1   **Title:** 2019 Novel Coronavirus (COVID-19) Pandemic: Built Environment Considerations To

2   Reduce Transmission

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23 **Abstract**

24 With the rapid spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) that

25 results in coronavirus disease 2019 (COVID-19), corporate entities, federal, state, county and

26 city governments, universities, school districts, places of worship, prisons, health care facilities,

27 assisted living organizations, daycares, homeowners, and other building owners and occupants

28 have an opportunity to reduce the potential for transmission through built environment (BE)

29 mediated pathways. Over the last decade, substantial research into the presence, abundance,

30 diversity, function, and transmission of microbes in the BE has taken place and revealed

31 common pathogen exchange pathways and mechanisms. In this paper, we synthesize this

32 microbiology of the BE research and the known information about SARS-CoV-2 to provide

33 actionable and achievable guidance to BE decision makers, building operators, and all indoor

34 occupants attempting to minimize infectious disease transmission through environmentally

35 mediated pathways. We believe this information is useful to corporate and public administrators

36 and individuals responsible for building operations and environmental services in their decision-

37 making process about the degree and duration of social-distancing measures during viral

38 epidemics and pandemics.

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Introduction

Increased spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2)

causing coronavirus disease 2019 (COVID-19) infections worldwide has brought

increased attention and fears surrounding the prevention and control of SAR-CoV-2

from both the scientific community and the general public. While many of the precautions

typical for halting the spread of respiratory viruses are being implemented, other

less understood transmission pathways should also be considered and addressed to

reduce further spread. Environmentally mediated pathways for infection by other

pathogens have been a concern in buildings for decades, most notably in hospitals.

Substantial research into the presence, abundance, diversity, function, and transmission

of microorganisms in the built environment (BE) has taken place in recent years. This

work has revealed common pathogen exchange pathways and mechanisms that could

lend insights into potential methods to mediate the spread of SARS-CoV-2 through

BE-mediated pathways.

Coronaviruses (CoVs) most commonly cause mild illness, but they have occasionally,

in recent years, led to major outbreaks of human disease. Typically, mutations that

cause structural changes in the coronavirus spike (S) glycoprotein enable binding to

new receptor types and permit the jump from an animal host to a human host (1)

(zoonotic transmission) and can increase the risk of large-scale outbreaks or epidemics

(2). In 2002, a novel CoV, severe acute respiratory virus (SARS), was discovered in the

Guangdong Province of China (3). SARS is a zoonotic CoV that originated in bats and

resulted in symptoms of persistent fever, chills/rigor, myalgia, malaise, dry cough,

69   headache, and dyspnea in humans (4). SARS had a mortality rate of 10% and was

70   transmitted to 8,000 people during an 8-month outbreak in 2002 to 2003 (5). Approximately

71   10 years after SARS, another novel, highly pathogenic CoV, known as Middle

72   East respiratory syndrome coronavirus (MERS-CoV), emerged and is also believed to

73   have originated from bats, with camels as the reservoir host (6). MERS-CoV was first

74   characterized in the Arabian Peninsula and spread to 27 countries, having a 35.6%

75   mortality rate in 2,220 cases (7).

76

77   **Coronavirus Disease 2019 (COVID-19)**

78   In December 2019, SARS-CoV-2, a novel CoV, was identified in the city of Wuhan, Hubei

79   Province, a major transport hub of central China. The earliest COVID-19 cases were linked to a

80   large seafood market in Wuhan, initially suggesting a direct food source transmission pathway

81   (8). Since that time, we have learned that person-to-person transmission is one of the main

