2019 Novel Coronavirus (COVID-19) Outbreak: A Review of the Current Literature and Built Environment (BE) Considerations to Reduce Transmission

Conflict of Interests: None

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Abstract

With the increasing spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) that results in coronavirus disease 19 (COVID-19), corporate entities, federal, state, county and city governments, universities, school districts, health care facilities, assisted living organizations, daycares, homeowners, and other building owners and occupants have an opportunity to reduce the potential for transmission through built environment (BE) mediated pathways. Over the last decade, substantial research into the presence, abundance, diversity, function, and transmission of microbes in the BE has taken place and revealed common pathogen exchange pathways and mechanisms. In this paper, we synthesize this microbiology of the BE research and the known information about SARS-CoV-2 to provide actionable and achievable guidance to BE decision makers, building operators, and all indoor occupants attempting to minimize infectious disease transmission through environmentally mediated pathways. We believe this information will be useful to corporate and public administrators and individuals responsible for building operations and environmental services in their decision-making process about whether to implement social-distancing measures and for what duration.

Introduction

Increased spread of SARS-CoV-2 causing 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 typical precautions typical for halting the spread of SARS-CoV-2 are being implemented, other less common 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 the microorganisms in the 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-2-CoV through BE mediated pathways.

Coronaviruses (CoVs) most commonly cause mild illness; but 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] (called "zoonotic" transmission). In 2002, a novel CoV, severe acute respiratory virus (SARS), was discovered in the Guangdong state of China[2]. SARS is a zoonotic CoV that originated in bats and resulted in symptoms of persistent fever, chills/rigor, myalgia, malaise, dry cough, headache, and dyspnea in humans [3]. SARS had a mortality rate of 10% and was transmitted to 8000 people during an 8-month outbreak in 2002-2003[4]. Approximately ten years after SARS, another novel, highly pathogenic CoV, known as Middle East Respiratory Syndrome Coronavirus (MERS-CoV), emerged and is also believed to have originated from bats, with the camel as the reservoir host[5]. MERS-CoV was first characterized in the Arabian Peninsula and spread to 27 countries, having a 35.6% mortality rate in 2220 cases[6].

2019 Novel Coronavirus (COVID-19)

In December 2019, a novel CoV (SARS-CoV-2) was identified in Wuhan, Hubei Province, a major transport hub of central China. The earliest COVID-19 cases were linked to a large seafood market in Wuhan, initially suggesting a direct food source transmission pathway[7]. Since that time, we have learned that person-to-person transmission is one of the main mechanisms of COVID-19 spread[8]. In the months since the identification of the initial cases, COVID-19 has spread to 112 countries and territories and there are approximately 114,230 confirmed cases (as of March 9, 2020). The modes of transmission have been identified as host-to-human and human-to-human. There is preliminary evidence that environmentally mediated transmission may be possible; specifically, that COVID-19 patients could be acquiring the virus through contact with abiotic (BE) surfaces [9,10].

