Indoor SARS-CoV-2 Herd Immunity and Infection Probability Estimates Based on Ventilation, Vaccination, Infections and Face Masks

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Abstract

A quantitative model linking infection probability and herd immunity (building reproductive number, Rao) to indoor carbon dioxide concentration is developed by extending the Rudnick and Milton (1) model to building systems with filtration, air sanitation, varying levels of occupants (infectious, immune and susceptible) and occupant activities (metabolism). Face mask usage is incorporated into the model with differing levels of mask efficiency for exhalation and inhalation assumed. The explicit model can be implemented by others using simple spreadsheet computations to analyze individual situations.

Carbon dioxide measurement is essential for controlling SARS-CoV-2 transmission in buildings. Carbon dioxide is a direct indicator of fresh air ventilation and a surrogate for contagion concentration. Carbon dioxide measurement is inexpensive, simple to implement, and should be used in every room and indoor space. Several examples of indoor environment carbon dioxide concentration measurements in a variety of buildings are included.

Based on model investigations, the following recommendations are proposed:

1) Control fresh air ventilation to maintain 800ppm of carbon dioxide, equivalent to doubling current building fresh air ventilation standards from 20cfm per person (9.4l/s per person) to 40cfm per person (18.8l/s per person)
2) Recirculate indoor air through high efficiency filters (MERV13 or better) with a combination of whole building air recirculation and room space filtration systems. Recirculation air flow levels should be similar to fresh air ventilation levels.
3) Consider adding UVGI (ultraviolet germicidal irradiation) with 0.02Wuv irradiation per cfm of recirculation air flow for 85% single pass virus kill efficiency.
4) Face mask usage is essential as long SARS-CoV-2 virus is detectable in a community, especially for susceptible individuals with comorbidities. Herd immunity does not protect susceptible individuals from an infectious person.

Introduction

Herd immunity (aka, herd protection) depends on many factors within the built environment, including building occupancy, occupant activity (eg, sleeping versus exercising), infectious occupants, susceptible occupants, immune occupants, fresh air ventilation, indoor air filtration, air sanitation (eg, UVGI, ultraviolet germicidal irradiation), and exposure time. The objective of this paper is development of a generalized relation for predicting SARS-CoV-2 infection probability and estimation of Covid-19 building reproductive number, Rao. Relations for infection probability and building reproductive number are developed by expanding the Rudnick and Milton (1) analysis linking an infectious dose of contagion to indoor carbon dioxide concentration.

Today's commercial, institutional and residential fresh air ventilation standards are based on odor, and odor is not an indicator of healthy air. SARS-CoV-2 is primarily transmitted in indoor environments because of inadequate building ventilation practices. Although the need to increase fresh air ventilation and to improve air filtration are generally acknowledged, recommendations for fresh air ventilation and filtration are qualitative and ambiguous.

The results of this study indicate today's fresh air ventilation standards should be doubled to 40cfm per person (19 liters per second per person). Ventilation air flow is difficult to measure and monitor in real time as occupancy and occupant activities vary. Carbon dioxide (CO_2) concentration measurement directly indicates fresh air ventilation flow. CO_2 is simple and inexpensive, and monitors can be placed in every indoor space (including transit and mobile platforms).

Air filtration levels should be increased to a minimum of MERV 13 filters with air circulation rates similar to fresh air ventilation levels. Air sanitation using UVGI (ultraviolet germicidal irradiation) provides an additional "belt-and-suspenders" level of protection to air filtration. In addition to improved building ventilation, predictions show face masks are essential within indoor spaces to reach herd immunity as the world awaits vaccination protection.

Achieving herd immunity levels within the built environment is practical and cost effective. Herd immunity does not mean that an individual's protection from infection has been improved. A susceptible individual's chance of infection remains the same within a space co-occupied with an infectious individual, regardless of immunization status of other occupants. Herd immunity is a metric describing a condition in which new infection cases are decreasing. Herd immunity varies from building to building based on many factors described by these analyses.

The cost to implement recommended levels of fresh air ventilation, filtration, and air sanitation are reasonable and practical. Doubling today's fresh air ventilation standards costs a penny per hour per building occupant without adding any energy recovery or other significant building capital cost, however, adding energy recovery equipment should occur as capital becomes available.

Air recirculation with improved filtration and air sanitation similarly cost a penny per hour per building occupant. The proposed improvements to indoor ventilation guidelines are cost effective regardless of Covid-19 by decreasing other infectious diseases (seasonal flu and colds), removing indoor particulates, improving conditions for occupants with respiratory sensitivities, and increasing human productivity.

Background

Indoor environments impact human health. Doubling today's fresh air ventilation standards have been found to decrease sick days by 40%, similar to influenza vaccine reduction of sick days (2). Additional increases of fresh air have not been found to further reduce sick days (3). A double blind study of UVGI (ultraviolet germicidal irradiation) of office ventilation air has shown statistically significant improvement of building occupant health (4).

Rudnick and Milton (1) developed a Wells-Riley relation for airborne disease transmission linked to carbon dioxide from building occupant respiration. The Rudnick and Milton relations for infection probability and building reproductive number (Rao) are based on occupants (susceptible and infectious), respiration rates, infectious dose emission and exposure time. Linking carbon dioxide to respiratory disease transmission is important because carbon dioxide measurement is inexpensive and is a direct measure of fresh air ventilation that can be implemented anywhere.

Carbon dioxide measurement accounts for occupant activity. Human carbon dioxide output varies by a factor of 10 from sleeping to vigorous exercise (5). Psychological stress (6) and cognitive loading (7,8) also impact respiration rates. Increased respiration increases both emission of carbon dioxide and viral particles.

Airborne transmission of SARS-CoV-2 is generally recognized as a major contributor to the spread of the disease (9). Capturing infectious virions without damaging them is a complex, multi-step technical challenge. Relatively sparse direct evidence of live, aerosolized microbes continues to fuel the airborne transmission debate (10-13).

Respiratory viruses often display seasonal variations (14) for several reasons including virus sensitivity to temperature and humidity, human immune system dependence on sunlight-derived vitamin D, variation of mucous layer protection of epithelial cells, seasonal building occupancy, and seasonal building ventilation variations. Newell (15) shows evidence of a link between Covid-19 spread and outdoor temperatures that correlate with building occupancy. A significance difference between Covid-19's "summer surge" during June and July, 2020 and the 1918 influenza pandemic's summer decline is the lack of air conditioning during the early 20th century. Without air conditioning, buildings and homes were opened to the outside for maximum ventilation during the summer. Today, buildings are sealed during the summer with air conditioning maintaining comfort while today's low fresh air ventilation rates and poor air filtration practices promote disease transmission.

Respiratory fluids are generally described as "large" droplets greater than 1 micron and smaller "aerosol" droplets that are less than 1 micron. The distinction is fuzzy, however, larger droplets tend to be generated by coughing, sneezing, talking, singing and other events in which larger droplets are sheared from the walls of upper respiratory passageways. Aerosols originate deeper within the lungs and are continuously emitted through nose and mouth from regular breathing (17,18). Curiously, only half of a populace seems to emit aerosols (17), with the majority of respiratory aerosols emitted by half of that group. Respiration generated aerosol droplets in the 0.3 to 0.5 micron range were found to be most numerous with up to 10,000 droplets per liter of exhaled breath.

Researchers have captured virions through extensive efforts to count and match genetic material to infectious individuals (19,20,21,22). Among important findings is the weak correlation between the amount of viral genetic material collected in (small) respiratory generated droplets and viral material collected through throat and nasal swabbings, indicating lower respiratory droplets have different infection levels than upper respiratory infections. Face masks have been found to effectively capture virions including SARS-CoV-2 (20). Lednicky and co-workers (22) were the first to successfully capture live SARS-CoV-2 virions in a room with infected patients, and to link the genetic material directly to the patients.