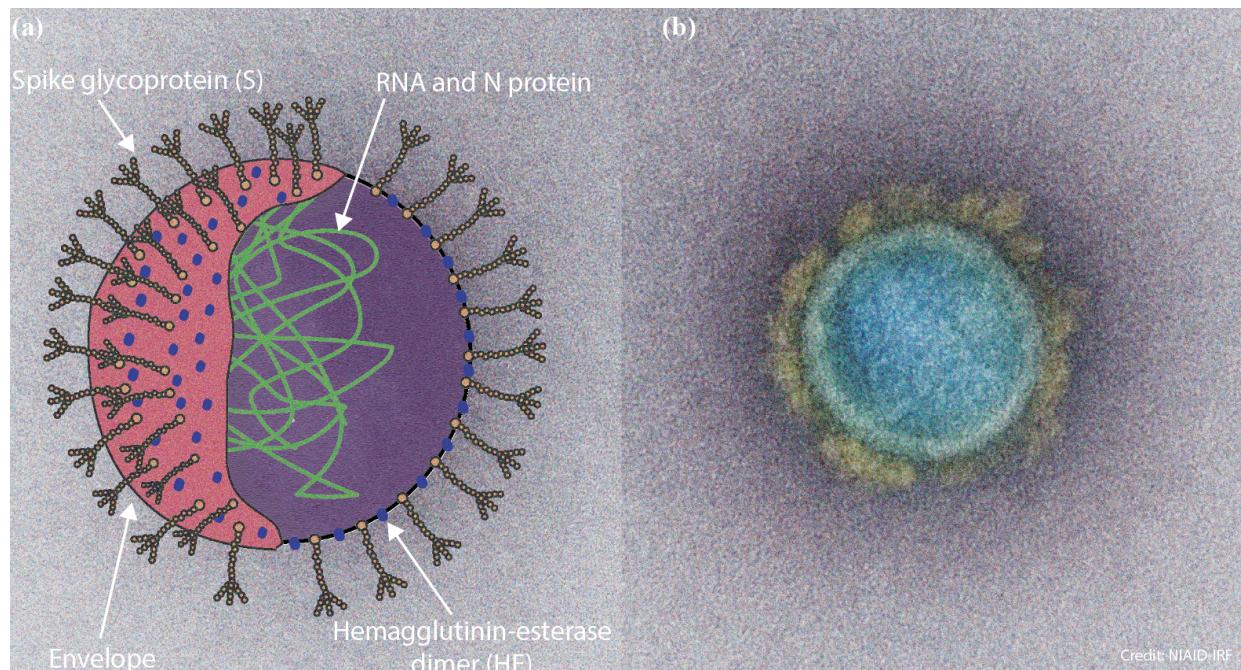
82   mechanisms of COVID-19 spread (9). In the months since the identification of the initial cases,

83   COVID-19 has spread to 171 countries and territories, and there are approximately

84   215,546 confirmed cases (as of 18 March 2020). The modes of transmission have been

85   identified as host-to-human and human-to-human. There is preliminary evidence that

86   environmentally mediated transmission may be possible, specifically, that COVID-19 patients

87   could be acquiring the virus through contact with abiotic BE surfaces (10, 11).

89   **Figure 1. Structure of SARS-CoV-2 virus.** (a) Artistic rendering of the structure and cross

90   section of the SARS-CoV-2 virus (12, 13) (b) Transmission electron micrograph of a SARS-

91   CoV-2 virus particle isolated from a patient and imaged at the NIH: National Institute of Allergy

92   and Infectious Disease (NIAID) Integrated Research Facility (IRF) in Fort Detrick, Maryland

93   (14).

94

95   **Epidemiology of SARS-CoV-2**

96   The *Betacoronavirus* SARS-CoV-2 is a single-stranded positive-sense enveloped RNA virus (

97   with a genome that is approximately 30 kb in length (12, 13). Spike glycoproteins, the club-like

98   extensions projecting from the cell surface, facilitate the transfer of viral genetic material into a

99   host cell by adhesion (14, 15) (Fig. 1). The viral genetic material is then replicated by the host

100   cell. The infection history of SARS-CoV-2 is believed to have begun in bats with a possible

101   intermediate host of pangolin (16). There are several other *betacoronaviruses* that occur in bats

102   as a primary reservoir, such as SARS-CoV and MERS-CoV (17). The manifestation of

103   SARSCoV-2 in a human population occurred late in December 2019, among persons known to

104   frequent a seafood market (18). The first symptoms observed clinically were fever,

105   fatigue, and dry cough, with symptoms ranging from mild to severe (19). Currently, the

106   protocol developed by the Centers for Disease Control and Prevention (CDC) for

107   diagnosis (20) is a combination of clinical observation of symptoms and a positive result

108   for the presence of the virus using real-time PCR (rt-PCR) (21).

109

110   **COVID-19 and the Impact of the BE in Transmission**

111   The built environment (BE) is the collection of environments that humans have constructed,

112   including buildings, cars, roads, public transport, and other human-built spaces (22). Since most

113   humans spend >90% of their daily lives inside the BE, it is essential to understand the potential

114   transmission dynamics of COVID-19 within the BE ecosystem and the human behavior,

115   spatial dynamics, and building operational factors that potentially promote and mitigate

116   the spread and transmission of COVID-19. BEs serve as potential transmission

117   vectors for the spread of COVID-19 by inducing close interactions between individuals,

118   by containing fomites (objects or materials that are likely to carry infectious diseases),

119   and through viral exchange and transfer through the air (23, 24). The occupant density

120   in buildings, influenced by building type and program, occupancy schedule, and indoor

121   activity, facilitates the accrual of human-associated microorganisms (22). Higher occupant

122   density and increased indoor activity level typically increase social interaction and

123   connectivity through direct contact between individuals (25) as well as environmentally

124   mediated contact with abiotic surfaces (i.e., fomites). The original cluster of patients

125   were hospitalized in Wuhan, China, with respiratory distress (December 2019), and

126   approximately 10 days later, the same hospital facility was diagnosing patients outside

127   the original cohort with COVID-19. It is presumed that the number of infected patients

128   increased because of transmissions that potentially occurred within the hospital BE (10).