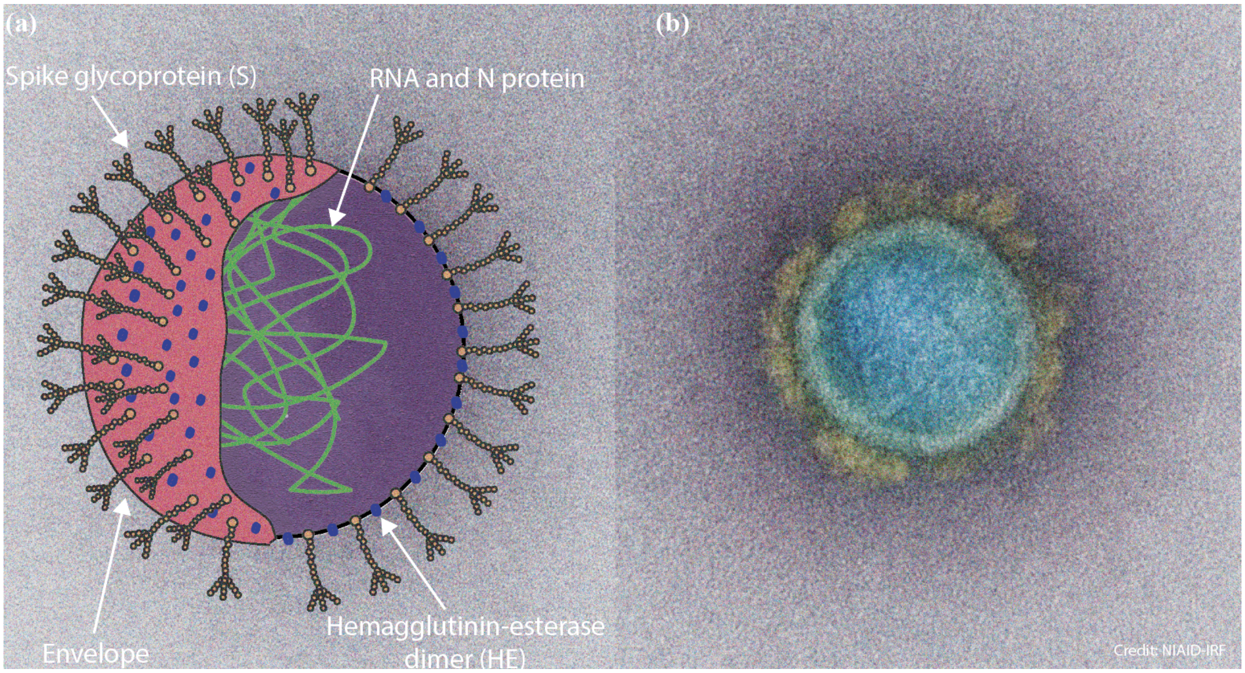

Figure 1. Structure of SARS-CoV-2 virus. (a) Artistic rendering of the structure and cross section of the SARS-CoV-2 virus [11,12] (b) Transmission electron micrograph of a SARS-CoV-2 virus particle isolated from a patient and imaged at the NIH NIAID Integrated Research Facility in Fort Detrick Maryland[13].

Epidemiology of SARS-CoV-2

The betacoronavirus SARS-CoV-2 is a single-stranded positive-sense enveloped RNA virus (++ssRNA) with a genome that is approximately 30 kilobases in length.[14,15] Spike glycoproteins, the club-like extensions projecting from the cell surface, facilitate the transfer of viral genetic material into a host cell by adhesion [11,12] (Fig. 1). The viral genetic material is then replicated by the host cell. As is characteristic for viruses in the genus *Betacoronavirus*, they infect and are carried by a variety of mammals, including bats. The infection history of SARS-CoV-2 is believed to have begun in bats with a possible intermediate host of pangolin[16]. There are several other *Betacoronaviruses* that occur in bats as a primary reservoir, such as SARS-CoV and MERS-CoV[17]. The manifestation of SARS-CoV-2 in a human population occurred late in December 2019, among persons known to frequent a seafood market [18]. The first symptoms observed clinically were fever, fatigue and dry cough, with symptoms ranging from mild to severe[15]. Currently, the protocol developed by the Center for Disease Control (CDC) for diagnosis [19] is a combination of clinical observation of symptoms and a positive result for the presence of the virus using real-time Polymerase Chain Reaction (rt-PCR)[20].

COVID-19 and the Impact of the BE in Transmission

The built environment (BE) is the collection of environments that humans have constructed, including buildings, cars, roads, public transport, and other human-built spaces[21]. Since most humans spend >90% of their daily lives inside the BE, it is essential to understand the potential transmission dynamics of COVID-19 within the BE ecosystem and the human behavior, spatial dynamics and building operational factors that potentially promote and mitigate the spread and transmission of COVID-19. BEs serve as potential transmission vectors for the spread of COVID-19 by forcing close interactions between individuals, by acting as fomites (objects or materials which are likely to carry infectious diseases), and through viral exchange and transfer through the air [22,23].

