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Prevention of community respiratory infection transmission: a new era must start now

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61 ***Abstract***

62 Children and adults around the world suffer multiple airborne respiratory infections each year.
63 Infections cause suffering, deaths, massive economic loss and disrupt the functioning of the
64 society. Despite this, for numerous reasons, respiratory infections are considered an
65 inescapable part of daily life. Very little has been done to limit their impact, and their
66 prevention still awaits a systematic approach. However, we argue that it does not have to be
67 this way. We need a profound change in how we view this risk and how we apply scientific
68 knowledge, building engineering solutions and public health policies to reduce it. This change
69 will lead to clean air with a significantly reduced pathogen count, which will improve people's
70 health, together with societal economic benefits. While the scale of the changes required is
71 enormous, this is not beyond the capabilities of our society, as has been shown in relation to
72 food and waterborne disease, which have largely been controlled and monitored.

73

74 ***Disparity in approaches to different sources of environmental infections***

75 There is great disparity in the way we think about different sources of environmental infection.
76 For drinking water or food, most developed countries would not tolerate a risk of infection
77 greater than 1 in 10,000. Yet in these same countries, children have multiple respiratory
78 infections every year, with influenza a major cause of death in the elderly (1-8). Governments
79 for the last 150 years have promulgated a large amount of legislation and invested heavily in
80 sanitation and drinking water for public health purposes. However, respiratory infections
81 continue to be regarded as an unavoidable part of daily life, with the measures governments
82 suggest being like “shifting deckchairs on the Titanic” (9). Which means, up until now,
83 governments did not really take notice of the iceberg below water level, e.g., the consequences
84 of airborne respiratory infectious diseases and a pandemic of the scale of COVID-19. Being
85 ‘surprised’ by the pandemic, short-term actions cannot provide a solution to deal with the
86 iceberg below the water. It is argued that it would take large investments in infrastructure and
87 changes in social behavior to reduce respiratory infections, whereas in fact the impact would
88 likely be less than one percent increase in the construction cost of a typical building (10, 11).
89 For a building as a whole, Evans et al. (1998) (12) show a ratio of costs of 1:5:200, where for
90 every dollar spent on construction cost, five are spent on maintenance and building operating
91 costs and \$200.00 on staffing and business operating costs. For the vast inventory of existing
92 buildings, although the economic estimations are more complex due to a large number of
93 variables, there are also numerous cost-effective solutions enhancing their performance to
94 minimize the risk of infection transmission. Two factors may have contributed to our

95 relatively weak approach to fighting airborne transmission of infectious diseases when
96 compared with our strategies to prevent waterborne and foodborne transmission.

97

98 First, it is much harder to trace airborne infections than those that are waterborne or
99 foodborne. Food and water contamination nearly always come from an easily identified point
100 source with a discrete reservoir, such as a pipe, well, or package of food. Its impact on human
101 health is also early if not immediate in terms of characteristic signs and symptoms, so that
102 diligent epidemiology can track and identify the source relatively easily. Over the years, this
103 has led to the establishment of current public health structures in well-resourced countries. We
104 have standards enacted for all aspects of food and water processing, as well as wastewater and
105 sewage. Public health officials, environmental health officers, and local councils are trained in
106 surveillance, sampling, and investigation of any clusters of potential food and waterborne
107 outbreaks, often alerted by local microbiology laboratories. There are published infection rates
108 for a large range of pathogens, with morbidity and mortality risks now well established. For
109 example, in Scotland, there have been high profile outbreaks of *Escherichia coli* 0157,
110 *Salmonella* and *Listeria* spp. over the last few years, and annual spring-time alerts for
111 cryptosporidium, the latter necessitating a ban on water consumption and council supply of
112 bottled water (13-16). The latest outbreaks were community cases of *Clostridioides difficile*,
113 which have been linked to main water supplies (17). By contrast, airborne studies are much
114 more difficult to conduct because air as a contagion medium is nebulous, widespread, not
115 owned by anybody, and uncontained. Airborne studies are also difficult because buildings and
116 their airflows are complicated, and the measurements methods for such studies are also
117 complex and not generally standardized.

118

119 Second, a long-standing misunderstanding and lack of research into airborne transmission
120 of pathogens has negatively impacted an otherwise wider recognition of the significance of
121 this route (18). In our modern era, most building construction has occurred subsequent to a
122 decline in the belief that airborne pathogens are important, driven by a range of factors
123 including the influential work of Charles V Chapin 1910, who denied an important role of
124 airborne transmission of contagious diseases (19). Therefore, the design and construction of
125 modern buildings make no modifications for this airborne risk, and as such, respiratory
126 outbreaks have been repeatedly ‘explained away’ by the arguments of droplet transmission and
127 handwashing. On one hand, John Snow’s (20) work correctly highlighted waterborne
128 infections like cholera as a major public health risk, while on the other hand, Chapin
129 downplayed the airborne public health risk – and building regulations for water vs air sanitation

130 may have diverged in their emphasis because of this. For decades, the focus of architects and
131 building engineers was on thermal comfort, odor control, initial investment cost, energy use
132 and other performance issues, and as Janssen (21) suggested, the neglect of infection control
133 could in part be based on perceived risk or on the assumption that there are more important
134 ways to control infectious disease, despite ample evidence that healthy indoor environments
135 with a significantly reduced pathogen count are essential for public health. Therefore, it is not
136 surprising that there are investigative and preventive structures, and legislation for food and
137 water-borne incidents, but almost nothing for airborne contagion.