129   The increased exposure risk associated with high occupant density and consistent

130   contact was demonstrated with the COVID-19 outbreak that occurred on the Diamond

131   Princess cruise ship in January 2020 (26). Current estimates of the contagiousness

132   (known as the R0) of SARS-CoV-2, have been estimated from 1.5 to 3 (27, 28). R0 is

133   defined as the average number of people who will contract a disease from one

134   contagious person (29). For reference, measles has a famously high R0 of approximately

135   12 to 18 (30), and influenza (flu) has an R0 of _2 (31). However, within the confined

136   spaces of the BE, the R0 of SARS-CoV-2 has been estimated to be significantly higher

137   (estimates ranging from 5 to 14), with _700 of the 3,711 passengers on board the

138   Diamond Princess (~19%) contracting COVID-19 during their 2-week quarantine on the

139   ship (26, 32). These incidents demonstrate the high transmissibility of COVID-19 as a

140   result of confined spaces found within the BE (33). With consideration to the spatial

141   layout of the cruise ship, the proximity of infected passengers to others likely had a

142   major role in the spread of COVID-19 (33).

143

144   As individuals move through the BE, there is direct and indirect contact with the

145   surfaces around them. Viral particles can be directly deposited and resuspended due to

146   natural airflow patterns, mechanical airflow patterns, or other sources of turbulence in

147   the indoor environment such as foot fall, walking, and thermal plumes from warm

148   human bodies (22, 34). These resuspended viral particles can then resettle back onto

149   fomites. When an individual makes contact with a surface, there is an exchange of

150   microbial life (35), including a transfer of viruses from the individual to the surface and

151   vice versa (36). Once infected, individuals with COVID-19 shed viral particles before,

152   during, and after developing symptoms (37, 38). These viral particles can then settle

153   onto abiotic objects in the BE and potentially serve as reservoirs for viral transmission

154   (18, 34, 39). Evidence suggests that fomites can potentially be contaminated with

155   SARS-CoV-2 particles from infected individuals through bodily secretions such as saliva

156   and nasal fluid, contact with soiled hands, and the settling of aerosolized viral particles

157   and large droplets spread via talking, sneezing, coughing, and vomiting (34, 40). A

158   study on environmental contamination from MERS-CoV demonstrated that nearly every

159   touchable surface in a hospital housing MERS-CoV patients had been contaminated

160   with the virus (41), and a survey of a hospital room with a quarantined COVID-19 patient

161   demonstrated extensive environmental contamination (18, 34). Knowledge of

162   the transmission dynamics of COVID-19 is currently developing, but based upon studies

163   of SARS and MERS-CoV, preliminary data on SARS-CoV-2, and CDC recommendations,

164   it seems likely that SARS-CoV-2 can potentially persist on fomites ranging from a couple

165   of hours to 5 days (39, 42, 43) depending on the material (43). Based upon preliminary

166   studies of SARS-CoV-2 survival, the virus survives longest at a relative humidity of 40%

167   on plastic surfaces (half-life median=15.9 h) and shortest in aerosol form (half-life

168   median=2.74 h) (43); however, survival in aerosol was determined at a relative humidity

169   of 65%. Based on data related to SARS and MERS, we predict that the viability

170   of SARS-CoV-2 in aerosol is likely longer at lower relative humidity levels. Survival of

171   SARS-CoV-2 at 40% relative humidity on copper (half-life median=3.4 h), cardboard

172   (half-life median=8.45 h), and steel (half-life median=13.1 h) collectively fall between

173   survival in the air and on plastic (43). However, it should be noted that there are no

174   documented cases thus far of a COVID-19 infection originating from a fomite. There is

175   preliminary data demonstrating the presence of SARS-CoV-2 in stool, indicating that

176   transmission can potentially occur through the fecal-oral pathway (18, 29, 34, 44). While

177   transmission of COVID-19 has been documented only through respiratory droplet

178   spread and not through deposition on fomites, steps should still be taken to clean and

179   disinfect all potential sources of SARS-CoV-2 under the assumption that active virus

180   may be transmitted by contact with these abiotic surfaces (34, 39). With an abundance

181   of caution, it is important to consider the possibility that the virus is transmitted

182   through aerosols and surfaces (45). For a conceptualization of SARS-CoV-2 deposition,

183   see Fig. 2.

184

185   **Figure 2: Conceptualization of SARS-CoV-2 deposition.** (a) Once infected with SARS-CoV-

186   2, viral particles accumulate in the lungs and upper respiratory tract (b) droplets and aerosolized

187   viral particles are expelled from the body through daily activities such as coughing, sneezing,

188   talking, and non-routine events such as vomiting, and can spread to nearby surroundings and

189   individuals (35, 41) (c) Viral particles, excreted from the mouth and nose, are often found on the

190   hands and (d) can be spread to commonly touched items such as computers, glasses, faucets, and

191   countertops. There are currently no confirmed cases of fomite-to-human transmission, but viral

192   particles have been found on abiotic BE surfaces (35, 40, 43).