A building's interaction with viral matter has been examined in actual buildings (23), and in realistic building ventilation systems (24, 25). These studies demonstrate that improved filters (MERV 11 and greater) capture viral-ladened aerosols. Kunkel and co-workers (24) found interesting characteristics of bacterial and viral droplet dispersions in ventilated rooms. Droplets with bacterial matter have a significantly different droplet size spectrum than viral-ladened aerosols. Bacteria-ladened droplets tended to be larger and to fall to the ground closer (within 2 meters) to the emission source. Virus-ladened droplets were smaller and more numerous farther from the emission source (3 to 6 meters), indicating that the infectious range of a virus is greater than the commonly accepted "6 foot" distancing guidance and that a virus is more likely to have airborne qualities.

Regardless of the airborne transmission debate, evidence clearly indicates that SARS-CoV-2 is most efficiently transmitted indoors. Direct contact transmission by fomites (objects coated with infectious microbes) as well as larger droplets are impacted by ventilation levels. Higher concentrations of airborne microbes increase microbe deposition density on objects and surfaces. Furthermore, if the indoor environment is not an important factor, disease transmission for similar size gatherings and activities should be the same for indoor and outdoor environments. A tracking study (26) of Covid-19 outbreaks, defined as 3 or more infections, found all outbreaks to have occurred indoors. The authors re-examined their data by defining "2-person outbreaks" and found only one instance of outdoor transmission.

A nursing home facility experienced a Covid-19 outbreak in one of its buildings with automated fresh air ventilation that maintained 1000ppm of carbon dioxide concentration, typical of today's ventilation standards (27). The building also lacked air recirculation filtration. Poor ventilation, lack of filtration, and residents' long exposure time all combine to create high infection probability and building reproduction numbers. The facility's other buildings with continuous fresh air ventilation and continuous recirculation of indoor air through filters did not experience Covid-19 outbreaks. Unfortunately, no information on carbon dioxide concentration is available for the other buildings, however the authors indicate higher levels of fresh air ventilation than in the building with automated ventilation.

Kwon, et al (28) traced airborne transmission of two infections in a restaurant with recirculating air conditioning systems that provided no filtration and no fresh air. In one case, indirect co-occupation of the restaurant between infectious occupant and susceptible occupant was 5 minutes. The infector and the infected individual were more than 6 meters apart as recorded by video security cameras, with no direct contact between the individuals. The second infected individual spent 20 minutes of co-occupation with the infector and was more than 4 meters away.

Based on Lednicky et al (22) measurement of 74 live viral copies per liter of air in a Covid-19 hospital room, the relations developed in this work indicate a potential release of 750 viral copies per second per infectious person (see App B), or nearly 222,000 copies released over a 5 minute period. Assuming virions are homogeneously spread throughout the restaurant without deposition, decay, filtration or dilution, the restaurant would have an average 1 copy per liter after 5 minutes of shedding. Based on Kwon et al (28) air flow measurements around the infector and two infected customers, virion concentration would be much higher in the air conditioning recirculation system's coherent flow structures. In fact, the customer infected with only 5 minutes of shared space was directly downstream of the air flow passing over the infector with 200,000 viral particles passing through their space. Fabian et al (17,18) found individual emission of aerosol droplets up to 10,000 particles per liter. In the restaurant, 400,000 aerosol droplets could have been emitted during 5 minutes, resulting in 1 virion per 2 respiratory droplet estimate.

Herd Immunity

"Herd immunity", also known as "Herd Protection", is simple conceptually but complex in reality. When a collection of infectious persons are no longer able to infect the same number of people, herd immunity has been reached, and ideally, disease transmission decreases. A simple ratio of susceptible people who contract a disease per infectious person, called the "basic reproduction number", Ro, is commonly used as a metric to define herd immunity. When Ro is reduced to 1 or less, a disease is no longer self-sustaining and new infections decrease.

SARS-CoV-2 has an estimated Ro of 2 to 3 within a fully susceptible populace, requiring 60 to 70% populace immunity to reduce Ro to 1. Anderson et al (29) discusses the transient, varying nature of Ro. As more of a populace become infected or vaccinated, Ro is reduced. The speed of vaccination versus the propagation of virus infection determines whether a populace reaches herd immunity by vaccination before the more costly and deadly infection-acquired immunity occurs. As discussed by Aschwanden (30), the behavior of a populace (eg, social distancing, face mask wearing, improved ventilation, etc) lowers Ro, however, once behaviors return to "normal", Ro will revert to a level commensurate with those behaviors. Omer et al (31) show Ro and herd immunity levels for several diseases, including SARS-CoV-2, in different countries. Aguas et al (32) demonstrates Rao variations due to susceptibility and exposure behaviors. Kwok et al (33) estimate Ro by using early pandemic growth rates.

Rudnick and Milton (1) develop a "building reproductive number", Rao, that links building occupancy and building ventilation to infection probability. Buonanno et al (34) assume virus density (counts per mL) in droplets are the same as obtained in upper respiratory swabbings. The authors link human activity with viral particle emission, and relate the number of viral particles emitted to an infectious dose (quantum). Transient, numerical modeling of viral loading of an indoor space under varying occupancy, occupant activity, exposure time, and building ventilation yields estimates of infection probability and building reproductive number in different indoor environments (eg, pharmacy, restaurant, store).

Ventilation, Health and Productivity

Building ventilation has been recognized as an important factor in disease transmission for more than a century. Nightingale (35) listed fresh air as the most important item on her list of essential aspects for healing patients and stated that without fresh air, all other items on her list are for naught. Nightingale also recognized the responsibility of architects, builders and building operators regarding occupant health, and stated that if they (architects, builders and owners) were responsible for health costs of their buildings' occupants, we would have very different buildings. Ironically, in October, 2019 as Covid-19 was emerging in Asia, the Florence Nightingale Museum in London was holding a special exhibit on the 1918 influenza pandemic (Figure 1).

Lerum (36) provides a historical review of 19th century building ventilation systems, and the care devoted to fresh air supply and stale air exhaust design. The "new" University of Glasgow building constructed in the 1860s, with engineering luminaries Lord Kelvin and Professor Rankine on the building committee, required 0.6 cubic feet per second of fresh air supply to each seat in the building, and an exhaust designed to collect and remove air in a manner that eliminated air stagnation. The specified fresh air flow rate is twice today's typical fresh air ventilation standard.

Konzo (37) discusses the history of building ventilation and comfort conditioning. Today's odor-based ventilation standards are rooted in 1930's research in which a recently washed, clean clothed, sendentary (office work activity) person was placed in a sealed chamber with differing amounts of fresh air blown through the chamber. A human nose smelled exhaust air from the chamber to determine acceptable air quality, forming the basis for today's fresh air flow of 15 to 20 cfm/person (cubic feet per minute per person, or 7.5 to 10 liters per second per person).

Odor ventilation standards are intended to cause "only" 20% indoor air quality dissatisfaction, which does not mean the 80% are satisfied. A survey (38) of over 30,000 building occupants shows that only 20% of buildings achieve air quality with 20% occupant dissatisfation. Similar levels of dissatisfaction in building comfort were found in the survey, indicating that we have much to do to improve the indoor environment and human productivity in addition to reducing the spread of airborne disease.

Fanger's (39) pioneering work at the Danish Technical University demonstrated that human productivity is affected by subtle differences in perceived air quality. Air quality olfactory sensation is defined by the "olf". One olf is the air quality sensation perceived by humans in a space that is occupied by a recently washed, clean-clothed, sedentary person with 20cfm (10liter/s) per person fresh air ventilation. Standard ventilation with air quality of one olf degrades human performance as demonstrated in an assortment of blind tests in the work environment.

Humans emit carbon dioxide as well as a soup of volatile organic compounds (VOCs). The "pig-pen" effect describes the personal cloud of pollutants, particulates and microbes surrounding each person (40). In addition to aerosolized respiratory droplets, other particulates from people are formed by VOC reactions, such as squalene (skin oil) reacting with ozone. In a similar manner to CO_2, infectious respiratory droplets may correlate with a human's pig-pen cloud of pollutants and particulates. Accurate, reliable, and low cost particulate measurement is difficult despite an abundance of indoor air quality sensors purporting to monitor particulates. Continued development of particulate sensors may result in reliable sensors that provide an additional piece of air quality monitoring and control capability for managing airborne microbes.

