection.[15]

59 Ventilation plays a vital role in ensuring the dilution and effective elimination of
60 potentially pathogenic aerosols. The fresh air flow rate and the ventilation strategy have a
61 direct impact on the risk of infectious disease propagation.[3,4,16] The minimum ventilation level
62 recommended by the ASHRAE 170-2008 standard for a bronchoscopy unit is 12 air changes
63 per hour, two of which are fresh air.[17] This is one of the standards used by the *ministère de la*
64 *Santé et des Services sociaux* (MSSS, Québec department of health and social services) and
65 the Québec Realty Corporation in their recommendations for hospitals. The room must be at
66 negative pressure and the air exhausted from the room must be evacuated outdoors.[17] The
67 difference in pressure between the room and the immediate environment must be 2.5 Pa.[18] In
68 order to better control the difference in pressure, ASHRAE recommends installing an
69 anteroom at the entrance to the room.[18,19] Previous studies have shown that, in bronchoscopy
70 rooms, fresh air admission through the ceiling and exhaust outlets located 20 to 30 cm from
71 the floor on the opposite wall is the best way of maintaining acceptable air contamination
72 levels.[18] From our discussions with people from this community, very few hospitals comply
73 with this recommendation which is not a standard.

74 Computational fluid dynamics (CFD) is a necessary technique for understanding air
75 and heat movements in closed spaces.[20] Numerical resolution of airflow conservation
76 equations can help in understanding the phenomena of gaseous and particulate contaminant
77 transport and diffusion in hospitals. The impact of the supply air flow and temperature as well
78 as the ventilation strategy can be studied without using experimental means.

79 The objective of this study was to measure the sizes and concentrations of the
80 fluorescent particles (bioaerosols) and non-fluorescent particles produced during
81 bronchoscopy examinations, and to propose preventive or corrective measures.

82

83 # METHOD

84 ## Choice of rooms

85 Two bronchoscopy rooms in two Québec hospitals were chosen. The choice was based on
86 ventilation parameters.

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87 The first bronchoscopy room evaluated is shown in Figure 1. According to its
88 designers, this room meets the current ventilation standards of ASHRAE and the American
89 Institute of Architects (AIA) that are used in designing bronchoscopy departments.[17,21] For
90 this reason, it will be called the "control room" in this document. Two 0.6 m × 0.6 m square
91 diffusers installed in the ceiling provide ventilation to the room. The return grille, also
92 installed in the ceiling, has a surface area of 0.09 m^2. The volume of this room was 79 m^3. It
93 also contained three tables, one bed, one LCD screen, cupboards and storage space. This room
94 was designed to be at negative pressure in relation to its anteroom. The number of theoretical
95 air changes per hour should be 12 in order to correspond to what is recommended by the
96 ANSI/ASHRAE/ASHE 170-2008 standard.[17]

97 The other evaluated room had a volume of 59.8 m^3 (see Figure 2). Ventilation was
98 provided by two slot diffusers 1.2 m long, installed in the ceiling. Three exhaust systems
99 equipped with fans and HEPA (*High Efficiency Particulate Air*) filters evacuated the air to the
100 outdoors. An LCD screen was located above the stretcher; it descended from the ceiling to the
101 centre of the room. The equipment necessary for the examination, including the
102 bronchoscope, were placed on a tray beside the stretcher. This room had two entrances, one
103 for the stretcher that the patient lies on, and the other leading to a material storeroom. This
104 room will be called the "investigated room" in this document.

105 On the sampling days, 10 bronchoscopies were performed in the investigated room
106 and 5 in the control room. For each room, sampling was done for the entire day. In this study,
107 the number of bronchoscopies necessary to be statistically representative ($p \leq 0.05$) with an
108 acceptable error of 20% was 14.[22]

109 The measurements were taken consecutively for all the steps in the bronchoscopy
110 operations, from the arrival of the patient until his departure. The samples were all stationary
111 samples near the bronchoscopy operations and downstream from the air flow in relation to the
112 patient. During the bronchoscopies, the measuring instruments were installed within a radius
113 of 1.5 m from the patient's mouth. This layout was chosen at the request of the pneumologists
114 and inhalation therapists so as not to impede their work. All the sampling equipment was
115 close together, within an area of approximately 80 cm, to allow a better comparison of the
116 samples.
117

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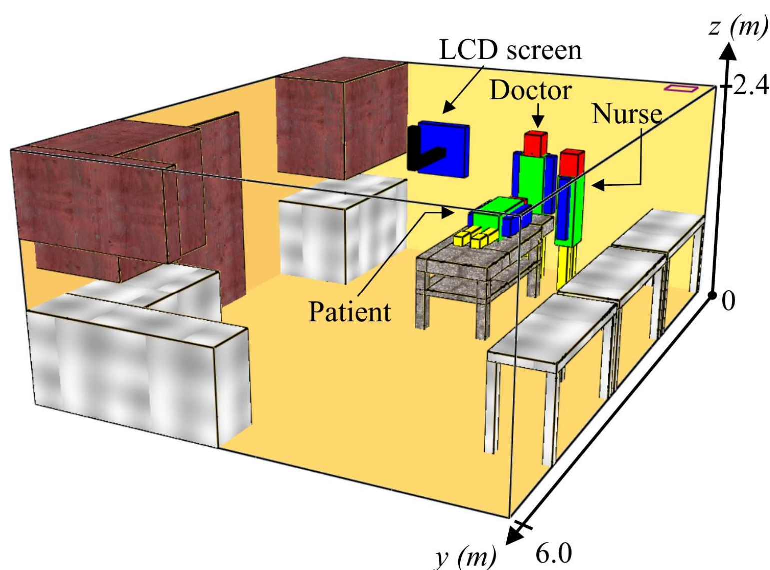
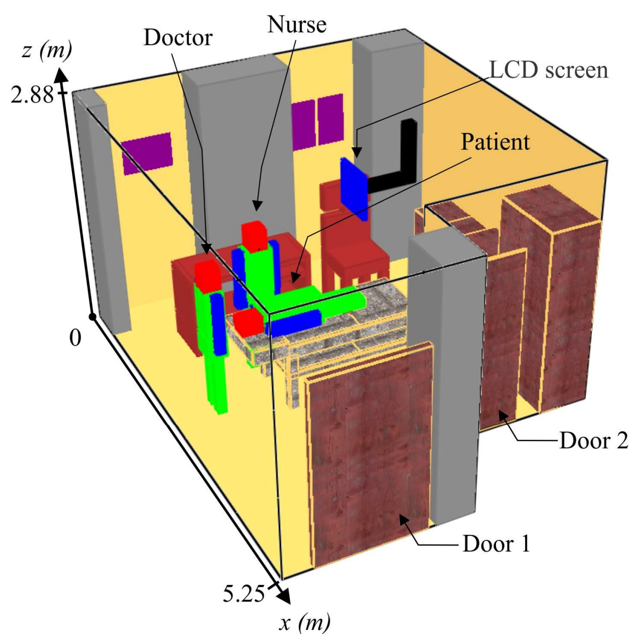