193

194   Previously, it has been confirmed that SARS can be, and is most often, transmitted

195   through droplets (46). Considering that SARS-CoV-2 is from a sister clade to the 2002

196   SARS virus (47) that is known to transmit from person-to-person, the high incidence of

197   observed person-to-person transmission and the rapid spread of COVID-19 throughout

198   the world and communities, it is accepted at this time that SARS-CoV-2 can also be

199   spread through droplets (13, 48). Based upon previous investigation into SARS (49),

200   spread through aerosolization remains a potential secondary transmission method,

201   especially within the BE. Mitigation of viral transmission through BE air delivery systems

202   is most often reliant on inline filtration media. Residential and commercial systems

203   typically require a minimum efficiency reporting value (MERV) of 8, which is rated to

204   capture 70 to 85% of particles ranging from 3.0 to 10.0 um, a strategy employed to

205   minimize debris and loss of efficiency impacts to cooling coils and other heating,

206   ventilation, and air conditioning (HVAC) components. Higher MERV ratings are required

207   to filter incoming outside air based on local outdoor particulate levels. Protective

208   environment (PE) rooms in hospitals require the most stringent minimum filtration

209   efficiency (50). A MERV of 7 (MERV-7) or greater is required as a first filter before heating

210   and cooling equipment, and a second high-efficiency particulate air (HEPA) filter is

211   placed downstream of cooling coils and fans. HEPA filters are rated to remove at least

212   99.97% of particles down to 0.3 um (51). Most residential and commercial buildings

213   utilize MERV-5 to MERV-11, and in critical health care settings, MERV-12 or higher and

214   HEPA filters are used. MERV-13 filters have the potential to remove microbes and other

215   particles ranging from 0.3 to 10.0 um. Most viruses, including CoVs, range from 0.004

216   to 1.0 um, limiting the effectiveness of these filtration techniques against pathogens

217   such as SARS-CoV-2 (52). Furthermore, no filter system is perfect. Recently, it has been

218   found that gaps in the edges of filters in hospitals has been a contributing factor of the

219   failure of filtering systems to eliminate pathogens from the shared air environment (53).

220   In recent years, the sharing economy has created environments and added new

221   components to how multiple people share the same spaces. It is possible that infectious

222   disease transmission may be impacted by this shift to the sharing economy.

223   Shared workspaces such as cowork environments, rooms in homes, cars, bikes, and

224   other elements of the BE may increase the potential for environmentally mediated

225   pathways of exposure and add complexity to enacting social-distancing measures. For

226   example, in cases where alternate modes of transportation were previously single occupancy

227   vehicles, these trips are now often replaced with rideshare programs or

228   transportation network companies, the potential for exposure may increase.

229

230   **Control and Mitigation Efforts in the BE**

231   The spread of COVID-19 is a rapidly

232   developing situation, but there are steps that can be taken, inside and outside the BE,

233   to help prevent the spread of disease. On an individual level, proper handwashing is a

234   critical component of controlling the spread of SARS-CoV-2, other coronaviruses, and

235   many respiratory infections (54–56). Individuals should avoid contact and spatial proximity

236   with infected persons and wash hands frequently for at least 20 s with soap and

237   hot water (39). Furthermore, since it is difficult to know who is infected and who is not,

238   the best way to avoid spread in some situations is by avoiding large gatherings of

239   individuals, also known as "social distancing." At this time, the Food and Drug Administration

240   (FDA) does not recommend that asymptomatic individuals wear masks during

241   their everyday lives to preserve masks and materials for individuals who have been

242   infected with COVID-19 and for health care workers and family that will be in consistent

243   contact with individuals infected with COVID-19 (57). Additionally, wearing a mask can

244   give a false sense of security when moving throughout potentially contaminated areas,

245   and the incorrect handling and use of masks can increase transmission (58). However,

246   as masks become available, and while prioritizing access to masks for health care

247   workers that are in a higher risk environment daily, wearing a mask would be prudent.

248   There is sufficient evidence to suggest that airborne transmission is possible (49)

249   through aerosolized particles beyond six feet and that a mask would aid in preventing

250   infection through this route.

251

252   Since the end of January 2020, many countries have issued travel bans to prevent

253   person-to-person contact and particle-based transmission. These mobility restrictions

254   have been confirmed to help contain the spread of COVID-19 (59). Within local

255   communities, a variety of measures can also be taken to prevent further spread (60). As

256   a whole, these measures are known as non-health-care-setting social-distancing measures.