138

139 We envision airborne infection policies similar to those for food and water be instituted within
140 public health over the next decade. For this to happen, however, there is a need for a paradigm
141 shift in how we view the transmission of respiratory infections to protect present and future
142 generations from unnecessary suffering and economic losses due to the direct and indirect cost
143 of the infections. This means a fundamental change in how we apply the science of infection
144 transmission to every aspect of modern society to reduce this risk. It starts with a recognition
145 that preventing respiratory infection, like reducing waterborne or foodborne disease, is a
146 tractable problem.

147

148 ***Science and engineering of respiratory infection transmission***

149 Over the past decades, we have witnessed a dramatic growth in our understanding of the
150 mechanisms behind respiratory infection transmission, across all the relevant scientific
151 disciplines, including microbiology, immunology, aerosol physics and building sciences. We
152 know that respiratory infections are caused by pathogens emitted through the nose or mouth of
153 an infected person and transported to a susceptible host. The pathogens are encapsulated in
154 fluid-based particles aerosolised from sites in the respiratory tract during respiratory activities
155 such as breathing, speaking/singing/shouting, sneezing, and coughing. The particles
156 encompass a wide size range, but most lie within the range from sub-micrometres to a few
157 micrometres (22, 23).

158

159 We also understand that in immediate proximity to the source – the face of an infected person
160 – the concentration of particles of all sizes is the highest. This is where the infection risk of a
161 susceptible individual is the largest, either by inhalation of particles in exhaled plumes (24), or
162 by deposition of the particles on the mucous membranes and further inoculation through the
163 mouth, nose, or eyes (25). While individuals can be infected in close proximity, community

164 outbreaks of infection most frequently occur at larger distances through the inhalation of
165 airborne virus-laden particles in indoor spaces shared with infected individuals (26, 27).
166 Airborne transmission is potentially the dominant mode of transmission of numerous
167 respiratory infections, including influenza (28), rhinoviruses (29, 30), tuberculosis (31, 32),
168 measles (33), Middle East respiratory syndrome coronavirus (MERS-CoV) (34), respiratory
169 syncytial virus (RSV) (35) and, as recently shown, COVID-19 (25, 36, 37), in shared room air
170 as close range aerosol transmission (25) and superspreading events (38). By contrast, fomites
171 play a much smaller role in overall infection transmission (38, 39).

172

173 We also have strong evidence that the way we design, operate, and maintain our buildings
174 influences transmission. Evidence about this emerges from the COVID-19 outbreaks already
175 investigated, for example during choir practice (40, 41), in a restaurant (42), on a cruise liner
176 (43). There is also evidence from past studies on other diseases, for example, from the SARS-
177 CoV-1 epidemic (44), or in relation to other diseases, for example, measles at schools (45-51).
178 In each of these cases, inadequate ventilation contributing to high levels of infectious aerosol
179 proved to be a critical problem.

180

181 Yet, before COVID-19, to the best of our knowledge, almost no engineering based measures
182 to limit community respiratory infection transmission had been employed in public buildings
183 (excluding health care facilities) or transport infrastructure anywhere in the world, despite the
184 frequency of such infections, and despite the very large health burden and economic losses they
185 cause (52). The key engineering measure is ventilation, supported by air filtration and air
186 disinfection (53). In this context, ventilation includes a minimum amount of outdoor air
187 combined with recirculated air that is cleaned using effective filtration and disinfection. There
188 are of course ventilation guidelines and standards to which architects and building engineers
189 must adhere: are they inadequate to mitigate indoor respiratory infection transmission?

190

191 ***Future ventilation systems to control respiratory infection transmission***

192 The objectives of the existing guidelines and regulations regarding building ventilation are to
193 address the issues of odor and occupant-generated carbon dioxide (CO₂), which is indicative
194 of bioeffluent production, by specifying minimum ventilation rates and other measures to
195 provide an acceptable IAQ for most occupants. Similarly, there are other guidelines and
196 regulations to ensure thermal comfort. To achieve this, the amount of outdoor air delivered to
197 indoor spaces is recommended or mandated in terms of set values of air change rate per hour,

198 or liters of air per person per second (L/person/s). There are also prescribed threshold values
199 of CO₂ and a range of indoor air temperatures and relative humidity. Different to the above are
200 health-based indoor air quality guidelines. The most important is the World Health
201 Organization (WHO) Indoor Air Quality (IAQ) guidelines, providing guideline values for
202 benzene, carbon monoxide, formaldehyde, naphthalene, nitrogen dioxide, polycyclic aromatic
203 hydrocarbons, radon, trichloroethylene and tetrachloroethylene, based on the duration of
204 exposure (54). There are, however, no ventilation guidelines or standards set to specifically
205 control the concentration of these pollutants indoors. The WHO *Dampness and Mold*
206 guidelines do not recommend specific concentration limit values of mold, and reasons for this
207 are explained in the document (55). None of the above or any other documents provide
208 recommendations or standards for mitigating bacteria or viruses in indoor air, originating from
209 human respiratory activities. Therefore, we need to reconsider the objective of ventilation to
210 include not only the control of CO₂ and odor levels to ensure acceptable IAQ for a vast majority
211 of occupants but also air pollutants linked to health effects AND airborne pathogens. Can this
212 be achieved based on existing knowledge, by setting new required ventilation rate values? The
213 challenge is that the ventilation rates required to protect against infection transmission cannot
214 be derived in the same way as the rates for other pollutants.