In an unpublished study (see Daily Illini Oct 26, 2020 news article) the author with colleagues from the University of Illinois Environmental Engineering and Jazz Performance programs staged a "Covid-free" Jazz performance in a local venue to collect indoor carbon dioxide, VOC, particulate mass, and particulate number/size data during a 2 hour performance. Two university student jazz performance groups, one with vocals and one horns and woodwinds, each performed a 45 minute set with a 15 minute break. Approximately 20 to 25 people attended the event (including musicians and researchers). During the performances, fresh air ventilation and air recirculation through a MERV13 filter were alternately varied.

Among the interesting results is a strong correlation between occupancy and small particle density (0.5 micron and below), and very weak correlation between larger particle densities and occupancy. Musician performances, performance breaks, and type of performance (with and without vocalists) did not impact results. All attendees not performing wore masks. The performance venue demonstrated reduction of airborne particulates by both increased fresh air ventilation and air recirculation through a MERV13 filter. Note that the University of Illinois' "Safer" rapid test program requires all University of Illinois personnel to test twice per week for Covid-19, providing a pool of Covid-free participants. Unfortunately, a second November performance to verify initial data results had to be canceled with shutdown of Illinois restaurants due to high Covid-19 infection growth.

People in the US are indoors more than 90% of the time (41). On average, people spend more than 60% of time in their residences. Beyond disease transmission concerns, the built environment impacts human health and productivity. Bedrooms are a source of high carbon dioxide concentrations, and high carbon dioxide concentrations plus the impact of human emitted VOCs have been shown to impair sleep and next day productivity (42). Recent studies have shown degraded human cognition at carbon dioxide concentrations previously thought to be benign (43, 44, 44, 45). Similar to doubling today's ventilation standards for reduction of sick days (2), MacNaughton et al (43) estimate increased human productivity to have a value 100 times greater than the associated energy cost of increased ventilation in harsh climates without any added energy conservation modifications.

Figure 2 illustrates the balance of indoor air quality characteristics that create a healthy indoor environment. Fresh air is required to reduce carbon dioxide and VOC concentrations to levels that maintain peak human performance and enhance sleep. Table 1 shows the correspondence between carbon dioxide from sedentary human respiration and fresh air ventilation rate. Assuming no other sources of carbon dioxide production, such as indoor combustion or fermentation processes, carbon dioxide concentration and fresh air ventilation rates are synonymous. VOCs are also reduced by fresh air ventilation assuming outdoor VOC sources are low. In today's homes, most VOC generation is from humans, human activities (eg, cooking, cleaning, vapping) and indoor furnishings. Not all VOCs are bad, with Grandmother's chicken soup providing a sense of healing comfort as well as a beneficial treatment for respiratory illness (46).

Inhalation of particulates is generally considered unhealthy, and in today's sealed and insulated homes, most particulates are generated indoors. Particulate removal is best achieved by filtration, with filter ratings of MERV 11 and greater required for removal of micron and sub-micron level particulates. MERV 8 is a common filter used in HVAC (Heating, Ventilation and Air Conditioning) systems, however, MERV 8 filters are ineffective for removing viral matter and primarily are used to keep heating and cooling heat exchanger surfaces clean.

MERV 11 and greater filters have been shown to effectively remove sub-micron virus-ladened aerosols (24, 25), with Kunkle et al (24) finding that MERV 11 filtration removed 85% of viral matter and MERV 16 filtration removed 95% of viral matter from their residential ventilation experiment. Kunkle et al (24) also demonstrated that MERV 8 filtration of viral matter was the same as no filter in the air recirculation system. Note that MERV 16 and HEPA filters were found to have comparable filtration performance within a mining cab environment (47).

Menzies et al (4) demonstrated the effectiveness of UVGI (ultraviolet germicidal irradiation) in relieving respiratory-related symptoms in the indoor environment. Bahnfleth (48) provides background and design guidelines for UVGI in indoor spaces and ventilation systems. A level of 0.02 Watts of UV irradiation per cfm of airflow is sufficient for an 85% "single pass kill efficiency" of viral particles in ducted UVGI systems. Assuming 25% electrical to UV energy conversion efficiency, 20cfm per person (9.4 l/s per person) of air recirculated through a ducted UVGI system requires 1.6W per person, or 14kWh per year per person for continuous usage for an estimated annual energy cost of $1.7 per person (assuming $0.12 per kWh utility cost).

ASHRAE is an international engineering organization that is recognized internationally as an authority on building ventilation. ASHRAE's Covid-19 guidance recognizes the importance of fresh air, filtration, and sanitation (49, 50, 51), however, specific ventilation recommendations combining disease transmission control with control of other pollutants are not quantified. Relations developed in the next section provide quantitative guidance for low infection probability and achieving herd protection while also creating a productive indoor environment with reduced air quality dissatisfaction.

ASHRAE's 62.1 (commercial buildings) and 62.2 (residences) form the bases for most building ventilation standards in the US. Other ventilation guidelines, such as EPA's "airPLUS" program, are based on ASHRAE standards. As an example of ventilation levels, EPA airPLUS currently allows ASHRAE 62.2-2010 for residential ventilation. A 1000ft^2 (93m^2) 2 bedroom home or apartment should have 32.5 cfm (15l/s) of fresh air ventilation air flow. The 62.2-2010 standard assumes occupancy to be 1 more person than the number of bedrooms, resulting in 10.8cfm per person (5l/s per person). From Table 1, we would expect carbon dioxide concentrations to reach 2000ppm on average, however, individual regions of a home, such as bedrooms, often reach higher concentration levels.

EPA's airPLUS version 2 (expected release Fall, 2021) requires ASHRAE 62.2-2013 or later ventilation standards. ASHRAE 62.2-2013 or later specifies 52.5cfm (24.6l/s) of ventilation air for a 2 bedroom, 1000ft^2 (93m^2) residence, or 17.5cfm per person (8.2l/s per person), reducing average expected CO_2 concentration levels near 1200ppm. Although this is a notable improvement, this ventilation is less than desired for achieving herd protection in the home.

Ventilation standards based on "air changes per hour" (ACH) are common, too. ACH specifications do not reflect human occupancy or activity and should not be used as a ventilation metric. For example, the Passive Haus Institute recommends 0.3ACH for residential ventilation. The 1000ft^2(93m^2), 2 bedroom home would have 40cfm of fresh air based on 0.3ACH ventilation, or 10cfm per person for 4 person occupancy with CO_2 average of 2000ppm. Commercial airlines tout 20ACH ventilation as superior ventilation in relation to much lower ACH levels used for homes. A full aircraft, however, with only 30 to 40 ft^3 (0.85 to 1.1m^3) of volume per passenger, supplies only 10 to 13 cfm per person (4.7 to 6.3l/s per person). Although people are sitting and most are physically inactive, passenger stress can increase respiration (6), resulting in higher emission of carbon dioxide and contagions.

Indoor Infection Probability and Herd Immunity Based on Carbon Dioxide Concentration

Buildings are complex with diverse levels of occupancy, occupant activities, climate, and purpose. Commercial buildings design air ventilation systems for delivering “conditioned” air (heated, cooled, humidified, dehumidified) and fresh air based on ASHRAE 62.1 ventilation standards. Residences have not historically specified any fresh air ventilation and instead have relied on construction flaws, vents, flues, and other openings for uncontrolled infiltration to provide “fresh” air. Despite the wide range of building parameter variations, SARS-CoV-2 and other airborne contagion transmissions can be quantified for specific situations.

A generalized relation for determining the concentration of an indoor pollutant (eg, carbon dioxide, VOCs, particulates, microbes) is presented in Appendix A. Figure 3 is a schematic of the generalized indoor environment modeled by the pollutant concentration model. Outdoor air flows into a building through uncontrolled (infiltration) and controlled (fresh air ventilation) means. Fresh air brought in by a ventilation system can be filtered and sanitized (eg, UVGI). Infiltrated air, which is primarily driven into a building by wind and buoyancy (temperature difference between indoor and outdoor air) is somewhat filtered by the cracks and passageways and impacts transport of outdoor particulate levels into a building, however, outdoor ambient particulates are not considered here to have contagious microbes.