257   These measures include closing high-occupancy areas such as schools and

258   workplaces. These community-level measures act to prevent disease transmission

259   through the same mechanisms as the worldwide travel restrictions by reducing typical

260   person-to-person contact, decreasing the possibility of fomite contamination by those

261   that are shedding viral particles, and decreasing the possibility of airborne, particle

262   transmission between individuals in the same room or close proximity. These decisions

263   are made by individuals with administrative authority over large jurisdictions, communities,

264   or building stock and are weighed in balance with numerous factors, including

265   health risks and social and economic impacts. Furthermore, despite substantial social distancing

266   and quarantine practices in place, specific building types and space uses are

267   considered critical infrastructure and essential to maintaining communities, such as

268   health care facilities, housing, and groceries. Better understanding of BE mediating

269   variables can be helpful in decision-making about whether to implement social distancing

270   measures and for what duration, and to individuals responsible for building

271   operations and environmental services related to essential and critical infrastructure

272   during periods of social distancing, and all building types before and after social distancing

273   measures are enacted.

274

275   Within the BE, environmental precautions that can be taken to potentially prevent

276   the spread of SARS-CoV-2 include chemical deactivation of viral particles on surfaces

277   (39). It has been demonstrated that 62 to 71% ethanol is effective at eliminating MERS,

278   SARS (42), and SARS-CoV-2 (34). This ethanol concentration is typical of most alcohol based

279   hand sanitizers, making properly applied hand sanitizer a valuable tool against

280   the spread of SARS-CoV-2 in the BE. Items should be removed from sink areas to ensure

281   aerosolized water droplets do not carry viral particles onto commonly used items, and

282   countertops around sinks should be cleaned using a 10% bleach solution or an

283   alcohol-based cleaner on a regular basis. Again, it is important to remember that the

284   main and much more common spread mechanism of previous CoVs has been identified

285   as droplets from talking, sneezing, coughing, and vomiting than by the fecal-oral

286   pathway (34, 38, 39). Administrators and building operators should post signage about

287   the effectiveness of handwashing for at least 20 s with soap and hot water, ensure soap

288   dispensers are full, provide access to alcohol-based hand sanitizer, and implement

289   routine surface cleaning protocols to high-touch surfaces where contamination risks

290   are high, such as around sinks and toilets (39). Most importantly, to prevent the

291   transmission of microbes and thus, undesirable pathogens, it is important to exercise

292   proper handwashing hygiene (39, 61).

293

294   Enacting enhanced building HVAC operational practices can also reduce the potential

295   for spread of SARS-CoV-2. Even though viral particles are too small to be contained

296   by even the best HEPA and MERV filters, ventilation precautions can be taken to ensure

297   the minimization of SARS-CoV-2 spread. Proper filter installation and maintenance can

298   help reduce the risk of airborne transmission, but it is important to understand that

299   filters should not be assumed to eliminate airborne transmission risk. Higher outside air

300   fractions and higher air exchange rates in buildings may help to dilute the indoor

301   contaminants, including viral particles, from air that is breathed within the BE. Higher

302   outside air fractions may be achieved by further opening outside air damper positions

303   on air-handling units, thus exhausting a higher ratio of indoor air and any airborne viral

304   particles present (62). There are some cautions to consider relative to these building

305   operations parameters. First, increasing outside air fractions may come with increased

306   energy consumption. In the short term, this is a worthwhile mitigation technique to

307   support human health, but building operators are urged to revert to normal ratios after

308   the period of risk has passed. Second, not all air-handling systems have the capacity to

309   substantially increase outside air ratios, and those that do may require a more frequent filter

310   maintenance protocol. Third, increasing airflow rates that simply increase the

311   delivery of recirculated indoor air, without increased outside air fraction, could potentially

312   increase the transmission potential. Higher airflow rates could increase resuspension

313   from fomites and increase the potential for contamination throughout the building

314   by distributing indoor air more quickly, at higher velocities and volumes, potentially

315   resuspending more ultrafine particles (62). Additionally, increasing the indoor air

316   circulation rate could increase the human exposure to viable airborne viral particles

317   shed from other building occupants. Administrators and building operators should

318   collaborate to determine whether increased outside air fractions are possible, what

319   limitations or secondary implications must be considered, and determine a plan around

320   managing the outside air fraction and air change rates.

321

322   Increasing evidence indicates that humidity can play a role in the survival of

323   membrane-bound viruses, such as SARS-CoV-2 (63–65). Previous research has found

324   that, at typical indoor temperatures, relative humidity (RH) above 40% is detrimental to

325   the survival of many viruses, including CoVs in general (63, 66, 67), and higher indoor

326   RH has been shown to reduce infectious influenza virus in simulated coughs (67). Based

327   upon studies of other viruses, including CoVs, higher RH also decreases airborne

328   dispersal by maintaining larger droplets that contain viral particles, thus causing them

329   to deposit onto room surfaces more quickly (63, 68, 69). Higher humidity likely

330   negatively impacts lipid-enveloped viruses, like CoVs, through interactions with the

331   polar membrane heads that lead to conformational changes of the membrane, causing

332   disruption and inactivation of the virus (70, 71). Furthermore, changes in humidity can