The occupant density in buildings, influenced by building type and program, occupancy schedule, and indoor activity, facilitates the accrual of human-associated microorganisms[21]. Higher occupant density and increased indoor activity level typically increases social interaction and connectivity through direct contact[24] as well as environmentally mediated contact (i.e. fomites). The original cluster of patients were hospitalized in Wuhan with respiratory distress (Dec 2019), and approximately ten days later, the same hospital facility was utilizing rt-PCR to diagnose patients with COVID-19. It is presumed that the number of infected patients increased because of transmissions that occurred within the hospital BE[9]. The increased exposure risk associated with high occupant density and consistent contact was demonstrated with the COVID-19 outbreak that occurred on the Diamond Princess cruise ship in January 2020[25]. Current estimates of contagiousness of SARS-CoV-2 (known as the R0), have been estimated from 1.5-3[26,27]. R0 is defined as the average number of people who will contract a disease from one contagious person[28]. For reference, measles has a famously high R0 of roughly 12-18[29], and influenza (flu) has an R0 of <2[30]. However, within the confined spaces of the BE, the R0 of SARS-CoV-2 of SARS-CoV-2 has been estimated to be significantly higher (estimates ranging from 5-14), with ~700 of the 3,711 passengers on board (~19%) contracting COVID-19 during their two week quarantine on the ship [25,31]. These incidents demonstrate the high transmissibility of COVID-19 as a result of confined spaces found within the BE[32]. With consideration to the spatial layout of the cruise ship, the proximity of infected passengers to others likely had a major role in the spread of COVID-19[32].

As individuals move through the BE, there is direct and indirect contact with the surfaces around them. Viral particles can be directly deposited and resuspended due to natural airflow patterns, mechanical airflow patterns, or other sources of turbulence in the indoor environment such as foot fall, walking, and thermal plumes from warm human bodies [21,33]. These resuspended viral particles can then resettle back onto fomites. Whenever an individual makes contact with a surface, there is an exchange of microbial life[34], including a transfer of viruses from the individual to the surface and vice-versa [35]. Once infected, individuals with COVID-19 shed viral particles before, during, and after developing symptoms[36]. These viral particles can then settle onto abiotic objects in the BE and potentially serve as reservoirs for viral transmission [18,33,37]. Evidence suggests that fomites can potentially be contaminated with SARS-CoV-2 particles from infected individuals through bodily secretions such as saliva, nasal fluid, contact with soiled hands, and the settling of aerosolized viral particles and large droplets spread via talking, sneezing, coughing, and vomiting [33,38]. A study on environmental contamination from the MERS-CoV demonstrated that nearly every touchable surface in a hospital housing MERS-CoV patients had been contaminated with the virus[39], and a survey of a hospital room with a quarantined COVID-19 patient demonstrated extensive environmental contamination [18,33]. The knowledge of the transmission dynamics of COVID-19 is still currently developing, but based upon studies on SARS-, MERS-CoV, preliminary data on SARS-CoV-2, and CDC recommendations, it seems likely that SARS-CoV-2 can potentially persist on fomites anywhere from a couple of hours up to nine days[37,40]. However, it should be noted that there are no documented cases to date of a coronavirus infection originating from a fomite. There is, however, preliminary data demonstrating the presence of SARS-CoV-2 in stool, indicating that transmission can potentially occur through the fecal-oral pathway [18,28,33,41]. While transmission of coronavirus has only been documented through respiratory droplet spread and not through deposition on fomites, steps should still be taken to clean and disinfect all potential sources of SARS-nCoV-2 under the assumption that active virus may be transmitted through these abiotic surfaces [33,37].