118

119 **Fig. 1** Bronchoscopy control room



120

121 **Fig. 2** Bronchoscopy investigated room

122 The samples for establishing the base concentrations or background concentrations were
123 collected at the start of the day, before the bronchoscopies were performed and after the
124 sampling equipment was installed. The researchers also asked the hospital staff not to enter
125 the room, insofar as possible, during the sampling. The fluorescent and non-fluorescent
126 particle concentrations obtained were used as a basis of comparison with those concentrations
127 obtained during the bronchoscopies. Other end-of-day samples after the bronchoscopies,

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128 performed under similar conditions, were used to evaluate the time required for the ambient
129 aerosol concentrations to return to the same level as those at the start of the day, equivalent to
130 the background concentrations.

131 In addition to one member of the research team, three people on average (the doctor,
132 nurse and patient) were present in the bronchoscopy room. Continual comings and goings
133 were observed in the control room and the investigated room, to the point that up to seven
134 people were seen during one bronchoscopy examination.

135

136 **Measurement of the number of air changes per hour (ACH)**

137 The number of air changes per hour was determined using the tracer gas technique of ASTM
138 International, 1993. A uniform concentration of tracer gas, SF6, is first established in the
139 investigated room. The SF6 concentrations were then measured as a function of time and at
140 different locations. They were used to estimate the age of the air at the different measurement
141 positions with the decreasing method and its rate of change. The SF6 concentrations were
142 measured at a height of 1.7 m with a portable Autotrac electron capture chromatograph
143 (Autotrac 101, Lagus Applied Technology Inc., California, USA). This instrument's precision
144 is ±5%. With these measured concentrations, the basic ventilation parameters for CFD
145 modeling were obtained and the results validated.

146

147 **Concentrations and sizes of the fluorescent and non-fluorescent particles**

148

149 The concentrations and particle sizes of the aerosols emitted during the bronchoscopy
150 examinations were measured in real time, with stationary sampling, with a fluorescent
151 aerodynamic particle sizer (TSI UV-APS 3314, Minnesota, USA) using an excitation
152 wavelength of 355 nm and measuring the ultraviolet fluorescence between 420 and 575 nm.[24]
153 This wavelength is considered as appropriate for microorganisms. The UV-APS allows the
154 user to differentiate the biological fraction associated with fluorescence from the non-
155 biological fraction. In fact, because proteins in biological material fluoresce when they are
156 excited by a source of ultraviolet light, measurement of this fluorescence makes it possible to
157 determine, in real time, all the biological aerosols without distinction. It also establishes the
158 the particle size of an aerosol, almost instantaneously, for particles whose aerodynamic
159 diameter is between 0.5 and 15 µm. This range of diameters corresponds to the diameters of
160 particles likely to reach the lower respiratory tract.[6,11,12,14] This instrument was necessary for

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161 such a project because an instantaneous evaluation cannot be done using conventional
162 methods with culture or molecular biology. Due to its characteristics, this instrument can be
163 used to evaluate the time necessary for the concentrations of the emitted aerosols to reach
164 their base levels and to correlate them with the different ventilation rates. For purposes of
165 comparison with the analysis of the aerosol concentrations, all the data obtained with the UV-
166 APS cover a five-minute sampling duration. A total of 88 five-minute samples were collected,
167 namely 58 in the investigated bronchoscopy room and 30 in the control room.
168

169 **Ventilation modeling**

170 Ventilation and bioaerosol transport were modeled using *Fire Dynamics Simulator* software
171 (FDS, version 6) based on the *Large eddy simulation* method developed by the National
172 Institute of Standards and Technology.[25] This software is in the public domain and has been
173 the subject of numerous verification and validation studies.[26,27] It consists of several sub-
174 models, with the most important for this study being the hydrodynamic model capable of
175 solving modified Navier-Stokes equations for low velocity and thermally induced flows. The
176 partial derivatives of the equations of mass conservation, quantity of movement, and energy,
177 are solved by an explicit predictor–corrector scheme with second order precision in time and
178 space. Closure of the equations is completed by the ideal gas relationship applied to a mixture.
179 The model that was used for modeling the aerodynamic behaviour of the bioaerosols
180 used the transport equation for a passive scalar.
181 Given the small mass fraction of droplet nuclei, their effect on the flow could be
182 disregarded. Also, the sedimentation velocity of droplet nuclei between 0.1 µm and 10 µm is
183 less than 0.02 m per minute in a calm environment.[28] In such a context, the droplet nuclei will
184 follow the lines of flow created by the cough and then be transported into the flow induced by
185 the room's ventilation system. The particles will very closely follow the behaviour of a
186 passive scalar. With this model, bioaerosols behave exactly like an air flow. This model does
187 not take into account the inertia of the particles, does not solve the velocity field of the latter,
188 and the result is a mass fraction field expressed as kg of bioaerosol per kg of air. This mass
189 fraction varies with time and space. The "passive scalar" model implies that the ventilation
190 and the respiration of hospital personnel are the only mechanisms responsible for the
191 reduction in bioaerosol concentrations.
192 By taking into account the assumptions made above, the bioaerosol conservation
193 equation is expressed by the following relationship:

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194 $$\frac{\partial}{\partial t}(\rho Z)+\nabla\cdot(\rho Z\,\mathbf{u})=\nabla\cdot(\rho D\nabla Z) \quad (1)$$

195 where Z and $\mathbf{u}$ respectively represent the mass fraction of bioaerosols (kg/kg of air) and the air
196 flow velocity vector. The air density is represented by ρ, and D is the contaminant's
197 coefficient of diffusion.

198 In the bronchoscopy rooms, no source of heat was considered with respect to lighting,
199 because the interventions were generally performed without light. However, a heat transfer
200 rate of 40 W was imposed for the LCD screen located above the patient, which was in
201 operation throughout the intervention. The air temperature at the air outlets was set at 18°C,
202 which corresponds to the temperature measured with a TSI Velocicalc 8347 anemometer with
203 a precision of ± 0.3°C. The walls, floor and ceiling were considered as adiabatic. Also, the
204 condition of adherence was imposed at the solid boundaries.

205 Table 1 presents the air delivery rates chosen for the two rooms. The investigated
206 bronchoscopy room was at negative differential pressure (≈5 Pa) with respect to the adjacent
207 corridor.

208 **Table 1: Air delivery rates chosen for the simulated cases**

ACH (h^{-1})	8	12	18	24
Investigated room (m^3/s)	0.064 (diffusers) 0.025 (infiltration)	0.149 (diffusers) 0.039 (infiltration)	0.231 (diffusers) 0.051 (infiltration)	0.299 (diffusers) 0.077 (infiltration)
Control room (m^3/s)	0.153	0.230	0.344	0.459

209 ACH: Number of air changes per hour

210 The measurements confirmed that the exhaust flow in the investigated room was slightly
211 greater than the air delivery rate; the difference was mainly due to air infiltration under door 2
212 (Figure 2) under the effect of depressurization. Air infiltration under this door was measured
213 and considered in the numeric code. The measurements in the control room showed that this
214 room was not maintained at differential negative pressure. As a result, no infiltration flow was
215 considered.

216 The respiration of hospital personnel was calculated during the simulations by
217 imposing a flow rate varying between -0.67 m/s (respiration) and 0.67 m/s (expiration) for the
218 mouth, which corresponds to an inhaled air flow of 6 l/min.[29] The temperature of the exhaled
219 air was 37°C. The source of the bioaerosols was simulated at the patient's mouth by three
220 coughs occurring at 60, 120 and 180 seconds respectively. For each cough, the flow velocity

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221 went from 0 to 25 m/s in 0.1 s, and then decreased linearly to 0 m/s within an interval of 0.5 s.
222 The velocity profile was similar to the one used by Redrow et al. (2011).[30]

223 Numerical solutions for the governing equations for air flow and bioaerosol transport
224 require the domain to be discretized. In the FDS, the computational domain is discretized in a
225 Cartesian reference system. The grid elements consist of a volume parallelepiped ($\delta x \times \delta y \times \delta z$),
226 where δx, δy, δz represent the distances between two neighbouring nodes in the x, y and z
227 directions respectively. The time step is set in such a way as to comply with the Courant-
228 Friedrichs-Lewy (CFL) condition. With this condition, a "fluid particle" cannot cover more
229 than one cell within a time interval. The independence of the spatial discretization on the
230 numerical results was determined by the GCI (*Grid Convergence Index*), which is used to
231 evaluate the numerical error in the response related to the quality of the grid in a
232 computational domain. The numerical results presented in this report required up to 100 hours
233 of calculations (by simulation) on a workstation equipped with a Xeon 2.66 GHz six-core
234 processor (Intel, CA, USA). It is therefore important to choose an "optimal" grid density in
235 order to obtain precise results within a reasonable time. The characteristics of the grids
236 retained for the simulations in the two rooms are presented in Table 2.

237 **Table 2: Characteristics of the grids chosen for the simulations**

	Volume of an element in m^3 (minimum/maximum)	Number of nodes in the computational domain
Investigated room	6.2×10^{-6} / 6.4×10^{-5}	1,407,456
Control room	8.0×10^{-6} / 5.4×10^{-5}	1,725,000

238

239 **Statistical analyses**

240 The data were analyzed using multivariate variance tests, and multiple comparisons (Tukey-
241 Kramer parametric tests). When necessary, they were normalized by logarithmic
242 transformation in order to comply with the applicability criteria of the parametric tests used.[31]
243 NCSS 2007 software was used to perform all of the statistical analyses.

244

245 # RESULTS

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246 **Measurement of the number of ACH**

247 The arithmetic mean for six series of ACH measurements for the control room was 17 (± 1.1)
248 and that for five series of measurements for the investigated room was 24.4 (± 0.6) ACH.

249 **Concentrations and sizes of fluorescent particles (bioaerosols) and non-fluorescent**
250 **particles**

251 The concentrations of non-fluorescent and fluorescent particles measured with the TSI UV-
252 APS 3314 for the two rooms are presented in Table 3. The results for each patient are given in
253 relation to the time, to the order in the day, as well as to the moment of introduction of the
254 bronchoscope which corresponds to the period zero. The periods are given by 5-minute range.