Within a building, air is often circulated through a comfort conditioning system in which recirculated air can be filtered and sanitized (shown as filter 1 and UVGI 1 in Figure 3). An indoor space such as a classroom, living room, or office, may have a local space unit for filtering and sanitizing air (shown as filter 2 and UVGI 2 in Figure 3). Air leaves buildings at the same rate that it enters by a combination of exfiltration and exhaust ventilation.

Building occupants are assumed to be the source of airborne contagion released indoors. A fraction of building occupants are assumed to be wearing masks, and the masks are assumed to filter a fraction of microbes exhaled from infectious occupants. Building occupant metabolism and respiration rates depend on gender, weight, age, and activity level, which impacts the emission of carbon dioxide (5) and contagion from infectious individuals.

Infectious microbes released in the air can be filtered, deactivated (UVGI), deposited on surfaces, exhausted or naturally inactivated. An infectious dose of microbes inhaled by susceptible building occupants depends on contagion density in the air. A susceptible building occupant’s mask filters a fraction of contagion from their inhalation air. Note that mask exhalation filtration and inhalation filtration of microbes can be different.

Mask leakage is an extremely important factor in mask filtration efficiency (52). The prediction model includes the impact of mask usage and mask filtration efficiency, with separate parameters assumed for inhalation filtration and exhalation filtration in the App A model. A “perfect” face mask could capture/kill all emitted contagion exhaled by an infectious person and capture/kill all contagion in air inhaled by a susceptible person, resulting in zero infectious dosage inhaled and a basic reproductive number of zero.

Two expressions derived from the generalized pollutant concentration model for calculation of carbon dioxide concentration and infectious dose concentration are included in App A. Combining the two expressions results in a relation for infectious dose concentration as a function of carbon dioxide concentration and other parameters depicted in Figure 3.

A susceptible person's infection probability is determined by inhaled infectious dosage. One infectious dose is a quantum, and results in 63% chance of becoming infected, as described by Rudnick and Milton (1). Rudnick and Milton (1) assume all contagion exhaled by an infectious person is airborne, and that dilution is the only means of affecting contagion density. We follow Rudnick and Milton (1) to express infection probability based on carbon dioxide concentration.

Rudnick and Milton (1) developed a building reproductive number, Rao, that is a ratio of the number of infections per infectious person in a building. The building reproductive number is a ratio of infection probability times the number of susceptible occupants divided by the number of infectious occupants. Note that vaccinated occupants have susceptibility based on the efficacy of the vaccine. 5% of vaccinated occupants are assumed susceptible for a 95% effective vaccine.

An individual's infection probability depends only on the number of infectious occupants, not on the number of immune and susceptible occupants for a given number of total occupants. The building reproductive number, Rao, however, is dependent on the mix of susceptible and immune occupants, with increased immunity decreasing Rao. When conditions are met that decreases Rao to less than 1, "building" herd immunity is achieved and the disease should recede within that environment. Susceptible individuals, especially those with comorbidities, must still take preventative measures, such as high quality face masks, as long as Covid-19 exists in measurable numbers.

Comparison of Infection Probability and Building Rao with Other Predictions

A comparison of prediction model results to Rudnick and Milton (1) for a base case condition of no filtration, air sanitation or face mask filtration of microbes is presented. A second comparison to Buonanno, Stabile, and Morawska (34) transient infection model results is presented. Following the comparisons, a systematic progression through a series of indoor environment situations with varying levels of occupancy, protection (filtration, air sanitation, masking), and exposure time is presented.

Rudnick and Milton (1) presented results for varying levels of indoor carbon dioxide concentration (500ppm, 1000ppm, 1500ppm, and 2000ppm) with varying indoor occupancies (1 infectious and the remaining susceptible) for measles (570q/h, 10 hour exposure), influenza (100q/h, 4 hour exposure), and cold viruses (4q/h, 24 hour exposure).

Fresh air flows associated with Rudnick and Milton (1) carbon dioxide levels are 86cfm/person (41l/s-person), 20cfm/person (9.4l/s-person), 11cfm/person (5.3l/s-person), and 8cfm/person (3.7l/s-person) for 500, 1000, 1500, and 2000ppm cases. Outdoor carbon dioxide concentration assumed in (1) is 350ppm whereas today's average outdoor carbon dioxide concentration is 400ppm and increasing.

Highly contagious measles is predicted to have Rao of 14.6 and susceptible occupant infection probability of 37% at 500ppm carbon dioxide concentration for an occupancy of 40 (1 infectious and 39 susceptible occupants), in agreement with Rudnick and Milton results. As carbon dioxide increases above 1000ppm, contagion concentration reaches Rao of 40 with an infection probability reaching 100%, again in agreement with Rudnick and Milton (1) results.

Cold viruses are less transmissible with an estimated infection shedding rate of 4q/h (1). Rao ranges from 0.3 to 4 as carbon dioxide concentrations increase from 500ppm to 2000ppm in agreement with Rudnick and Milton (1). Infection probabilities range from 0.8 to 8.7% in contrast to measles high infection rates.

Influenza has a similar basic reproductive number (Ro) to SARS-CoV-2 with an estimated value of 2 to 3 when averaged over a population. For a building with 40 occupants, the building reproductive number ranges from 1.3 to 12, as also found by Rudnick and Milton (1) with infection probability from 3.3 to 30% for the 500ppm to 2000ppm carbon dioxide concentration range.

The present model allows extension of Rudnick and Milton (1) results to situations that typify building operations. An indoor environment with 40 occupants as discussed above with 800ppm carbon dioxide concentration would have Rao of 3.7 with infection probability of 9.4%. Replacing a MERV 8 filter with a MERV 13 (90% virus removal) in filter system 1 (see Figure 3) and an assumed flow rate of 550cfm (260l/s) reduces Rao to 2.6 and infection probability to 6.7%. Note that 550cfm (260l/s) is half of the fresh air flow required for maintaining 800ppm in the building. Adding a second air recirculation, filtration unit to the occupied space with an additional 550cfm (260l/s) air flow through a MERV13 filter further reduces Rao to 2.0 and infection probability to 5.2%. Rao is significantly reduced with the two filtration systems, however Rao remains above the self-sustaining infection level of 1.

Face masks reduce both infection probability and building reproductive number, Rao. If the infectious person in the above example is wearing a face mask that captures 50% of exhaled virus, infection probability for susceptible (unmasked) persons in the space are reduced to 2.6% from 5.2%, and the building Rao is reduced from 2.0 to 1.02, or nearly to the point where disease transmission is not self-sustaining. Susceptible persons who wear a face mask with 50% capture of virus during inhalation reduce infection probability to 1.3% and building Rao is 0.51, sufficient for decaying virus propagation.

A second comparison of the model's prediction is made with results from Buonanno, Stabile, and Morawska (34) transient model. Buonanno et al (34) formulated a flexible airborne contagion transmission model that relates respiration, coughing, sneezing and speaking to virus shedding. Deriving a transient form of the Wells-Riley airborne infection model, building reproductive numbers for scenarios ranging from a pharmacy to restaurant are modeled based on varying levels of occupancy, ventilation, and exposure time.

The present model is a steady state model, which provides conservative estimates of infection probability and building Rao because sufficient time Is assumed for reaching steady levels of contagion concentration within an indoor space. The simple format of the steady state model presented in App A is usable by practitioners who are trying to design safe spaces. Additionally, while transient modeling provides an in depth view of human interactions that may lead to infection, steady state modeling provides more cautious, yet practical predictions for situations in which a longer than anticipated occupancy occurs.

A comparison with the mechanically ventilated pharmacy case ("before" and "after" scenarios) from Buonanno et al (34) is examined. The mechanically ventilated pharmacy example assumed 97cfm (45.6l/s) fresh air flow with 15 person occupancy before Covid-19 and 5 person occupancy after Covid-19 actions. The before scenario assumes 5 employees and one customer entering the pharmacy every minute, with 10 minute occupation per customer, resulting in a continuous 15 person occupancy. The after scenario assumes 3 employees with 2 new customers every 5 minutes for a 5 minute customer occupancy period and a continuous occupancy of 5. The first pharmacy customer is infectious, and inhaled quanta for succeeding customers and employees are calculated, with an integrated building reproductive number determined (3 hour 10 minutes for the before scenario and 3 hour 5 minutes for the after scenario).