Figure 2: Conceptualization of SARS-CoV-2 deposition. (a) Once infected with SARS-CoV-2, viral particles accumulate in the lungs and upper respiratory tract (b) droplets and aerosolized viral particles are expelled from the body through daily activities such as coughing, sneezing, talking, and non-routine events such as vomiting, and can spread to nearby surroundings and individuals [33,38] (c) Viral particles, excreted from the mouth and nose, are often found on the hands and (d) can be spread to commonly touched items such as computers, glasses, faucets, and countertops. There are currently no confirmed cases of fomite-to-human transmission, but viral particles have been found on abiotic BE surfaces [33,37,37,40].

Previously, it has been confirmed that SARS can be, and is most often, transmitted through droplets[42]. Considering that SARS-CoV-2 is from a sister clade to the 2002 SARS virus[43], that is known to transmit from person-to-person, the high incidence of observed person-to-person transmission, and the rapid spread of COVID-19 throughout the world and communities, it is generally accepted at this time that SARS-CoV-2 can also be spread through droplets [44,45]. Based upon previous investigation into SARS[46], spread through aerosolization remains a potential secondary transmission method, especially within the BE that contain heating, ventilation, and air conditioning (HVAC) units[46]. Mitigation of viral transmission through BE air delivery systems is most often reliant on inline filtration media. Residential and commercial systems typically require a minimum efficiency reporting value (MERV) of 8, which is rated to trap 70-85% of particles ranging from 3.0-10.0 microns, a strategy employed to minimize impacts to cooling coils and other HVAC equipment. Higher MERV ratings are required in these settings to filter incoming outside air based on local outdoor particulate levels. Protective environment rooms in hospitals require the most stringent minimum filtration efficiency. A MERV 7 or greater is required as a first filter before heating and cooling equipment, and a second high-efficiency particulate air (HEPA) filter is placed downstream of cooling coils and fans. HEPA filters are rated to remove at least 99.97% of particles down to 0.3 microns. In most residential and commercial buildings, these are often MERV -5 to MERV -11, and in critical healthcare settings, MERV -12 or higher and HEPA filters are used. MERV -13 filters have the potential to remove microbes and other particles ranging from 0.3-10.0 microns. HEPA filters are also able to filter out particles 0.3 microns and larger. Most viruses, including coronaviruses, range from 0.004 - 1.0 microns, limiting the effectiveness of these filtration techniques against pathogens such as SARS-CoV-2[47]. Furthermore, no filter is perfect. Recently, it has been found that gaps in the edges of filters in hospitals has been a contributing factor of the failure of filters to eliminate pathogens from the shared air environment[48].

In recent years, the sharing economy has created environments where multiple people share the same spaces. It is possible that infectious disease transmission may be impacted by this shift to the sharing economy. Shared workspaces such as co-work environments, rooms in homes, cars, bikes, and other elements of the BE may increase the potential for environmentally mediated pathways of exposure. In cases where alternate modes of transportation were previously single occupancy vehicles, these trips are now often replaced with rideshare programs or transportation network companies, the potential for exposure may increase.

Control and Mitigation Efforts in the BE

The spread of COVID-19 is a rapidly developing situation, but there are steps that can be taken, inside and outside of the BE, to help prevent the spread of disease. On a personal level, proper handwashing is a critical component of controlling the spread of SARS-CoV-2, other coronaviruses, and many respiratory infections [49–51]. Individuals should avoid contact and spatial proximity with infected persons and wash hands frequently for at least 20 seconds with soap and hot water [37]. At this time, the Food and Drug Administration (FDA) does not recommend that asymptomatic individuals wear masks during their everyday lives in order to preserve masks and materials for individuals that have been infected with COVID-19 and healthcare workers and family that will be in consistent contact with individuals infected with COVID-19[52]. Additionally, wearing a mask can give a false sense of security when moving throughout potentially contaminated areas, and the incorrect handling and use of masks can increase transmission[53].