215
216 Firstly, the ventilation rates must be risk-based rather than absolute, which means they need to
217 be developed based on the assessment of the infection risk, considering the pathogen emission
218 rates and the infectious dose with respect to which exists a body of data for a number of
219 diseases, including influenza, SARS-CoV-1, MERS, TB, SARS-CoV-2 (56-61). Part of the
220 challenge is also that we often have limited knowledge of viral emission rates, and they differ
221 depending on the physiology of the respiratory tract (which varies with age, for example), the
222 stage of the disease, and the type of respiratory activity (e.g., loud speaking, singing, or heavy
223 breathing during sport or exercise). It is worthwhile to note, regarding the infectious dose, that
224 it may differ depending on the mode of transmission. This is well established for influenza A
225 where the infectious dose is smaller with an aerosol inoculum than with nasal instillation (28).
226 Furthermore, some infectious agents display “anisotropy”, where the severity of disease vary
227 according to the mode of transmission (62), e.g., for influenza and smallpox aerosol inocula
228 are associated with more severe illness (28, 62).

229
230 Secondly, future ventilation systems with higher airflow rates and distributing the supplied
231 clean/disinfected air so that it reaches the breathing zone of occupants must be demand
232 controlled and thus be flexible: the ventilation rate will differ for different venues according to

233 the activities conducted there (e.g., higher ventilation rates will be required for gyms because
234 of higher emissions during exercising, than for movie theatres – quiet resting), while
235 considering all other parameters. While this may sound complicated due to the inherent need
236 to consider room and micro-environment air distribution aspects, there are already models
237 enabling assessments of ventilation rates and their effective distribution in the occupant
238 microenvironments (40), and in general this is a rapidly expanding field. Demand control and
239 flexibility are necessary not only to control the risk, but also to address other requirements
240 including the control of indoor air pollution originating from inside and outside sources and,
241 very importantly, to control energy use: higher ventilation means higher energy use; therefore,
242 ventilation should be made adequate on demand, but not unreasonably high while considering
243 energy, sick building syndrome symptoms and thermal comfort. Energy consumption
244 associated with control of the indoor environment is a critical concern, given that buildings
245 consume over 36% of energy globally (63), and the associated emissions contributing to
246 climate affecting pollutants. Much of this energy is expended on heating/cooling outdoor air
247 as it is brought indoors to maintain indoor air quality and, in some cases, thermal comfort.
248 Therefore, while building designs should optimize the indoor environment quality in terms of
249 health and comfort, they should do that in an energy-efficient way in the context of local
250 climate and outdoor air pollution.

251

252 Thirdly, in some settings it will not be possible to increase ventilation to the point of reducing
253 the risk to an acceptable level, regardless of the quality of the ventilation system. This refers to
254 either the individual risk of infection for each susceptible occupant or to the event reproduction
255 number, the expected number of new infections arising from a single infectious occupant at an
256 event (64). Management of the event reproduction number is very important for the control of
257 an epidemic, especially for indoor spaces with a high density of people, high emission rate
258 (vocalization or exercising), and long periods of shared time. Spaces like this will require air
259 purification measures, including air filtration and disinfection, enabling additional risk
260 reduction. Air filtration can be achieved by incorporating filters into the building heating,
261 ventilation and air conditioning (HVAC) system or by portable air purifiers (65), and air
262 disinfection can be achieved by using ultraviolet (UV) devices (53). Importantly, the necessity
263 of such measures and their effective per-person additional removal rate, and thus their efficacy
264 in risk reduction, can be incorporated into the risk assessment and prospectively modelled.

265

266 The growing evidence of airborne transmission of respiratory infections through shared room
267 air requires a shift in the way we think about ventilation and air purification measures (as

268 discussed above), in order for them to become intrinsic to the way we operate as a modern
269 urbanized society residing indoors over 90% of the time. It does not mean that every indoor
270 space should become a biosafety facility, but it means that a building should be designed and
271 operated according to its purpose and according to the activities conducted there, so that the
272 airborne infection risk is lowered to below an acceptable level (Figure 1). A critical problem is
273 that such measures cannot easily be taken during the pandemic because most current building
274 systems have not been designed for limiting respiratory infection, building operators owners
275 and operators were not trained to operate the systems during the pandemic, and ad hoc measures
276 are often not sufficient. Appropriate and regular training for building operators and owners
277 with emphasis on appropriate measures that can be implemented should form a part of national
278 strategies in prevention of spread of airborne diseases/infections.