The before scenario for a 10 minute exposure (customer shopping) time has Rao of 1.2 from the steady state model, in agreement with Buonanno et al (34) results. The before scenario has a steady carbon dioxide concentration of 2900ppm, indicating poor air quality. The after scenario with 5 minute exposure time per customer has Rao of 0.2, also in reasonable agreement with transient model prediction results. Carbon dioxide concentration reaches 1250ppm, similar to today's inadequate ventilation standards. Note that the building reproduction number included employee infection probability.

The pharmacy example examined transient passing of an infected customer through the store. A different, but likely scenario would be one in which an employee is infectious. The employee is emitting contagion for the entire time (3 hours plus) as customers pass through. The above results for customers are the same as before, but susceptible employees have a much longer exposure time to airborne contagion. The "before" scenario for an infectious employee and a susceptible employee shows an infection probability of 81% in contrast to 8.3% for a customer. The after scenario also has an infection probability of 81% for the susceptible employee because the steady amount of contagion in the air, and the susceptible employee's inhalation of contagion are the same.

Discussion

A set of indoor scenarios systematically display variations of infection probability and building reproductive number (Rao) using the steady state contagion model in Appendix A. Building environments with 5, 10 and 100 occupants are assumed. In each case, one occupant is assumed to be infectious with remaining occupants either susceptible or immune, however, the App A model is generalized, allowing any mix of infectious, susceptible and immune building occupants. A virus shedding rate of 100quanta per hour per infectious person is assumed for all cases, which can be adjusted as desired.

The infection probability and building reproductive number model provide a means to examine the effects of immunity. Immunity may be acquired from infection recovery or from vaccination with an assumed efficacy. A vaccine efficacy of 75% indicates that 25% of those vaccinated are susceptible. Adjustment of viral shedding and vaccine efficacy allows one to determine sensitivity of emerging SARS-CoV-2 variants.

Figure 4 is a short exposure time (1 hour) example with varying indoor carbon dioxide concentrations, indicating differing levels of fresh air ventilation. The situation is representative of exposure time for shopping, attending a meeting or class, or customer interaction at a business. Plots for infection probability and building reproductive number (Rao) as a function of indoor carbon dioxide level are shown in Figure 4. Table 1 can be used to determine fresh air flow per occupant for different carbon dioxide concentrations in Figure 4 assuming low metabolism (1.2 to 1.5 Met) levels typical of sedentary to standing activities.

An infectious customer shopping for one hour may be insufficient for an indoor space to reach steady contagion conditions, and in such a case, steady state prediction is a conservative limit. More importantly, this situation reflects an infectious employee (front line worker) who emits contagion during an 8 hour work period that reaches steady contagion concentration level as customers shop for 1 hour exposure periods.

Infection probability drops as the number of people increases because the fraction of carbon dioxide (and amount of contagion) from the infectious person is reduced. In contrast, Rao increases as number of susceptible occupants increases because there are more opportunities for the infectious person to infect others. In a room with two people, one infectious and one susceptible, Rao has an upper limit of 1 because only one other person can be infected. In a room with 100 susceptible people for a sufficiently long exposure time and poor ventilation, Rao has an upper limit of 100. This situation reflects the difficulty of infection tracking in short exposure time, high occupancy situations such as restaurants and political rallies. High occupancy conditions have low infection probabilities and high reproductive numbers that encourages self-sustaining disease propagation.

Figure 4 also demonstrates how increased ventilation impacts building reproductive number and infection probability. Standard ventilation with approximately 20cfm per person (9.4l/s per person) results in 1200ppm (see Table 1) of carbon dioxide at low (1.5Met) metabolism levels with self-sustaining building reproductive numbers (Rao>1) for the modeled occupancies. Standard building filtration (MERV8 filters) for dust protection of ventilation components does not remove viral matter (24). An increase of ventilation levels to 40cfm per person (18.8l/s per person), reducing carbon dioxide concentration to 800ppm, is sufficient for decreasing Rao below 1 for short exposure periods and SARS-CoV-2 transmission characteristics.

Figure 5 is the same as Figure 4 with the addition of 25cfm per person (11.8l/s per person) air recirculation through a MERV13 filter assumed have 90% virus removal (24). Improved air filtration reduces Rao below 1 for short (1 hour) exposure time. Figure 5 indicates that standard ventilation (1200ppm carbon dioxide concentration) with filtration is sufficient for unsustainable disease transmission. Increased fresh air flow with 800ppm carbon dioxide further reduces infection probability as well as increases human productivity (42, 43, 44, 45) with the cost for doubling standard ventilation amounting to a one penny per occupant-hour in harsh climates (43). In terms of improved filtration, experimental studies have shown that MERV8 filters have similar pressure drop as MERV13 filters. Filter pressure drop is more dependent on filter quality (filtration material, pleating, filter depth) than filtration rating (53).

Figure 6 is the same situation as Figure 4 with 8 hour exposure time rather than 1 hour and no air filtration. Figure 6 represents work, school or home environments in which occupants are in place for an extended period of time. Increasing fresh air ventilation reduces infection probability, however, disease transmission remains self-sustaining with Rao greater than 1 for all occupancies. Note that doubling standard ventilation (reducing carbon dioxide from 1200ppm to 800ppm) from 20cfm/person (9.4l/s per person) to 40cfm/person (18.4l/s per person) reduces infection probability by 40% (eg, for the 10 person occupancy case, infection probability is reduced from 75% to 50%), similar to field results observed by Milton et al (2).

Figures 7, 8 and 9 are systematic improvements of an indoor space with 8 hour exposure time due to improved filtration (Figure 7, 25cfm/person recirculation through MERV13 filter), infectious occupant wearing a 50% effective face mask (Figure 8), and both infectious and susceptible persons wearing 50% effective exhalation/inhalation face masks (Figure 9). Each step results in reduction of infection probability and reduction of building reproduction number. Note that under steady state conditions, face mask usage is symmetrical for infectious and susceptible persons. That is, Figure 8 with an infectious person wearing a face mask and susceptibles not wearing masks is the same result as an infectious person not wearing a mask while susceptibles wear a mask because susceptible persons are inhaling the same amount of contagion. Only the best case of doubled fresh air ventilation (800ppm carbon dioxide), air filtration through MERV13 or better filter, and face mask usage by all occupants reaches herd immunity (Rao=1).

Figure 10 illustrates how immunity moves a populace toward herd immunity under "normal" human interaction (that is, no face masks). Figure 10 is the same situation as Figure 7 with 8 hour exposure and air filtration through MERV13 filters. 75% of building occupants are assumed to be immune, either through vaccination or previous infection acquired immunity. Building reproductive number, a primary indicator for herd immunity, is reduced to 1 or less for all occupancies modeled at 800ppm of carbon dioxide in contrast to Rao of 2 to 5 in Figure 7 without 75% immunization. With total US infections approaching 10% as of January 2021, Figure 10 indicates a race between infection-acquired immunization and vaccination immunization over the next few months to reach 70% and higher immunization levels where herd protection occurs.

Another important aspect of Figure 10 regarding herd protection is that a susceptible individual's protection is not impacted by vaccination. The infection probability of a susceptible individual in a space with an infectious individual is exactly the same regardless of how many other indoor space occupants are immune or susceptible. Comparing Figure 7 and Figure 10 infection probability plots are identical. That is, herd immunity does not mean that a susceptible individual's infection probability is reduced by immunization. Herd immunity or herd protection is a metric that indicates that disease transmission is receding rather than growing. A susceptible individual with comorbidities should continue taking extra precaution protections (high efficiency face mask) until Covid-19 has disappeared from their region.