Over the last month, many countries have issued travel bans to prevent person-to-person contact, fomite contamination, and particle-based transmission. These mobility restrictions have been confirmed to help contain the spread of COVID-19[54]. Within local communities, a variety of measures can also be taken to prevent further spread [55]. As a whole, these measures are known as non-healthcare-setting social distancing measures. These include closing high-occupancy areas such as schools and workplaces. These community-level measures act to prevent disease transmission through the same mechanisms as the worldwide travel restrictions by reducing typical person-to-person contact, decreasing the possibility of fomite contamination by those that are shedding viral particles, and decreasing the possibility of airborne, particle transmission between individuals in the same room or close proximity. These decisions are made by individuals with administrative authority over large jurisdictions, communities, or building stock and are weighed in balance with a myriad of factors, including health risks and social and economic impacts. Better understanding of BE mediating variables can be helpful in decision-making about whether to implement social distancing measures and for what duration, and to individuals responsible for building operations and environmental services.

Within the BE, environmental precautions that can be taken to potentially prevent the spread of SARS-CoV-2 include chemical deactivation of viral particles on surfaces[37]. It has been demonstrated that 62-71% ethanol is effective at eliminating MERS and SARS [40]. This ethanol concentration is the same as most typical alcohol-based hand sanitizers, suggesting that properly applied hand sanitizer may be a valuable tool against the spread of SARS-CoV-2 in the BE. Items should be removed from sink areas to ensure aerosolized water droplets do not carry viral particles onto commonly used items, and countertops around sinks should be cleaned using bleach or an alcohol-based cleaner on a regular basis. Again, it is important to remember that the main and vastly more common spread mechanism of previous coronaviruses has been identified as droplets from talking, sneezing, coughing, and vomiting than by the fecal-oral pathway [33,37,56]. Administrators and building operators should post signage about the effectiveness of handwashing for at least 20 seconds with soap and hot water, ensure soap dispensers are full, provide access to alcohol-based hand sanitizer, and implement routine surface cleaning protocols to high touch surfaces where contamination risks are high, such as around sinks and toilets[37]. Most importantly, to prevent the transmission of microbes and thus, undesirable pathogens, it is important to exercise proper hand hygiene [37,57].

Building HVAC operational practices can also reduce the potential for spread of SARS-CoV-2. Even though viral particles are too small to be contained by even the best HEPA and MERV filters, ventilation precautions can be taken to ensure the minimization of SARS-CoV-2 spread. Higher outside air fractions and higher air exchange rates in buildings may help to dilute the indoor contaminants from air that is breathed within the BE. Higher outside air fractions may be possible by increasing ventilation damper positions on air-handling units, thus exhausting a higher ratio of indoor air and any airborne viral particles present[58]. There are some cautions to consider relative to these building operations parameters. First, increasing outside air fractions may come with increased energy consumption. In the short term, this is likely a worthwhile mitigation technique to support human health but building operators are urged to revert to normal ratios after the period of risk has passed. Second, not all air-handling systems have the capacity to substantially increase outside air ratios, and those that do may require a more frequent filter maintenance protocol. Third, increasing air flow rates that simply increase the delivery of recirculated indoor air, without increased outside air fraction, could potentially increase the transmission potential. Higher air flow rates could increase resuspension from fomites and increase the potential for contamination throughout the building by distributing indoor air more quickly, at higher velocities and volumes, potentially resuspending more ultrafine particles[58]. Administrators and building operators should collaborate to determine if increased outside air fractions are possible, what limitations or secondary implications must be considered, and determine a plan around managing the outside air fraction and air change rates.

Increasing evidence indicates that humidity can play a role in the survival of membrane-bound viruses, such as SARS-CoV-2[59,60]. Previous research has found that relative humidity above 40% is detrimental to the survival of many viruses, including coronaviruses in general [59,61], and higher indoor relative humidity has been shown to reduce infectious influenza virus in simulated coughs[59]. Maintaining a relative humidity between 40%-60% within the BE may help to limit the spread and survival of SARS-CoV-2 within the BE, while minimizing the risk of mold growth, and maintaining hydrated and intact mucosal barriers of human occupants[62]. Indoor humidification is not common in most HVAC system designs, largely around maintenance concerns and the risk of over-humidification increasing the potential of mold growth. While administrators and building operators should consider the costs, merits, and risks of implementing central humidification, it may be too time intensive to implement in response to a specific viral outbreak or episode. Therefore, targeted in-room humidification is another option to consider, and this may reduce the likelihood of a maintenance oversight causing over-humidification.