333   impact how susceptible an individual is to infection by viral particles (72) and how far

334   into the respiratory tract viral particles are likely to deposit (68). Decreased RH has been

335   demonstrated to decrease mucociliary clearance of invading pathogens and weakened

336   innate immune response (72–74). However, RH above 80% may begin to promote mold

337   growth, inducing potentially detrimental health effects (75). Although the current

338   ventilation standard adopted by health care and residential care facilities, ASHRAE

339   170-2017, permits a wider range of RH from 20% to 60%, maintaining a RH between

340   40% and 60% indoors may help to limit the spread and survival of SARS-CoV-2 within

341   the BE, while minimizing the risk of mold growth and maintaining hydrated and intact

342   mucosal barriers of human occupants (50, 67). Indoor humidification is not common in

343   most HVAC system designs, largely due to equipment cost and maintenance concerns

344   related to the risk of overhumidification increasing the potential of mold growth. While

345   administrators and building operators should consider the costs, merits, and risks of

346   implementing central humidification, especially during new construction or as a retrofit,

347   it may be too time intensive to implement in response to a specific viral outbreak

348   or episode. In addition, increased RH may lead to increased buildup on filters, decreasing

349   airflow. However, in pandemic situations, this practice likely increases the effectiveness

350   of capturing viral particles, and this benefit outweighs the increased filter

351   maintenance required. Therefore, targeted in-room humidification is another option to

352   consider, and this may reduce the likelihood of a maintenance oversight causing

353   overhumidification.

354

355   Building ventilation source and distribution path length can affect the composition

356   of indoor microbial communities. Ventilating a building by introducing air directly

357   through the perimeter of buildings into adjacent spaces is a strategy that does not rely

358   on the efficacy of whole-building filtration to prevent network distribution of microorganisms.

359   Delivering outside air directly through the envelope into an adjacent spatial

360   volume has been shown to increase the phylogenetic diversity of indoor bacterial and

361   fungal communities and create communities that are more similar to outdoor associated

362   microbes than air delivered through a centralized HVAC system (76). In some

363   buildings, a similar approach can be accomplished through distributed HVAC units,

364   such as packaged terminal air-conditioners (PTAC) frequently found in hotels, motels,

365   senior housing facilities, condominium units, and apartments or through perimeter

366   passive ventilation strategies such as perimeter dampered vents (77, 78). However, for

367   most buildings, the easiest way to deliver outside air directly across the building envelope is to

368   open a window. Window ventilation not only bypasses ductwork but

369   increases outside air fraction and increases total air change rate as well (79). Administrators

370   and building operators should discuss a plan for increasing perimeter, and

371   specifically window, ventilation when outdoor temperatures are adequate for this

372   practice. Care should be taken to avoid exposing occupants to extreme temperature

373   profiles, and caution should be taken where close proximity would promote potential

374   viral transfer from one residence to another (94, 95).

375

376   Light is another mitigation strategy for controlling the viability of some infectious

377   agents indoors. Daylight, a ubiquitous and defining element in architecture, has been

378   shown in microcosm studies to shape indoor bacterial communities in household dust

379   to be less human associated than in dark spaces (80). Moreover, daylight in both the UV

380   and visible spectral ranges reduced the viability of bacteria compared to dark controls

381   in these microcosm spaces (80). In a study simulating sunlight on influenza virus

382   aerosols, virus half-life was significantly reduced from 31.6 min in the dark control

383   group to approximately 2.4 min in simulated sunlight (81). In buildings, much of the

384   sunlight spectrum is filtered through architectural window glass, and the resulting

385   transmitted UV is largely absorbed by finishes and not reflected deeper into the space.

386   Therefore, further research is needed to understand the impact of natural light on

387   SARS-CoV-2 indoors; however, in the interim, daylight exists as a free, widely available

388   resource to building occupants with little downside to its use and many documented

389   positive human health benefits (80–83). Administrators and building operators should

390   encourage blinds and shades to be opened when they are not needed to actively

391   manage glare, privacy, or other occupant comfort factors to admit abundant daylight

392   and sunlight.

393   While daylight's effect on indoor viruses and SARS-CoV-2 is still unexplored, spectrally

394   tuned electric lighting is already implemented as engineering controls for disinfection

395   indoors. UV light in the region of shorter wavelengths (254-nm UV C [UVC]) is

396   particularly germicidal, and fixtures tuned to this part of the light spectrum are

397   effectively employed in clinical settings to inactivate infectious aerosols and can reduce

398   the ability of some viruses to survive (84). It is important to note that most UVC light

399   is eliminated in the atmosphere, while much of the UVA and UVB spectrum is eliminated

400   through building glass layers. Airborne viruses that contain single-stranded RNA

401   (ssRNA) are reduced by 90% with a low dose of UV light, and the UV dose requirement

402   increases for ssRNA viruses found on surfaces (85, 86). A previous study demonstrated