255

256 **Table 3. Concentrations of non-fluorescent and fluorescent particles and median**
257 **aerodynamic diameters (MAD) in number in the two rooms measured with the TSI UV-**
258 **APS 3314 .**

259

Room	Sample	Row	Conc. without fluo. (#/m³)	Conc. With Fluo. (#/m³)	NMAD Without Fluo. (µm)	NMAD With Fluo. (µm)	Period
CONTROL ROOM	Background concentration (morning)	1	48 399	13 000	1.11	3.11	-7
		2	20 200	5 200	1.01	1.84	-6
		3	12 200	2 600	0.95	1.75	-5
		4	26 999	7 400	1.19	3.96	-4
		5	107 398	28 999	1.04	3.41	-3
		6	62 399	19 200	1.11	3.43	-2
		7	51 199	20 200	1.03	3.81	-1
	Patient 1	8	2 252 555	27 599	0.98	3.79	0
		9	695 986	31 599	0.98	3.93	1
	Patient 2	10	16 177 084	42 999	1.01	3.66	0
		11	4 639 907	27 599	0.99	3.89	1
	Patient 3	12	12 137 356	30 999	0.99	3.51	0
	Patient 4	13	52 799	18 600	1.02	3.16	-1
		14	14 888 109	25 000	0.98	3.51	0
		15	4 209 716	17 400	0.97	2.95	1
		16	1 085 378	15 800	0.97	3.07	2
		17	348 593	14 600	0.96	3.76	3
		18	126 197	11 600	0.94	3.28	4
		19	65 799	20 400	1.07	4.25	5
		20	85 398	36 199	1.19	3.86	6
		21	37 599	20 800	1.17	4.28	7
	Patient 5	22	30 599	15 600	1.10	2.39	-3
		23	32 399	12 600	1.17	3.43	-1
		24	4 921 502	28 199	0.95	3.54	0
		25	1 414 772	16 000	0.95	3.52	1
		26	405 592	16 600	0.93	3.49	2
	Background concentration (at the end)	27	208-996	34 199	1.08	3.75	3
		28	68 399	10 200	1.10	3.38	4
		29	30 599	7 400	1.08	3.75	5
		30	25 400	6 800	1.10	3.38	6
	Background	31	429 991	25 599	0.77	2.64	-5

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INVESTIGATED ROOM	concentration (morning)	32	382 792	12 200	0.76	2.10	-4
		33	347 593	9 000	0.75	1.61	-3
		34	337 193	8 400	0.75	2.29	-2
	Patient 1	35	370 993	10 400	0.75	3.40	-1
		36	574 789	47 799	0.79	2.62	0
		37	527 989	18 600	0.77	1.83	1
		38	442 191	26 599	0.77	2.86	2
		39	473 391	25 199	0.78	1.98	3
		40	451 591	17 200	0.77	3.52	4
		41	448 791	17 600	0.77	2.81	5
	Patient 2	42	470 791	32 199	0.78	2.26	0
		43	367 593	14 600	0.78	2.02	1
	Patient 3	44	667 187	66 199	0.80	1.62	0
		45	457 791	25 599	0.78	2.55	1
		46	444 191	19 800	0.79	2.39	2
		47	641 788	1 200	0.80	3.19	3
	Patient 4	48	716 785	71 399	0.82	2.75	-3
		49	539 590	38 799	0.78	2.39	-2
		50	564 189	32 799	0.79	2.48	0
		51	493 790	17 600	0.78	1.91	1
		52	558 189	50 999	0.80	2.81	3
	Patient 5	53	765 385	53 399	0.81	3.06	-1
		54	604 988	37 799	0.79	2.63	0
		55	541 790	26 799	0.79	2.10	1
	Patient 6	56	661 787	60 599	0.80	3.00	-4
		57	647 188	61 999	0.80	2.82	-3
		58	608 588	46 599	0.79	2.48	-2
		59	675 187	30 199	0.80	2.23	0
		60	540 789	28 999	0.79	2.91	1
	Patient 7	61	559 789	46 999	0.80	2.58	-3
		62	616 388	47 999	0.80	2.54	-2
		63	696 586	39 799	0.81	2.91	-1
		64	607 789	19 800	0.80	2.59	0
		65	667 387	66 599	0.81	3.03	1
	Patient 8	66	683 787	67 999	0.80	2.35	-7
		67	641 387	44 399	0.79	3.30	-5
		68	620 788	38 599	0.79	2.81	-4
		69	856 382	52 199	0.81	2.96	0
	Patient 9	70	846 584	94 398	0.81	3.00	-7
		71	729 385	66 999	0.80	2.80	-6
		72	739 585	67 199	0.80	2.81	-5
		73	695 586	52 399	0.78	2.02	-4
		74	728 785	25 799	0.77	1.78	-3
		75	750 985	37 799	0.78	2.19	-2
		76	663 986	26 399	0.78	2.51	-1
		77	612 788	24 600	0.79	1.80	0
	Patient 10	78	605 589	52 399	0.79	2.00	-2
		79	862 783	62 399	0.82	2.16	-1
		80	653 587	28 999	0.80	1.83	0
		81	538 990	39 599	0.79	2.00	1
		82	483 590	26 599	0.79	1.71	2
		83	485 390	23 600	0.79	1.79	3
	Background concentration (at the end)	84	1 581 768	25 599	0.74	2.08	4
		85	1 331 774	15 600	0.74	2.29	5
		86	639 586	14 400	0.76	2.64	6
		87	511590	11 600	0.77	1.78	7
		88	496 790	10 600	0.77	1.95	8