Building ventilation source and distribution path length can affect the composition of indoor microbial communities. Ventilating a building by introducing air directly through the perimeter of buildings into adjacent spaces is a strategy that does not rely on the efficacy of whole building filtration to prevent network distribution of microorganisms. Delivering outside air directly through the envelope into an adjacent spatial volume has been shown to increase the phylogenetic diversity of indoor bacterial communities and create communities that are more similar to outdoor-associated bacteria than air delivered through a centralized HVAC system[63]. In some buildings, this can be accomplished through distributed HVAC units, such as packaged terminal air-conditioners (PTAC) frequently found in hotels, motels, senior housing facilities, condominium units and apartments or through perimeter passive ventilation strategies such as perimeter dampered vents [64,65]. However, for most buildings, the easiest way to deliver outside air directly across the building envelope is to open a window. Window ventilation not only bypasses ductwork but increases outside air fraction and likely increases total air change rate as well. Administrators and building operators should discuss a plan for increasing perimeter, and specifically window, ventilation when outdoor temperatures are adequate for this practice without substantial comfort or energy implications.

Light is another mitigation strategy for controlling the viability of some infectious agents indoors. Daylight, a ubiquitous and defining element in architecture, has been shown in microcosm studies to shape indoor bacterial communities in household dust to be less human-associated than in dark spaces[66]. Moreover, daylight in these microcosm spaces reduced the viability of bacteria compared to dark controls. Further research is needed to understand the impact of natural light on SARS-CoV-2 indoors; however, daylight exists as a free, widely available resource to building occupants[66]. Some electric lighting is already implemented as engineering controls for disinfection indoors. Ultraviolet light in the region of shorter wavelengths (254nm UV-C) is particularly germicidal and fixtures tuned to this part of the light spectrum are effectively employed in clinical settings to inactivate infectious aerosols[67]. However, ultraviolet germicidal irradiation (UVGI) has potential safety concerns if the high-energy light exposure occurs to room occupants. For this reason, UVGI is safely installed in mechanical ventilation paths or in upper-room applications to indirectly treat air through convective air movement[68,69]. More recently, far-UVC light in the 207-222nm range has been demonstrated to effectively inactivate airborne aerosolized viruses. While preliminary findings from in vivo rodent models and in vitro 3D human skin models appear favorable to not cause damage to human skin and eyes[70,71], further research must be conducted to verify the margin of safety before implementation. If implemented safely, UVC light offers a range of potential disinfectant strategies for buildings. Administrators and building operators should encourage blinds and shades to be opened when they are not needed to actively manage glare, privacy or other occupant comfort factors to admit abundant daylight and sunlight. Implementing targeted UVGI treatment may be prudent in spaces where individuals that tested positive for COVID-19 were known occupants, but routine treatment may have unintended consequences and should be implemented with appropriate precaution.

Spatial configuration of buildings can encourage or discourage social interactions. In recent years, Western society has valued design that emphasizes visual transparency and a feeling of "spaciousness" indoors, whether at home through the use of open plan concepts or at workplaces that harness open office concepts with spatial layouts that intentionally direct occupants to nodes of "chance encounters," thought to enhance collaboration and innovation among employees. While these spatial configurations are culturally important, they may inadvertently enhance or reduce opportunities for transmission of viruses through human interaction. For example, large, densely populated open office spaces may increase connectivity while private offices may decrease connectivity. Space syntax analysis demonstrates a relationship between spatial disposition and degrees of connectivity (Fig 3) and has been shown to correlate with the abundance and diversity of microbes within a given space[71]. Understanding these spatial concepts could be part of the decision-making process of whether to implement social-distancing measures, to what extent to limit occupant density, and for how long to implement the measures.