403   that 10 min of UVC light inactivated 99.999% of CoVs tested, SARS-CoV, and MERS-CoV

404   (87). However, UV germicidal irradiation (UVGI) has potential safety concerns if the

405   room occupants are exposed to high-energy light. For this reason, UVGI is safely

406   installed in mechanical ventilation paths or in upper-room applications to indirectly

407   treat air through convective air movement (88, 89). More recently, far-UVC light in the

408   207- to 222-nm range has been demonstrated to effectively inactivate airborne aerosolized

409   viruses. While preliminary findings from in vivo rodent models and in vitro

410   three-dimensional (3-D) human skin models appear favorable to not cause damage to

411   human skin and eyes (90, 91), further research must be conducted to verify the margin

412   of safety before implementation. If implemented safely, UVC and UVGI light offers a

413   range of potential disinfectant strategies for buildings and is a common strategy for

414   deep clean practices in health care settings. Implementing targeted UVC and UVGI

415   treatment may be prudent in other space types where individuals that tested positive

416   for COVID-19 were known occupants, but routine treatment may have unintended consequences

417   and should be implemented with appropriate precaution.

418

419   Spatial configuration of buildings can encourage or discourage social interactions. In

420   recent years, Western society has valued design that emphasizes visual transparency

421   and a feeling of "spaciousness" indoors, whether at home through the use of open plan

422   concepts or at workplaces that harness open office concepts with spatial layouts that

423   intentionally direct occupants to nodes of "chance encounters," thought to enhance

424   collaboration and innovation among employees. While these spatial configurations are

425   culturally important, they may inadvertently enhance opportunities for transmission of viruses

426   through designed human interaction. For example, large, densely populated

427   open office spaces may increase connectivity while private offices may decrease

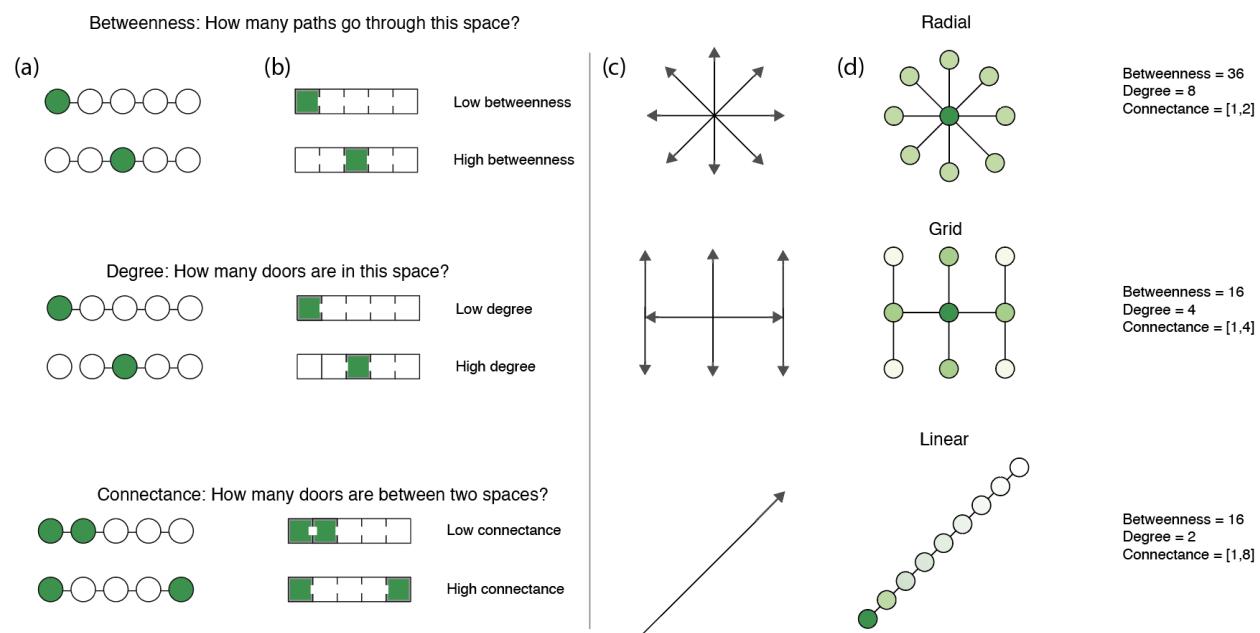
428   connectivity. Space syntax analysis demonstrates a relationship between spatial disposition

429   and degrees of connectivity (Fig. 3) and has been shown to correlate with the

430   abundance and diversity of microbes within a given space (92). Understanding these

431   spatial concepts could be part of the decision-making process of whether to implement

432   social-distancing measures, to what extent to limit occupant density, and for how long

433   to implement the measures.