260 (#/m³): number of particles per cubic metre of air; NMAD: Number Median Aerodynamic Diameter

261

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262 Tables 4 and 5 summarize the results of the measurements of fluorescent and non-fluorescent
263 particles for the two rooms. They were obtained by comparing the averages of the
264 concentrations and particle sizes during the bronchoscopies, and the background
265 concentrations at the end with the concentrations measured at the start of the day.
266 For both the control room and the investigated room, the average concentrations of the
267 particles with and without fluorescence measured at the beginning and end of the day were
268 significantly smaller than those measured during the bronchoscopies. No statistically
269 significant difference was found for the mean aerodynamic diameters in both rooms.
270 The particle concentrations measured during the bronchoscopies were also compared
271 with the background concentrations. For the two examination rooms, the average
272 concentrations of the non-fluorescent and fluorescent particles were significantly higher ($p \leq$
273 0.05) than the background concentrations measured at the start of the day. As an example, the
274 average concentration of non-fluorescent particles in the control room was 124 times higher
275 during the procedures than the room's background concentrations at the start of the day, while
276 that of the fluorescent particles was three times higher (Table 4). In the investigated room, the
277 average concentration of the fluorescent particles was also three times higher than that of the
278 background concentrations determined at the start of the day (Table 5).

279 The particle size profiles for the fluorescent and non-fluorescent particles were
280 different. The average of the median aerodynamic diameters in number for the fluorescent
281 particles (bioaerosols) was 2.9 μm and that for the non-fluorescent particles was 0.9 μm
282 (Tables 4 and 5).
283

284 **Table 4: Results of the particle measurements for the control room**

	Without fluorescence			With fluorescence		
	n	Average of the concentrations (±S.D.) (#/m³)	Average of the NMAD (μm)	n	Average of the concentrations (±S.D.) (#/m³)	Average of the NMAD (μm)
Background concentrations (start)	3	26,933 (19,016)	1.06	3	6,933 (5,412)	3.04
Bronchoscopy	19	3,344,555* (5,219,242)	1.02	19	22,640* (8,662)	3.54

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Background concentrations (end)	4	68,700 (72,910)	1.09	4	14,650 (13,120)	3.56

285 n: number of measurements; S.D.: standard deviation; (#/m³): number of particles per cubic metre of air;
286 NMAD: Number Median Aerodynamic Diameter; *: Statistically significant difference ($p \leq 0.05$)

287 **Table 5: Results of the descriptive statistical analysis of the particles for the investigated**
288 **room**

	Without fluorescence			With fluorescence		
	n	Average of the concentrations (±S.D.) (#/m³)	Average of the NMAD (µm)	n	Average of the concentrations (±S.D.) (#/m³)	Average of the NMAD (µm)
Background concentrations (start)	4	374,390 (41,890)	0.76	4	13,800 (8,041)	2.20
Bronchoscopy	46	610,830* (120,180)	0.79	46	41,238* (19,027)	2.53
Background concentrations (end)	4	744,935 (396,444)	0.76	4	13,050 (2,340)	2.16

289 n: number of measurements; S.D.: standard deviation; (#/m³): number of particles per cubic metre of air;
290 NMAD: Number Median Aerodynamic Diameter *: Statistically significant difference ($p \leq 0.05$)

291

292 *Comparison of the different tasks*

293 Multiple Tukey-Kramer comparisons performed for the two rooms having, as factors, the
294 waiting periods (negative periods in Table 3), the manipulations (period 0 and positive
295 periods in Table 3), and the measurements of the background concentrations (in the morning
296 and at the end of the day) showed that the concentrations of the non-fluorescent particles
297 measured during the manipulations were significantly higher than those for the waiting
298 periods or the background concentrations. This stage of bronchoscopy therefore dominates the
299 process of non-fluorescent aerosol generation caused by the introduction of the bronchoscope
300 (periods 0 and after in Table 3), the patient's multiple coughs and emissions, and the injection
301 of water and medications into the bronchi during the examinations. For the fluorescent
302 particles, the concentrations during the waiting periods and during the manipulations were
303 significantly higher than the background concentrations. This clearly shows that regardless of
304 the type of particle, the tasks in the rooms produce an increase in the existing concentrations.

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305 Once the significant impact on the particle concentrations shown for the "tasks
306 performed" factor had been identified, another log ANOVA was performed to isolate the tasks
307 (before insertion (negative periods in Table 3, during insertion (period 0 in Table 3) and after
308 insertion of the bronchoscope (positive periods in Table 3)). These concentrations for
309 bronchoscope insertion in the control room were significantly higher for the non-fluorescent
310 particles ($p = 0.014$ and $F = 6.80$) and fluorescent (bioaerosol) particles ($p = 0.009$ and $F =$
311 7.70).

312

313 However, this increase was not significant for the investigated room, for the two types
314 of particles.

315

316 **Modeling**

317 *Validation of the model*

318 Simulations were repeated for the actual ventilation conditions by imposing the initial mass
319 fraction of SF6 measured experimentally. Figures 3 and 4 compare the measured
320 concentrations as a function of time with the SF6 concentrations obtained numerically. The
321 mass fractions obtained from simulation were converted into a volume fraction (parts per
322 billion - ppb) to allow comparison. The correlation coefficients were 0.998 for the
323 investigated room and 0.997 for the control room. They were all highly significant.

324 *Bioaerosol dispersion*

325 It was difficult to represent the time evolution of bioaerosol dispersion in the modeled rooms.
326 Figures 5 and 6 indicate in a general way what happened to the bioaerosols released when the
327 patient coughed. Each flow line is represented by a line whose colour indicates the time
328 passed since the bioaerosols were suspended in the room. This behaviour was identical to the
329 one that emerged from our simulations except that it involved, in this case, a representation
330 based on actual phenomena (Figures 5 and 6).