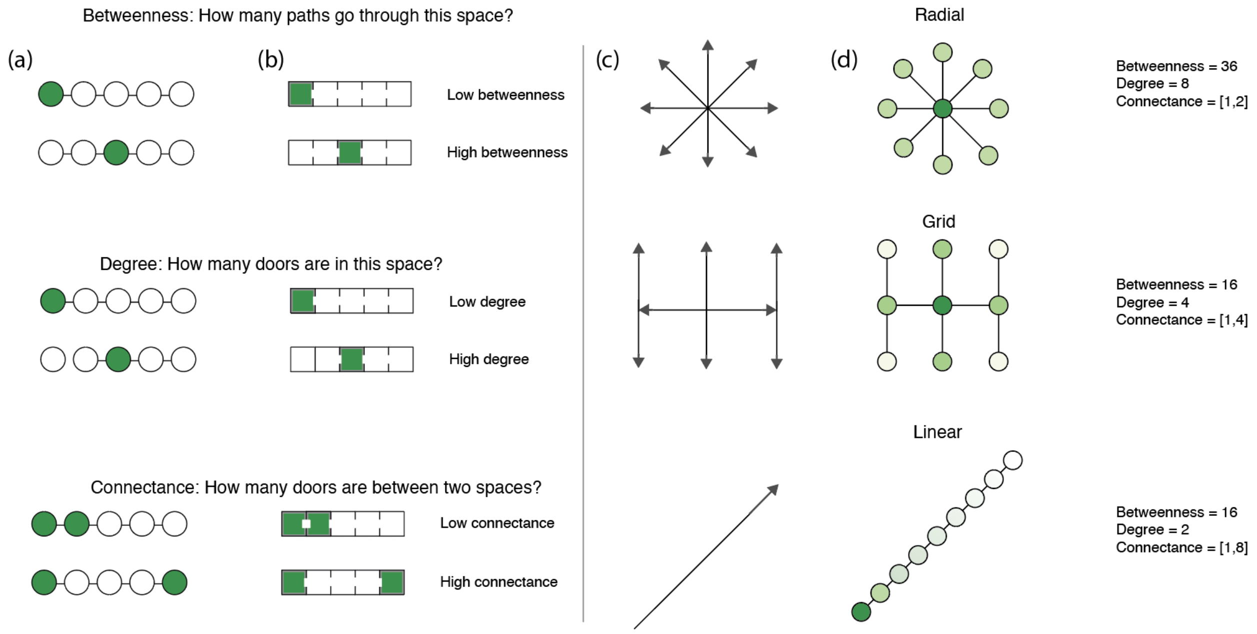

Figure 3. Spatial connectivity, highlighting betweenness and connectance of common room and door configurations. (a) Circles and lines follow the classic network representation. (b) The rectangles follow the architectural translation of networks. Shaded areas correspond to a measure of betweenness (the number of shortest paths between all pairs of spaces that pass through a given space over the sum of all shortest paths between all pairs of spaces in the building), degree (the number of connections a space has to other spaces between any two spaces), and connectance (the number of doors between any two spaces). (c) The arrows represent possible directions of microbial spread as determined by the layout of the BE. (d) The circles represent the current knowledge of microbial spread based on microbial abundance through BEs as determined by layout. Darker colors represent higher microbial abundance and lighter colors represent lower microbial abundance.

Conclusion

The number of individuals who have contracted COVID-19 or have been exposed to SARS-CoV-2 has been increasing dramatically. Over a decade of microbiology of the BE research has been reviewed to provide the most up-to-date knowledge into the control and mediation of common pathogen exchange pathways and mechanisms in the BE. We hope this information can help to inform the decisions and infection control mechanisms that are implemented by corporate entities, federal, state, county and city governments, universities, school districts, health care facilities, assisted living organizations, daycares, homeowners, and other building owners and occupants to reduce the potential for transmission through BE mediated pathways. This information will be useful to corporate and public administrators and individuals responsible for building operations and environmental services in their decision-making process about whether to implement social-distancing measures and for what duration.

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