434

435

436   **Figure 3. Spatial connectivity, highlighting betweenness and connectance of common room**

437   **and door configurations.** (a) Circles and lines follow the classic network representation. (b) The

438   rectangles follow the architectural translation of networks. Shaded areas correspond to a measure

439   of betweenness (the number of shortest paths between all pairs of spaces that pass through a

440   given space over the sum of all shortest paths between all pairs of spaces in the building), degree

441   (the number of connections a space has to other spaces between any two spaces), and

442   connectance (the number of doors between any two spaces). (c) The arrows represent possible

443   directions of microbial spread as determined by the layout of the BE. (d) The circles represent

444   the current knowledge of microbial spread based on microbial abundance through BEs as

445   determined by layout. Darker colors represent higher microbial abundance and lighter colors

446   represent lower microbial abundance.

447

448   **Special considerations for healthcare settings for current and future epidemics**

449   Hospitals present unique challenges during the process of mitigating and protecting

450   all inhabitants from an infectious disease outbreak. Not only do health care and

451   hospital facilities have limited options for social-distancing measures to prevent infectious

452   spread, but health care facilities also often cohouse patients with vastly different

453   requirements from the BE around them. For example, high-risk immunocompromised

454   patients are often kept within protective environment (PE) rooms, designed to limit

455   outside airborne infectious agents from entering into the room. To do this, these rooms

456   are positively pressurized, relative to the corridor space, with a minimum of HEPA

457   supply air (ASHRAE 170-2017 [50]). However, this pressurization differential also increases

458   the likelihood that aerosols in the patient room will migrate outside of the PE

459   room and into the higher traffic corridor space when the door is open. While PE rooms

460   typically function as intended for the occupant, if an immunocompromised patient is

461   also under treatment for an airborne infectious disease, the process of limiting pathogen

462   ingress into the room could potentially create involuntary exposure to health care

463   workers, other patients, and visitors via the corridor space. In comparison, airborne

464   infection isolation (AII) rooms utilize a negative pressure differential relative to the

465   corridor space and adjacent rooms, directly exhausting room air to the exterior of the

466   building to contain aerosolized pathogens from spreading into circulation and shared

467   spaces. The same negative pressure that aids in preventing spread of aerosolized

468   pathogens from inside the room can involuntarily expose the room occupants to

469   airborne pathogens that are sourced from occupants of the corridor space. Both PE and

470   AII rooms may be designed with an anteroom that is used as an additional buffer

471   between common areas and protected spaces to prevent pathogen spread and provide a location

472   for hospital staff to apply and remove personal protection equipment (PPE).

473   However, anterooms are not required for PE or AII rooms and have drawbacks during

474   routine operation; therefore, they exist in only some facilities. They use significant

475   additional floor area, create more travel distance. and increase the visual barrier

476   between patient and rounding care team, therefore, increase costs. These trade-offs

477   might be reconsidered in future design and operational protocols given the high costs

478   of pandemics and the critical role of health care environments during these times.

479

480   A discussion of PE and AII rooms does not adequately address the majority of

481   patient rooms within a hospital or health care facility that are not inherently designed

482   with airborne respiratory viruses in mind. Renewed consideration should be given to

483   general facility design to fulfill various requirements for different patient conditions and

484   operational requirements during both routine conditions and disease outbreaks. One

485   such consideration includes separating the means of thermal space conditioning from

486   ventilation provisions. Decoupling these functions permits decentralized mechanical or

487   passive ventilation systems integrated into multifunctional facades with heat recovery

488   and 100% outside air delivery. Mechanically delivering air through the facade would

489   permit all patient rooms to be operated in isolation and individually adjusted to be

490   positively or negatively pressurized, depending on patient requirements, with a higher

491   degree of operational resilience. Furthermore, future designs should reconsider the

492   best way to triage and complete initial assessment of patients that present symptoms

493   related to airborne viruses to minimize exposure to areas with other patient types if

494   possible. In planning for the future, architects, designers, building operators, and health

495   care administrators should aspire for hospital designs that can accommodate periods of

496   enhanced social distancing and minimize connectance and flow between common

497   areas, while also affording flexibility for efficient use of space during normal operating

498   conditions.

499

500   **Conclusion**

501   The number of individuals who have contracted COVID-19 or have

502   been exposed to SARS-CoV-2 has been increasing dramatically. Over a decade of

503   microbiology of the BE research has been reviewed to provide the most up-to-date

504   knowledge into the control and mediation of common pathogen exchange pathways

505   and mechanisms in the BE with as much specificity to SARS-CoV-2 as possible. We hope

506   this information can help to inform the decisions and infection control mechanisms

507   that are implemented by corporate entities, federal, state, county, and city governments,

508   universities, school districts, places of worship, prisons, health care facilities,

509   assisted living organizations, daycares, homeowners, and other building owners and

510   occupants to reduce the potential for transmission through BE mediated pathways. This

511   information is useful to corporate and public administrators and individuals responsible

512   for building design and operation in their decision-making process about the degree

513   and duration of social-distancing measures during viral epidemics and pandemics.

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