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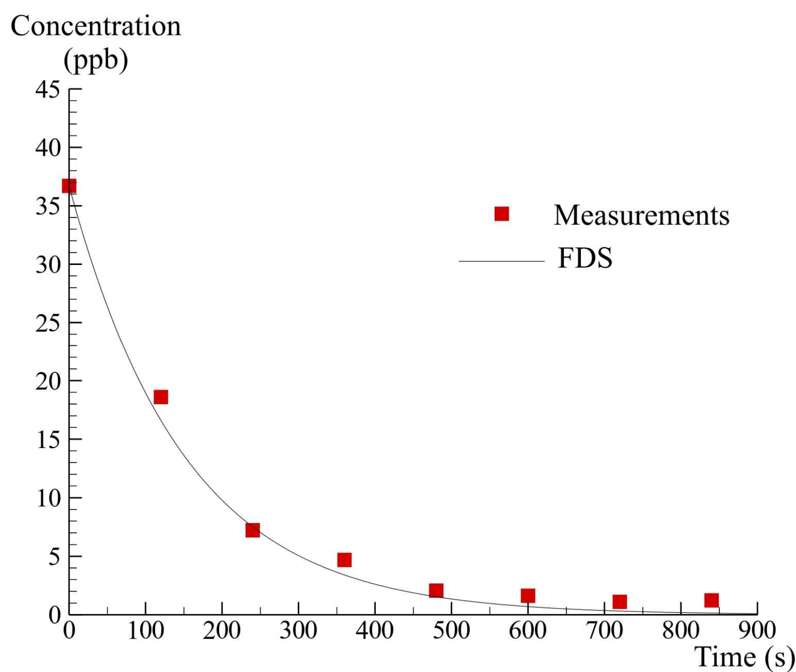
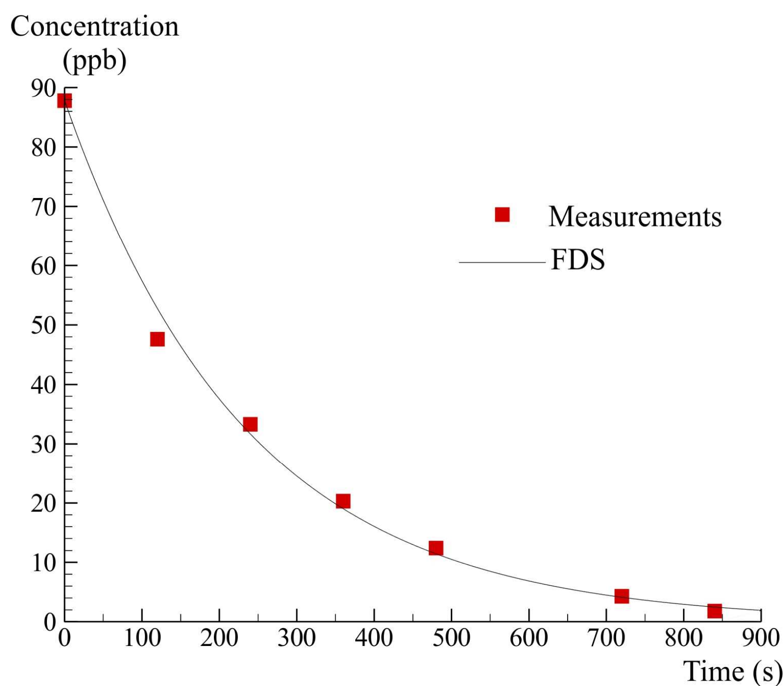