279

280 The only type of facilities where airborne infection control exists are health care facilities; in
281 hospitals, clinical risk evaluation is a norm, because rarely is there full evidence available to
282 support many of the measures taken for preventing infection. The requirements for hospital
283 ventilation rates are typically significantly higher than for other public buildings. For example,
284 the clean airflow rates recommended for infection control are more than double those specified
285 for other buildings for control of odors and chemical air contaminants, according to the
286 American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)
287 Standard 170 for healthcare and Standard 62.1 for other non-residential buildings (66, 67).
288 However, while modern hospitals comply with the relevant standards set to control infection,
289 this may not always be the case for some hospitals that are still located in very old buildings as
290 are still found in the UK, other European countries, and Quebec, Canada; such hospitals run
291 into the interesting problem that some are in fact old enough (prior to the late 19th century) to
292 have been designed according to the old anti-miasma theory that outside air has to be prevented
293 from getting in. In modern times, overzealous interpretation of energy efficiency standards may
294 lead to the same issue.

295

296 Clearly, comparing health care ventilation requirements with those for non-healthcare venues
297 suggests that non-healthcare rates should be higher for effective infection control or that more
298 recirculation with better filtration should be used.

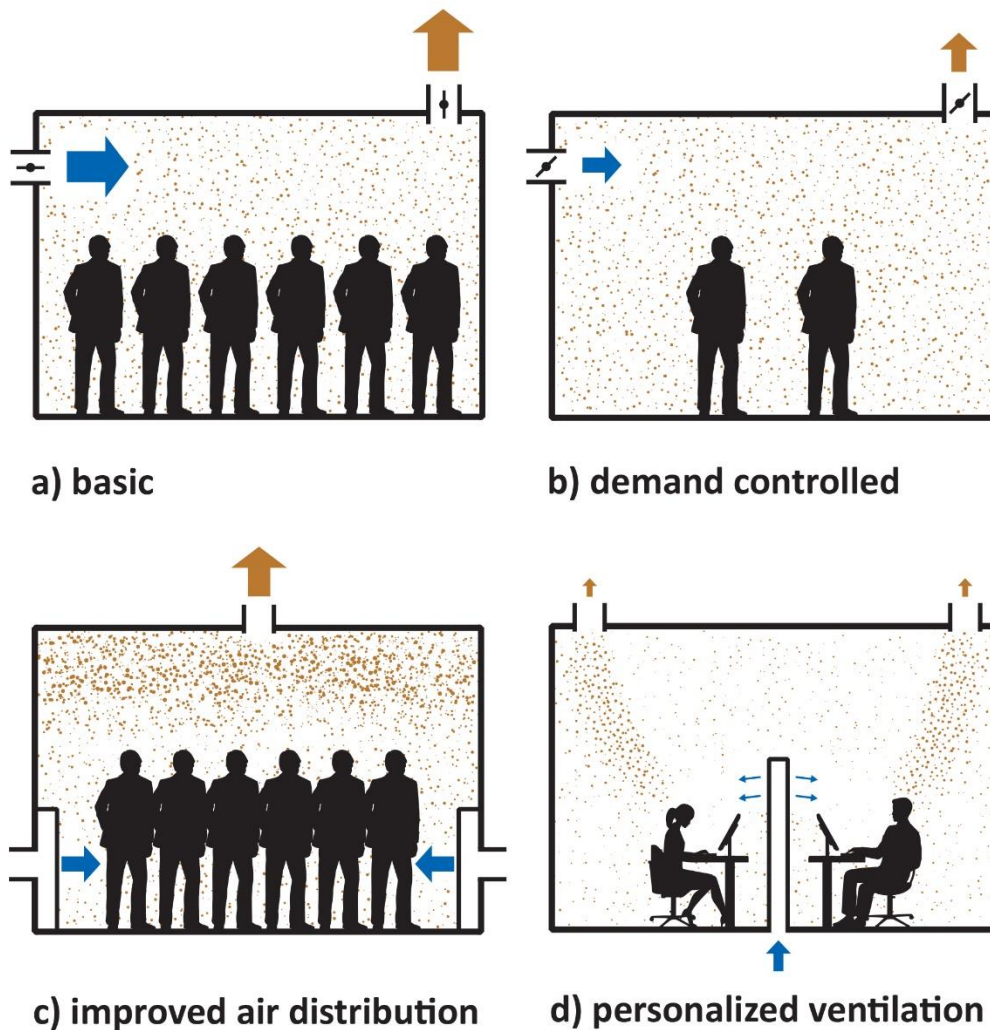
299

300 The paradigm shift we need is, however, much deeper than simply rethinking how we design
301 and operate buildings and transport; it must start at a much higher level than it did a century
302 ago, as facilitated by public health physicians. It requires a change in how humanity thinks

303 about respiratory infection transmission. This means in the first instance introducing, changing
304 and extending the way hygiene is taught in schools, how medical students are trained, and how
305 students of every relevant discipline related to this topic, from public health to engineering,
306 should be taught. Secondly, there needs to be a shift in the perception that we cannot afford
307 the cost of control, since the economic costs of infections by far exceed the initial infrastructure
308 costs to contain them. For example, in the USA alone the yearly cost (direct and indirect) of
309 influenza has been calculated at 11.2 billion in 2018 (68); for respiratory infections other than
310 influenza, the yearly cost stood at 40 billion in 2003 (69). As well, when the final tally of the
311 economic cost of the current pandemic will be available it will provide an even more striking
312 example of the cost incurred through inaction. These costs are paid from different pockets than
313 operating or health care costs, and there is often resistance to higher initial expenditure;
314 ultimately, however, society pays all the costs. In any complex system, costs and benefits are
315 never evenly distributed. It is inevitably the case that investment in one part of the system
316 generates savings in a different part of the system, so cross-system reallocation of budgets must
317 be facilitated or we get impasse. The benefits extend beyond infectious disease transmission.
318 An improvement in indoor air quality will reduce absenteeism in the workplace from other,
319 non-infectious causes, such as sick-building syndrome and allergic reactions, to the extent that
320 the reduction in productivity losses will cover the cost of any ventilation changes required (70).