The predictive estimates above are "collective" assessments, and not directly representative of a specific indoor space. When a coin is tossed, it may land on "heads" 100 times in a row while another coin may land on "tails" 100 times in a row. Statistically, heads or tails is a 50% probability, and it is within that spirit that this analysis should be applied. Quantitative guidelines for particular situations can be developed, but a specific site's experience may be much different. Collectively, providing guidelines for restaurants, gyms, schools, offices, homes, etc that keep Rao below 1 will result in decreasing the spread of SARS-CoV-2.

Carbon Dioxide Field Measurements

Appendix C and Appendix D display carbon dioxide field measurements in several situations. App C are photos of carbon dioxide concentration measured with simple handheld instruments while App D shows longer term monitoring data in different building environments. Note that handheld and desktop carbon dioxide measurement instruments can be purchased for $200 (US) with +/-30ppm accuracy.

The photos in Appendix C are from building environments with no objectionable odors. The bagel shop and BBQ takeout smelled delicious, however, the busy bagel shop has twice as much fresh air flow per person than the BBQ takeout. For short order pickup periods, customers with masks are relatively safe however, susceptible employees have much higher infection probability in the BBQ takeout than employees in the bagel shop if another employee on their shift is infectious.

App C photos for automobiles have "recirculation" and "vent" settings that result in very different interior air quality. Vent setting should always be used in order to bring in sufficient fresh air for driver cognition as well as reduced contagion concentration. Recirculation results in minimal fresh air with unacceptable air quality levels that can impair driver attention and decision making as well as enhanced contagion transmission.

Two App C photos from "Big Box" stores are notable because of carbon dioxide concentrations below 800ppm. Big Box stores tend to have excellent air quality because they know air quality and comfort (temperature and humidity) dissatisfaction leads to fewer customers. At standard building ventilation levels, 20% of the general populace is dissatisfied with air quality, and a significant fraction of the other 80% are not necessarily satisfied.

Two App C photos from a recent hotel stay show carbon dioxide concentration in the reception area and hallways, and in the hotel room after two people stayed overnight. Although reception and hallway concentrations are typical for standard ventilation, hotel room concentrations in the morning indicate no fresh air delivery to rooms. With no infectious room occupants, disease transmission does not occur, however, such high carbon dioxide levels (also typical of bedrooms in homes) does impact sleep quality and next day human productivity (42).

The App C photo from a commercial aircraft flight from Philadelphia to Burlington VT is undesirably high, and likely to result in SARS-CoV-2 transmission with infectious passengers aboard. Airport boarding bridges (connecting hallways between airport gate and aircraft) are a neglected section of airports that often have no active ventilation. As shown in the monitoring data, carbon dioxide reaches high levels during boarding and unloading periods, with boarding reaching higher carbon dioxide and contagion levels due to the slower loading process.

The App C photo from an Illinois Department of Motor Vehicle facility indicates standard ventilation with 1100ppm carbon dioxide. Several Illinois DMV facilities experienced frequent air quality complaints from staff and customers because DMV offices are often located in buildings designed for other applications (stores, offices). Several Illinois DMV facilities have had capital improvements with "DCV" (Demand Control Ventilation) installed that brings in fresh air when carbon dioxide exceeds a threshold (eg, 1000ppm). Monitoring data in App D for a different Illinois DMV facility shows data after installation of a DCV system, showing how carbon dioxide reaches 1000ppm as occupancy increases. As discussed in the paper, a nursing home facility with DCV control set at 1000ppm and no filtration experienced a Covid-19 outbreak (27). Reducing carbon dioxide settings to 800ppm carbon dioxide and ensuring improved filtration (MERV 13 or better) will further improve air quality and reduce infection probability.

Appendix D has carbon dioxide monitoring data from an older "leaky" home built in the 1950s and a high efficiency, certified Passive House that is sealed against infiltration and has a "balanced" ventilation system set at standard residential (ASHRAE 62.2) ventilation standards. Both homes have poor air quality. Note that the Passive House is polluted when occupied, and over-ventilated when unoccupied. The field data also shows the dynamic nature and complexity of managing air quality in buildings. The older home shows very high carbon dioxide in a bedroom with 2 young children, with levels that are indicative of high infection probability for cold viruses as well as higher quanta shedding viruses such as influenza and SARS-CoV-2.

Data from monitoring a 25,000sqft (2320sqm) business shows carbon dioxide levels averaged over a work week (Monday through Friday) and averaged over 6 monitoring stations placed throughout the 125 employee office. The focus of the study (conducted in 2013) was an analysis of employee productivity improvement with increased ventilation. The results indicated increased ventilation would have an estimated increase of annual employee productivity value of $750,000 (US) relative to annual total utility cost of $80,000 (US), indicating the ratio of human value to energy cost. Estimated reduced sick days due to improved ventilation were estimated to be $70,000 (US). The study estimated no significant change to annual utility cost due to increased ventilation.

Appendix D includes monitoring data from a house of worship in which most days of the week have good air quality with low carbon dioxide concentrations. During worship days, carbon dioxide concentrations exceed 2000ppm for the couple hour worship periods, significantly increasing infection probability and building reproduction numbers. One should note that religious leaders and clergy are "front line" essential workers who conduct ceremonies (weddings, funerals), visit the infirm and elderly, and conduct religious services.

Summary and Recommendations

A model has been developed for quantitative estimates of infection probability and building reproduction number based on indoor carbon dioxide concentration (fresh air ventilation), air filtration and air sanitation practices. The model is simple to implement (worksheet computation) and can be used to analyze different indoor environment situations based on occupancy, occupant activities, face mask usage, and occupant status (infectious, immune, or susceptible). The objective is to create indoor environments that lowers SARS-CoV-2 infection probability and reduces building reproductive number, Rao, below 1 for building herd immunity.

Based on systematic investigation over a range of building occupancy and ventilation conditions, the following general recommendations are proposed for building environments:

5) Control fresh air ventilation to maintain 800ppm of carbon dioxide, equivalent to doubling current building fresh air ventilation standards from 20cfm per person (9.4l/s per person) to 40cfm per person (18.8l/s per person)
6) Recirculate indoor air through high efficiency filters (MERV13 or better) with a combination of whole building air recirculation and room space filtration systems. Recirculation air flow levels should be similar to fresh air ventilation levels.
7) Consider adding UVGI (ultraviolet germicidal irradiation) with 0.02Wuv per cfm of recirculation air flow for 85% single pass virus kill efficiency. UVGI adds a "boots-and-suspenders" level of protection to filtration and can be placed inline with filtration systems.
8) Face mask usage is essential while SARS-CoV-2 virus is detectable in a community.

Good fitting face masks with low leakage and high filtration efficiency are important for reaching building reproductive numbers, Rao, less than 1 for SARS-CoV-2. Sustained Rao below 1 will cause Covid-19 to recede.

Herd immunity and high immunity levels within a populace does not protect susceptible individuals from infectious individuals. A susceptible person has the same infection probability in an indoor space with an infectious person whether everyone else is immune or also susceptible. As the disease recedes, susceptible individuals, especially those with comorbidities and inability to be vaccinated, must continue to be alert and wear effective face mask protection.

Finally, recommended levels of increased fresh air flow and improved air filtration and sanitation costs one or two pennies per occupant-hour. Capital spent to improve ventilation systems and enhance building energy efficiency is money spent on jobs within every community. Payback for the proposed improvements occurs from increased human productivity, improved cognition, decreased sick days, and overall improved well-being, independent of pandemic considerations.

Table 1 Relation between carbon dioxide concentration and fresh air flow rate per person through a room (room occupants assumed to be sedentary with 1.2 to 1.5 Met activity level).

Carbon dioxide conc (ppm)	Airflow/person (cfm)	Airflow/person (l/s)
400 (outside)	infinite	Infinite
500	160	75
600	80	38
800	**40**	**19**
1200	20	9.4
2000	10	4.7
3600	5	2.4

Table 2 Representative activity level in Metabolic Units (Met) (ASHRAE 55-2010).

Activity	Met
Sleeping	0.7
Seated, quiet	1.0
Standing, relaxed	1.2
Walking about	1.7
Cooking	1.8
House Cleaning	2.0-3.4
Exercise	3.0-4.0
Heavy exertion	7.0-9.0

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Figure 1 The author visiting the Florence Nightingale Museum in October, 2019.