331

332 **Fig. 3** SF6 concentration as a function of time for the investigated room

333



334

335 **Fig. 4** SF6 concentration as a function of time for the control room

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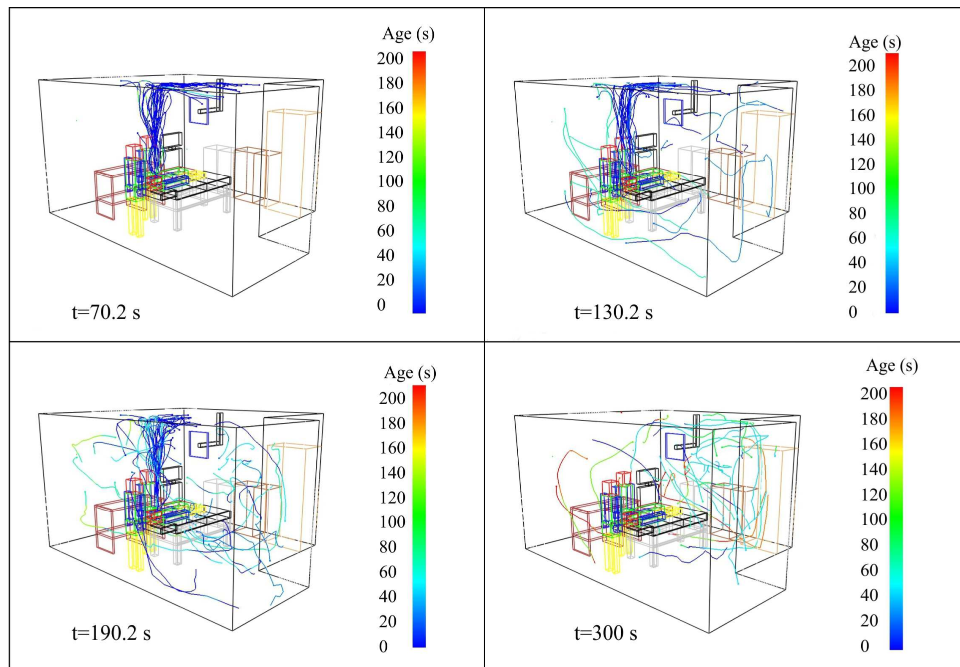
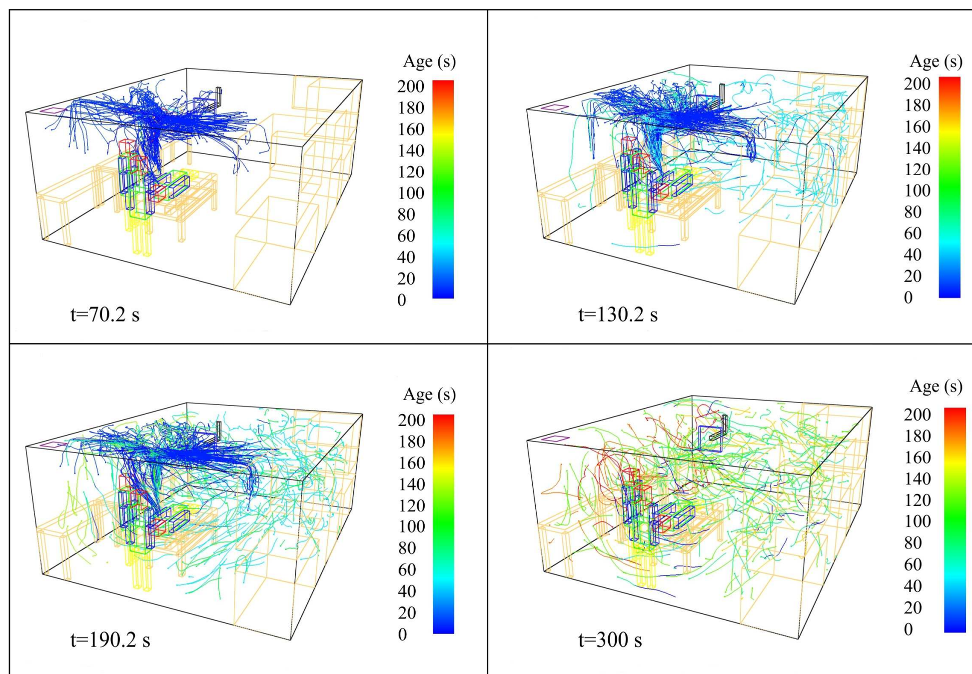


336

337 **Fig. 5** Trajectories of the bioaerosols as a function of time (from 70.2 to 300 sec) in the
338 investigated room

339



340

341 **Fig. 6** Trajectories of the bioaerosols as a function of (from 70.2 to 300 sec) in the control
342 room

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343
DISCUSSION

344
Number of air changes per hour

345 The number of air changes per hour measured in the two rooms complied with the standards
346 of ASHRAE Ventilation of Health Care Facilities (ANSI/ASHRAE/ASHE Standard 170-
347 2008) of 12 air changes per hour (ACH) for a bronchoscopy room. These standards requiring
348 that the examination room be at negative pressure, that all the exhausted air be evacuated
349 outdoors, and that the depressurization between the room and the peripheral rooms be at least
350 2.5 Pa (0.01 in. water) were respected for the investigated room, but not for the control room
351 at the time of sampling.[18]

352

353
Concentrations and sizes of fluorescent and non-fluorescent particles

354 The background concentrations and the particle size profiles will be discussed in the
355 following sub-sections.

356 The background concentrations in the investigated room were higher than those
357 measured in the control room. The concentrations in this room were as high as 14 times those
358 in the control room for non-fluorescent particles, while they were approximately two times
359 greater for the fluorescent particles.

360 A more rapid decrease was observed for the fluorescent particles in all the rooms; this
361 may be explained by their more rapid sedimentation related to their size. The smaller non-
362 fluorescent particles would remain in the air for a longer time due to their slower
363 sedimentation. The ambient air conditions may also explain these differences. At the end of
364 the day, after the bronchoscopies, the time it took for the concentrations to return to those at
365 the start of the day could be evaluated (ref. Tables 4 and 5). Thus, for the two rooms, it
366 appears that some fifteen minutes was necessary for the fluorescent particles to return to their
367 base level of the morning. A higher ventilation rate does not necessarily result in a more
368 rapid reduction in concentrations. The higher ventilation rate in the investigated room did not
369 shorten the time it took to return to the base level for the fluorescent particles. At this stage,
370 the observed differences can only be attributed to the ambient physical conditions, such as the
371 room's layout, the position of the air inlets and outlets, the air flows, etc.

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372 Bronchoscope insertion is another factor that contributes to the presence of particles in
373 the ambient air during the examinations. The dangers that these particles can present will vary
374 with their type.
375 The dimensions of the fluorescent and non-fluorescent particles measured in this study
376 correspond to aerosols or droplet nuclei as defined by the medical community.[4,6,11,13,14,32] At
377 these dimensions, the time required for particles to deposit from a height of three metres in
378 stagnant free air is several hours.[13] In ventilated locations, the deposition time is even longer,
379 and these particles can travel by following the air currents, and are likely to be inhaled by the
380 personnel present.[4,11,12,14,29,33-35] Under these conditions, it is recommended that personnel
381 working in these rooms wear disposable N95 respirators continuously in the context of a
382 complete respiratory protection program for infectious patients or those suspected of being
383 infectious.[36]

384

385 **Comparison of the different tasks**

386 In the control room, the concentrations measured during bronchoscope insertion into the
387 respiratory tract were significantly higher than those measured before and after its insertion.
388 This increase was not significant for the investigated room. The *a posteriori* analysis also
389 established a significant difference between the hospitals for the concentrations of non-
390 fluorescent and fluorescent particles measured during this period, which can be explained by
391 the different ventilation rates and air flow profiles for these rooms.
392 Bronchoscope insertion is a factor that contributes to the presence of particles in the
393 ambient air during the examinations, as shown at a short distance from the patient's mouth.
394 The dangers that these particles can present will vary with their type.