321
322 Proactive measures to reduce airborne transmission of respiratory diseases would align very
323 closely with the Sustainable Development Goals (SDGs) proposed in 2015 by the United
324 Nations to secure health and wellbeing for all humans (71). The SDGs were adopted by all 193
325 UN Member States in 2015, who committed to mobilize human and financial resources towards
326 an ambitious “*plan of action for people, planet and prosperity*”. SDG3 is dedicated to health,
327 while several other SDGs address environmental, political, social and economic determinants
328 of health and well-being. The SDGs were presented as a paradigm shift from a relatively
329 selective focus on specific diseases in the Millennium Development Goals (MDGs) towards a
330 holistic vision of health and well-being which includes a healthy environment.

331



332

333 Figure 1. There must be a fundamental change in how we apply science of infection transmission to
 334 limit community respiratory infection transmissions in all our environments, dependent on their
 335 purpose and activities. Ventilation airflow rates must be controlled by the number of occupants in the
 336 space and their activity a) and b); better air distribution c) decreases exposure and saves energy. With
 337 personalized ventilation d) exposure can be reduced further, and energy efficiency improved with
 338 personalized ventilation.

339

340

341 ***Pathway towards the Paradigm Shift***

342 This profound paradigm shift cannot occur overnight, but it must start now, while the world is
 343 still enduring the pandemic, and before the painful lessons learnt from this pandemic are
 344 forgotten, just as the lessons from previous pandemics have been mostly forgotten. How are
 345 we to start this process? Here is the pathway we should follow:

346

347 *The hazard of airborne respiratory infection must be recognized so the risk can be controlled.*
348 The continuous global hazard of airborne respiratory infection transmission, not only during a
349 pandemic, but all through the year and in all public indoor spaces, has not been universally
350 accepted, despite strong evidence to support it and no convincing evidence to refute it.

351

352 *Global WHO IAQ guidelines must be extended to include airborne pathogens.* The guidelines
353 must recognize the need to control the hazard of airborne transmission of respiratory infections.
354 This includes recommendations on preventive measures addressing all modes of respiratory
355 infection transmission in a proper and balanced way, based on state-of-the-art science. The
356 recently published WHO Ventilation Roadmap (72) is an important step in the right direction,
357 however, it falls substantially short of a paradigm shift in terms of recognition of the hazard of
358 airborne respiratory infection transmission, and in turn, the necessity of risk control.

359

360 *National comprehensive IAQ standards must be developed, promulgated, and enforced by all*
361 *countries.* Some countries around the globe have IAQ standards, but none of them are
362 comprehensive enough to include airborne pathogens. In most countries that have IAQ
363 standards, there are no enforcement procedures in place. Most countries do not have any IAQ
364 standards.

365

366 *Comprehensive ventilation standards must be developed by professional engineering bodies.*
367 Organizations such ASHRAE and the Federation of European Heating, Ventilation and Air
368 Conditioning Associations (REHVA) have ventilation standards, and during the COVID-19
369 pandemic they have proposed building and system related control actions and design
370 improvements to mitigate the risk of infection (73, 74). However, the standards must be
371 improved to explicitly consider infection control in their statements of purposes and definitions.
372 Further, new approaches must be developed to encourage implementation of the standards (e.g.
373 ‘ventilation certificates’ similar to those that exist for food hygiene certification for
374 restaurants).

375

376 *Wide use of monitors displaying the state of IAQ must be mandated.* At present, the general
377 public is not aware of the significance of IAQ and have no means of knowing the condition of
378 the indoor spaces they occupy and share with others. Sensor technologies exist to display
379 numerous parameters characterizing IAQ, the most common of which is CO₂, but not
380 exclusively. All the existing IAQ sensing technologies have limitations and there is no doubt
381 that more research is needed to develop alternative indicator systems. However, visible

382 displays will help keep building operators accountable for ensuring good IAQ, and will
383 advance the public's awareness of the state of the indoor environment, leading to increased
384 demand for a safe indoor environment.