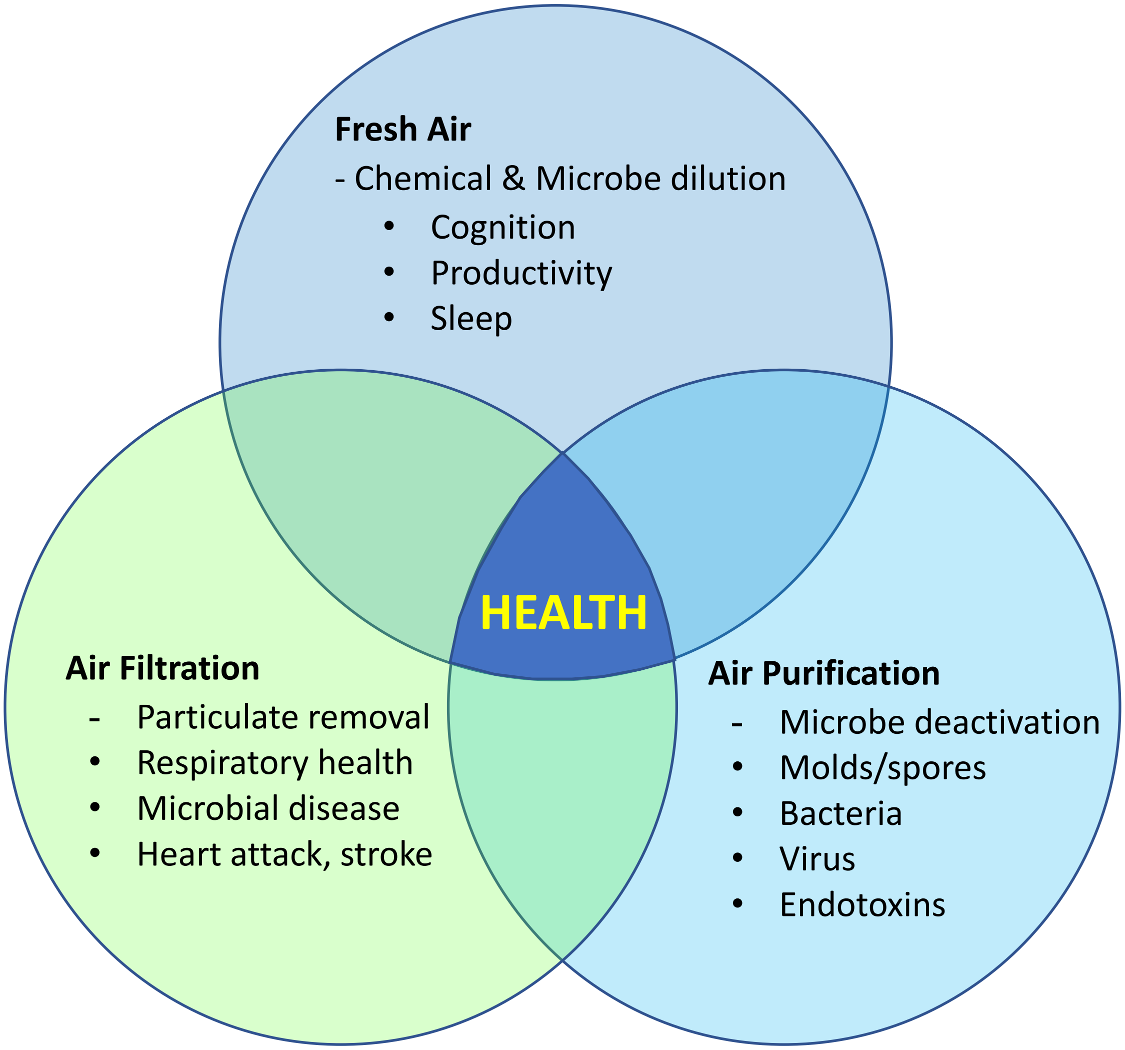


Figure 2 Interrelationship of fresh air, air filtration, and air sanitation processes to create healthy and productive indoor environments.

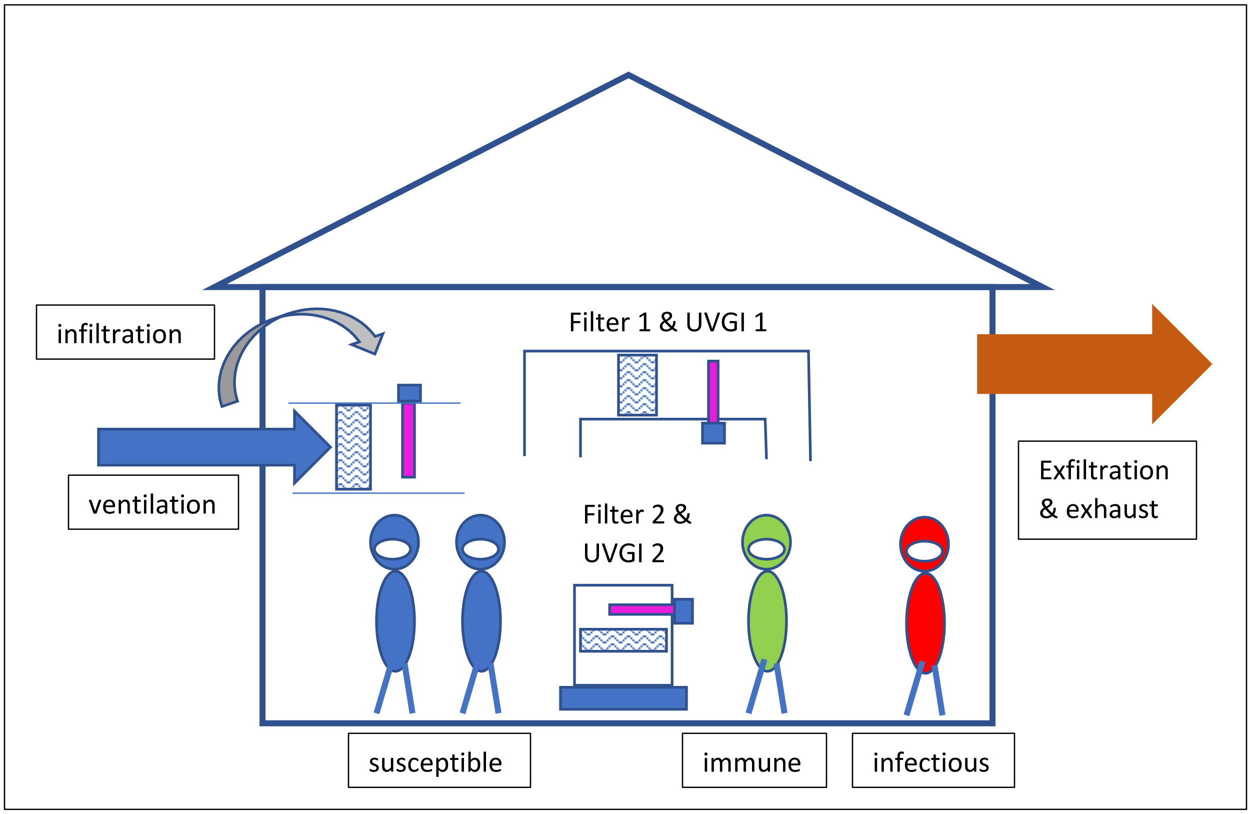


Figure 3 Schematic of indoor environment for generalized contaminant model. A contaminant such as carbon dioxide, particulates, and airborne microbes are impacted by some combination of the processes illustrated.