395

396 **Modeling**

397 *Validation of the model*

398 The numerical results for the rates of decrease of SF6 as a function of time were similar to the
399 rates of decrease measured experimentally (Figures 4 and 5). The coefficients of correlation in
400 these figures are 0.997 for the control room and 0.998 for the investigated room. These
401 coefficients are all statistically significant ($p \leq 0.05$). The imposed air flows for these
402 simulations were determined following flow velocity measurements at the supply and exhaust

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403 grilles. These flows correspond to 24 air changes per hour for the investigated unit and 15 for
404 the control unit. These simulation results compare to those measured experimentally,
405 presented in Table 3.

406 *Bioaerosol dispersion*

407 The flow lines presented at four different times (Figures 5 and 6) show that bioaerosols are
408 projected by coughing to the ceiling of the rooms, where their dispersion will depend on the
409 air movements induced by the ventilation. In the investigated room (Figure 5), most of the
410 bioaerosols dispersed in the direction of the y axis before being uniformly mixed with the air.
411 For the control room, the initial dispersion was more limited (Figure 6): at t=70, 130 and 190
412 s, the contaminant remained mostly in the region above the patient before being dispersed
413 throughout the room (t=300s). For the two rooms, general bioaerosol dispersion was observed
414 in the entire room. No zone was spared. The results of a laboratory study on the dispersion of
415 particles generated by a cough or a sneeze have shown that the particles propagated rapidly
416 throughout the room and that a worker located anywhere in the room was exposed to the
417 potentially infectious aerosols in less than five minutes.[37] This general dispersion throughout
418 the rooms was also noted by Lindsley et al. (2012) in their laboratory study on the dispersion
419 of aerosols produced by coughing or sneezing.

420 **Scope and limitations of this study**

421 The TSI UV-APS 3314 is the only instrument that can be used to detect non-fluorescent and
422 fluorescent (bioaerosol) particles and to establish their particle sizes in real time. However,
423 the samples were collected at a distance of approximately 1.5 metres from the patient's mouth
424 due to the dimensions of our measuring equipment. The concentrations would clearly have
425 been higher if they had been measured a few centimetres from the patient's mouth, but this
426 would have had a negative impact on how the bronchoscopies were performed.

427 This study was carried out in only two bronchoscopy rooms. Fifteen bronchoscopies
428 were nonetheless followed. This number is statistically representative.[22]

429 The models and numerical modeling techniques validated by experimental SF6
430 measurements provided an understanding and graphical representation of the air flows as well
431 as their effects on particle deposition. From a qualitative standpoint, our models corresponded
432 very well to our measurements. In fact, the maximum concentrations of particles were found
433 immediately after insertion of the bronchoscope when coughing occurs. The models could be

434 tools to be given priority in the reorganization of bronchoscopy rooms since an increase in
435 ventilation does not always translate into a reduction in concentrations.

436 The number of ACH for the two rooms was relatively high (17 and 24 ACH
437 respectively for the control and investigated rooms) and represents an almost ideal situation.
438 According to Nardell et al., (1991), due to the exponential relationship that exists between
439 ventilation and the presence of infectious bioaerosols, high ventilation rates have minimal
440 effect on their concentrations.[3] For the other bronchoscopy rooms in Québec with lower
441 ACH, the diversity and concentrations of microorganisms should be even higher.

442

443 CONCLUSION

444 The primary objective of this study, namely to measure and characterize the sizes and the total
445 concentrations of fluorescent and non-fluorescent particles during bronchoscopies and to
446 evaluate the effectiveness of the ventilation strategies, was achieved.

447 The numbers of ACH complied with all the standards in force. However, regarding
448 pressure, the control room did not comply with the standards, because it was at positive
449 pressure during our measurements.

450 The particle sizes and concentrations of the three types of particles were determined.
451 The average median aerodynamic diameter of the fluorescent particles (bioaerosols) was
452 between 2.9 µm. The average median aerodynamic diameter of the non-fluorescent particles
453 was smaller, namely 0.9 µm.

454 In the two rooms, the average concentrations of the non-fluorescent and fluorescent
455 (bioaerosol) particles were significantly higher during bronchoscopies when compared to the
456 background concentrations at the start of the day. Some fifteen minutes were necessary to
457 return to the base concentration of the fluorescent particles (bioaerosols) in the morning. The
458 time could be as long as 95 minutes for the investigated room for the non-fluorescent
459 particles.

460 In the analyses of the factors studied with ANOVA, the tasks (bronchoscope insertion,
461 before insertion and after insertion) constitute the only factor that produced a significant
462 difference for the three types of particles. In the control room, the concentrations of non-
463 fluorescent and fluorescent particles were significantly higher during bronchoscope insertion
464 when compared to the periods before and up to 15 minutes after insertion.

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465 The number of ACH was not the only factor having an impact on the concentrations.
466 This observation supports the hypothesis that the different concentrations could be due to the
467 different air flows.

468 Bioaerosol dispersion in relation to the number of air changes per hour was modeled.
469 Significant deviations were observed between 18 and 24 ACH. Regardless of the room
470 modeled, a ventilation flow of 24 ACH does not allow the asymptotic value of the average
471 age of the air to be achieved.

472 The numerical results for the rates of decrease of SF6 as a function of time were
473 similar to the rates of decrease measured experimentally. Our models have therefore been
474 validated.

475 In the principles of reduction of exposure at source, the location of the inlet and outlet
476 grilles in relation to the emission source is one of the most important aspects to be considered.

477

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