385

386 The COVID-19 pandemic has revealed how unprepared the world was to respond to it, despite
387 the knowledge gained from pandemics that have occurred over past centuries. As William
388 Wells, a pioneer of aerosol transmission, lamented in 1945 (75), the effort to remove pathogens
389 from drinking water and food had not been replicated for the air. Seven decades later, we find
390 ourselves in a similar place. Our societies, both the general population and decision-makers,
391 are acting in much the same way as societies did in the Middle Ages, when there was limited
392 understanding of the causes of respiratory infections and when emerging science was often
393 suppressed for a variety of reasons, some of which are still relevant today. Ironically, in the
394 19th century, significantly higher ventilation rates in buildings were recommended by
395 physicians focused on infectious disease than nowadays. In the 20th century, engineers have
396 led a major shift to design and operate systems to achieve a proper balance among thermal
397 comfort, air quality and energy consumption (21), rather than for controlling respiratory
398 infection transmission (21). The paradigm shift now has to be on the scale that occurred in 19th
399 century Britain, when the publication of the *Sanitary Report* (76) led the government to
400 encourage cities to organise clean water supplies and centralised sewage systems. In the 21st
401 century we need to establish the foundations to ensure that the air in our buildings is clean with
402 a significantly reduced pathogen count, contributing to the building occupants' health, just as
403 we expect for the water coming out of our taps.

404

405

406 **References**

407

- 408 1. F. M. de Benedictis, A. Bush, Recurrent lower respiratory tract infections in children. *BMJ*
409 **362**, k2698 (2018).
- 410 2. A. R. R. Freitas, M. R. Donalizio, Excess of mortality in adults and elderly and circulation of
411 subtypes of influenza virus in Southern Brazil. *Frontiers in Immunology* **8**, 1903 (2018).
- 412 3. A. C. Hayward *et al.*, Effectiveness of an influenza vaccine programme for care home staff to
413 prevent death, morbidity, and health service use among residents: cluster randomised
414 controlled trial. *BMJ* **333**, 1241 (2006).
- 415 4. R. E. Jordan, J. I. Hawker, Influenza in elderly people in care homes. *BMJ* **333**, 1229 (2006).
- 416 5. A. Martínez *et al.*, Risk factors associated with severe outcomes in adult hospitalized
417 patients according to influenza type and subtype. *PLoS One* **14**, e0210353 (2019).
- 418 6. P. K. Pattemore, L. C. Jennings, Epidemiology of respiratory infections. *Pediatric Respiratory*
419 *Medicine*, 435-452 (2008).
- 420 7. S. E. Talbird *et al.*, Impact of population aging on the burden of vaccine-preventable diseases
421 among older adults in the United States. *Human Vaccines & Immunotherapeutics*, 1-12
422 (2020).

- 423 8. S. Taylor *et al.*, Respiratory viruses and influenza-like illness: epidemiology and outcomes in
424 children aged 6 months to 10 years in a multi-country population sample. *Journal of*
425 *Infection* **74**, 29-41 (2017).
- 426 9. P. H. E. NHS, "Infection control precautions to minimise transmission of acute respiratory
427 tract infections in healthcare settings," (October 2016).
- 428 10. CDC. (Centers for Disease Control and Prevention, 2019).
- 429 11. REHVA *et al.*, "Indoor climate and productivity in offices," *REHVA Guidebook* (2006).
- 430 12. R. Evans, R. Haryott, N. Haste, A. Jones, *The long-term costs of owning and using buildings*.
431 (The Royal Academy of Engineering, London, United Kingdom, 1998).
- 432 13. K. G. Pollock, D. Young, H. V. Smith, C. N. Ramsay, Cryptosporidiosis and filtration of water
433 from Loch Lomond, Scotland. *Emerging Infectious Diseases* **14**, 115 (2008).
- 434 14. J. Cowden, S. Ahmed, M. Donaghy, A. Riley, Epidemiological investigation of the central
435 Scotland outbreak of Escherichia coli O157 infection, November to December 1996.
436 *Epidemiology & Infection* **126**, 335-341 (2001).
- 437 15. E. Okpo *et al.*, An outbreak of an unusual strain of Listeria monocytogenes infection in
438 North-East Scotland. *Journal of Infection and Public Health* **8**, 612-618 (2015).
- 439 16. R. M. Thomson, H. J. Henderson, A. Smith-Palmer, An outbreak of Salmonella Saintpaul in a
440 Scottish childcare facility: the influence of parental under-reporting. *BMC Infectious Diseases*
441 **19**, 847 (2019).
- 442 17. S. M. Kotila *et al.*, Clostridium difficile contamination of public tap water distribution system
443 during a waterborne outbreak in Finland. *Scandinavian Journal of Public Health* **41**, 541-545
444 (2013).
- 445 18. L. Morawska, D. K. Milton, It is time to address airborne transmission of COVID-19. *Clinical*
446 *Infectious Diseases* **6**, ciaa939 (2020).
- 447 19. C. V. Chapin, *The sources and modes of infection*. (John Wiley & Sons, New York, USA, 1910),
448 vol. First Edition, First Thousand.
- 449 20. J. Snow, *On the mode of communication of cholera*. (London, United Kingdom, 1855).
- 450 21. J. E. Janssen, The history of ventilation and temperature control: The first century of air
451 conditioning. *ASHRAE Journal* **41**, 48 (1999).
- 452 22. L. Morawska *et al.*, Size distribution and sites of origin of droplets expelled from the human
453 respiratory tract during expiratory activities. *Journal of Aerosol Science* **40**, 256-269 (2009).
- 454 23. G. Zayas *et al.*, Effectiveness of cough etiquette manoeuvres in disrupting the chain of
455 transmission of infectious respiratory diseases. *BMC Public Health* **13**, 811 (2013).
- 456 24. K. A. Prather *et al.*, Airborne transmission of SARS-CoV-2. *Science (New York, NY)*, eabf0521
457 (2020).
- 458 25. W. Chen, N. Zhang, J. Wei, H.-L. Yen, Y. Li, Short-range airborne route dominates exposure of
459 respiratory infection during close contact. *Building and Environment*, 106859 (2020).
- 460 26. S. Riley *et al.*, Community prevalence of SARS-CoV-2 virus in England during May 2020:
461 REACT study. *medRxiv*, (2020).
- 462 27. M. Kriegel *et al.*, Predicted Infection Risk for Aerosol Transmission of SARS-CoV-2. *medRxiv*,
463 (2020).
- 464 28. R. Tellier, Review of aerosol transmission of influenza A virus. *Emerging Infectious Diseases*
465 **12**, 1657 (2006).
- 466 29. N. H. Leung *et al.*, Respiratory virus shedding in exhaled breath and efficacy of face masks.
467 *Nature Medicine* **26**, 676-680 (2020).
- 468 30. T. A. Myatt *et al.*, Detection of airborne rhinovirus and its relation to outdoor air supply in
469 office environments. *American Journal of Respiratory and Critical Care Medicine* **169**, 1187-
470 1190 (2004).
- 471 31. A. R. Escombe *et al.*, The detection of airborne transmission of tuberculosis from HIV-
472 infected patients, using an in vivo air sampling model. *Clinical Infectious Diseases* **44**, 1349-
473 1357 (2007).
- 474 32. R. Riley *et al.*, Aerial dissemination of pulmonary tuberculosis. A two-year study of contagion
475 in a tuberculosis ward. *American Journal of Epidemiology* **142**, 3-14 (1995).

- 476 33. A. B. Bloch *et al.*, Measles outbreak in a pediatric practice: airborne transmission in an office
477 setting. *Pediatrics* **75**, 676-683 (1985).
- 478 34. S.-H. Kim *et al.*, Extensive Viable Middle East Respiratory Syndrome (MERS) Coronavirus
479 Contamination in Air and Surrounding Environment in MERS Isolation Wards. *Clinical*
480 *Infectious Diseases* **63**, 363-369 (2016).
- 481 35. H. Kulkarni *et al.*, Evidence of respiratory syncytial virus spread by aerosol. Time to revisit
482 infection control strategies? *American Journal of Respiratory and Critical Care Medicine* **194**,
483 308-316 (2016).
- 484 36. J. A. Lednicky *et al.*, Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients.
485 *International Journal of Infectious Diseases*, (2020).
- 486 37. S. Tang *et al.*, Aerosol transmission of SARS-CoV-2? evidence, prevention and control.
487 *Environment International* **144**, 106039 (2020).
- 488 38. D. Lewis, COVID-19 rarely spreads through surfaces. So why are we still deep cleaning.
489 *Nature* **590**, 26-28 (2021).
- 490 39. UK-SAGE. (2020), vol. 2020.
- 491 40. G. Buonanno, L. Morawska, L. Stabile, Quantitative assessment of the risk of airborne
492 transmission of SARS-CoV-2 infection: prospective and retrospective applications.
493 *Environment International* **145**, 106112 (2020).
- 494 41. S. L. Miller *et al.*, Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the
495 Skagit Valley Chorale superspreading event. *Indoor Air*, (2020).
- 496 42. J. Lu *et al.*, COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou,
497 China, 2020. *Emerging Infectious Diseases* **26**, (2020).
- 498 43. P. Azimi, Z. Keshavarz, J. G. C. Laurent, B. R. Stephens, J. G. Allen, Mechanistic Transmission
499 Modeling of COVID-19 on the Diamond Princess Cruise Ship Demonstrates the Importance of
500 Aerosol Transmission. *Proceedings of the National Academy of Sciences* **118**, e2015482118
501 (2020).
- 502 44. S. Xiao, Y. Li, T.-w. Wong, D. S. Hui, Role of fomites in SARS transmission during the largest
503 hospital outbreak in Hong Kong. *PloS one* **12**, (2017).
- 504 45. Y. J. Choe *et al.*, An outbreak of measles in a university in Korea, 2014. *Journal of Korean*
505 *Medical Science* **32**, 1876-1878 (2017).
- 506 46. K. B. Gibney, A. Brahmī, M. O'Hara, R. Morey, L. Franklin, Challenges in managing a school-
507 based measles outbreak in Melbourne, Australia, 2014. *Australian and New Zealand Journal*
508 *of Public Health* **41**, 80-84 (2017).
- 509 47. R. Ma *et al.*, A measles outbreak in a middle school with high vaccination coverage and
510 evidence of prior immunity among cases, Beijing, PR China. *Vaccine* **34**, 1853-1860 (2016).
- 511 48. W. N. Pickles. (SAGE Publications, 1935).
- 512 49. E. Riley, G. Murphy, R. Riley, Airborne spread of measles in a suburban elementary school.
513 *American Journal of Epidemiology* **107**, 421-432 (1978).
- 514 50. O. Wichmann *et al.*, Large measles outbreak at a German public school, 2006. *The Pediatric*
515 *Infectious Disease Journal* **26**, 782-786 (2007).
- 516 51. L. F. Yeung *et al.*, A limited measles outbreak in a highly vaccinated US boarding school.
517 *Pediatrics* **116**, 1287-1291 (2005).
- 518 52. W. J. Fisk, A. H. Rosenfeld, Estimates of improved productivity and health from better indoor
519 environments. *Indoor Air* **7**, 158-172 (1997).
- 520 53. L. Morawska *et al.*, How can airborne transmission of COVID-19 indoors be minimised?
521 *Environment International* **142**, 105832 (2020).
- 522 54. WHO, "Guidelines for Indoor Air Quality, Selected Pollutants " (World Health Organization,
523 Geneva, 2010).
- 524 55. WHO, "WHO Guidelines for Indoor Air Quality - Dampness and Mould " (2009).
- 525 56. U. Adhikari *et al.*, A case study evaluating the risk of infection from Middle Eastern
526 Respiratory Syndrome Coronavirus (MERS-CoV) in a Hospital Setting Through Bioaerosols.
527 *Risk Analysis* **39**, 2608-2624 (2019).

- 528 57. R. M. Jones *et al.*, Characterizing the risk of infection from Mycobacterium tuberculosis in
529 commercial passenger aircraft using quantitative microbial risk assessment. *Risk Analysis: An*
530 *International Journal* **29**, 355-365 (2009).
- 531 58. A. Mikszewski, L. Stabile, G. Buonanno, L. Morawska, The airborne contagiousness of
532 respiratory viruses: a comparative analysis and implications for mitigation. *medRxiv*, (2021).
- 533 59. T. Watanabe, T. A. Bartrand, T. Omura, C. N. Haas, Dose-response assessment for influenza A
534 virus based on data sets of infection with its live attenuated reassortants. *Risk Analysis: An*
535 *International Journal* **32**, 555-565 (2012).
- 536 60. T. Watanabe, T. A. Bartrand, M. H. Weir, T. Omura, C. N. Haas, Development of a dose-
537 response model for SARS coronavirus. *Risk Analysis: An International Journal* **30**, 1129-1138
538 (2010).
- 539 61. X. Zhang, Z. Ji, Y. Yue, H. Liu, J. Wang, Infection risk assessment of COVID-19 through aerosol
540 transmission: a case study of South China Seafood Market. *Environmental Science &*
541 *Technology*, (2020).
- 542 62. D. M. Milton, What was the primary mode of smallpox transmission? Implications for
543 biodefense. *Frontiers in Cellular and Infection Microbiology* **2**, 150 (2012).
- 544 63. UNE-IEA, "Global Status Report 2017: Towards a zero-emission, efficient, and resilient
545 buildings and construction sector," (UN Environment and International Energy Agency (UNE-
546 IEA), 2017).
- 547 64. E. A. Nardell, Wells Revisited: Infectious Particles vs. Quanta of Mycobacterium tuberculosis
548 Infection—Don't Get Them Confused. *Mycobacterial Diseases* **6**, 1000231 (2016).
- 549 65. P. M. Bluysen, M. Ortiz, D. Zhang, The effect of a mobile HEPA filter system on 'infectious'
550 aerosols, sound and air velocity in the SenseLab. *Building and Environment*, 107475 (2020).
- 551 66. ASHRAE, "Ventilation of Health Care Facilities; ANSI/ASHRAE/ASHE Standard 170-2017,"
552 (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 2017).
- 553 67. ASHRAE, "Ventilation for Acceptable Indoor Air Quality. ANSI/ASHRAE Standard 62.1-2019 "
554 (2019).
- 555 68. W. C. Putri, D. J. Muscatello, M. S. Stockwell, A. T. Newall, Economic burden of seasonal
556 influenza in the United States. *Vaccine* **36**, 3960-3966 (2018).
- 557 69. A. M. Fendrick, A. S. Monto, B. Nightengale, M. Sarnes, The economic burden of non-
558 influenza-related viral respiratory tract infection in the United States. *Archives of Internal*
559 *Medicine* **163**, 487-494 (2003).
- 560 70. W. J. Fisk, "Health and Productivity Gains from Better Indoor Environments and their
561 Relationship with Building Energy Efficiency," *Annual Revue of Energy and the Environment*
562 *2000* (Lawrence Berkley National Laboratory, Berkley, California., 2000).
- 563 71. G. UN, Transforming our world: The 2030 agenda for sustainable development. A/RES/70/1,
564 21 October. (2015).
- 565 72. WHO, "Roadmap to improve and ensure good indoor ventilation in the context of COVID-19.
566 World Health Organisation," (2021).
- 567 73. ASHRAE, "ASHRAE Position Document on Infectious Aerosols," (2020).
- 568 74. REHVA, "REHVA COVID-19 guidance document, August 3, 2020," (Federation of European
569 Heating, Ventilation and Air Conditioning Associations (REHVA), 2020).
- 570 75. W. F. Wells, Sanitary ventilation by radiant disinfection. *The Scientific Monthly* **60**, 325-334
571 (1945).
- 572 76. E. Chadwick, "Report on the Sanitary Condition of the Labouring Population of Great
573 Britain," (1842).
- 574