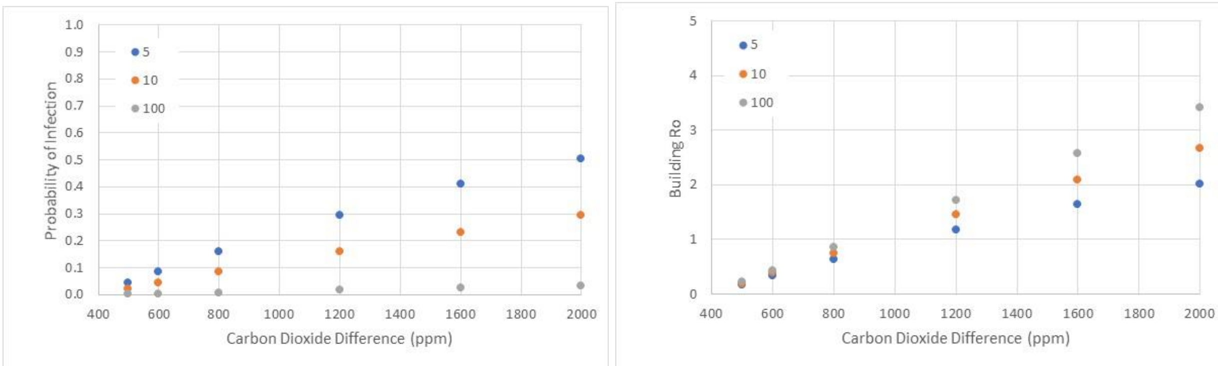


Figure 4 Probability of infection in a building versus carbon dioxide concentration for 1 hour exposure with 5, 10, and 100 occupants (1 occupant infectious and all others susceptible). Note that standard ventilation (1200ppm, or 20cfm fresh air per occupant) is 50% more likely to infect people than 800ppm (40cfm per occupant). More importantly, note that Rao for 800ppm is less than 1 while 1200ppm is greater than 1, indicating self-sustained disease propagation.

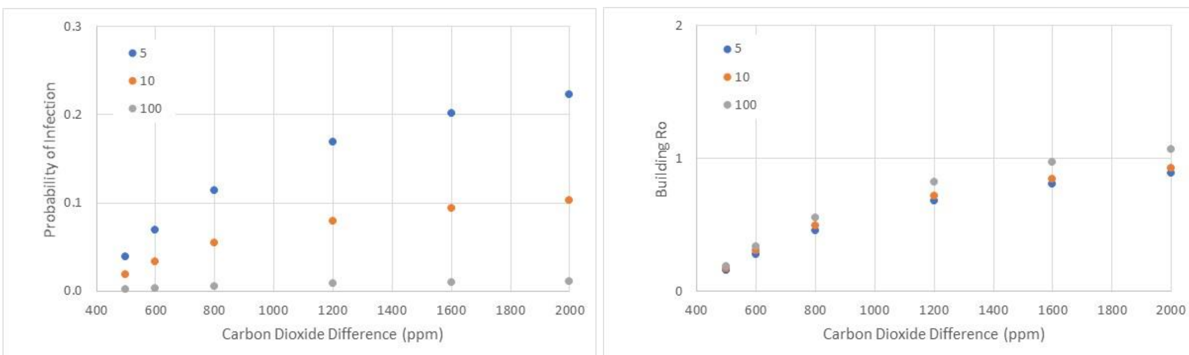


Figure 5 Recirculating air at 25cfm per occupant through a MERV 13 filter reduces infections and reduces infection probability and Rao below 1 for a 1 hour exposure time for the same situation as described for Figure 4.

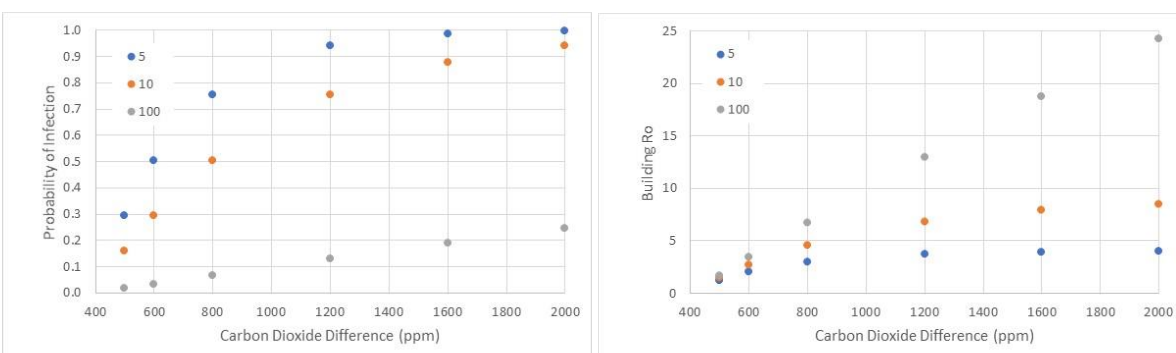


Figure 6 8 hour exposure time with no air recirculation and filtration for 5, 10 and 100 occupants. 800ppm significantly reduces probability of infection compared to standard (1200ppm) ventilation, however, the building reproductive number remains above 1.

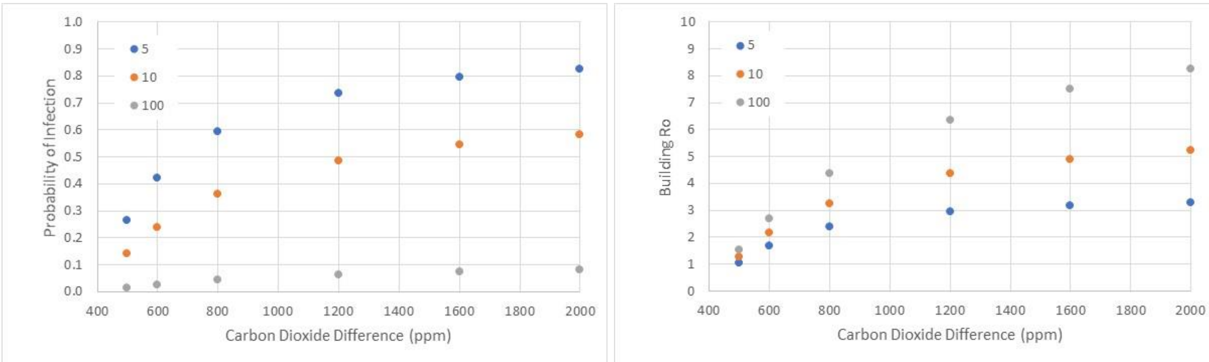


Figure 7 25cfm per person of air recirculation through a MERV 13 filter significantly reduces probability of infection over an 8 hour exposure time, however, building Rao continues to remain above 1 at self-sustaining disease transmission levels.

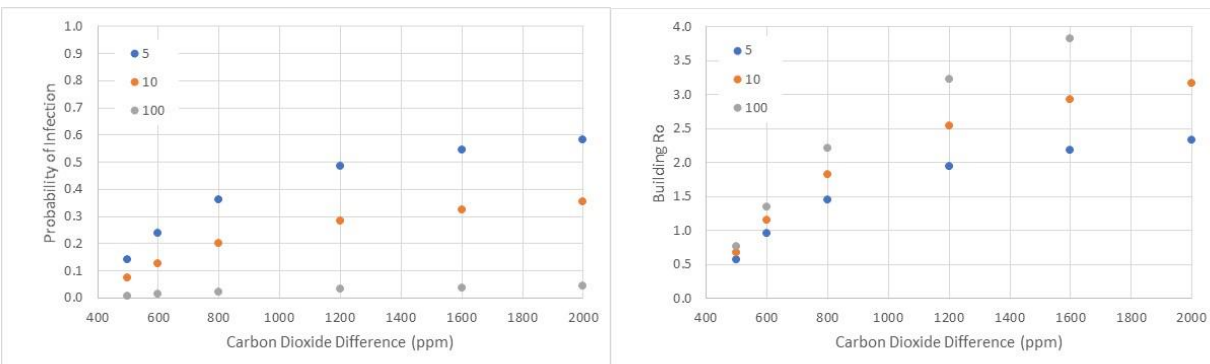


Figure 8 An infectious occupant wearing a 50% effective face mask (susceptible occupants wearing no face masks) further reduces infection probabilities and building Rao from Figure 7 conditions (8 hour exposure, MERV13 filtration). At steady state, the situation is symmetrical when the infectious person wears no face mask, but susceptible persons wear face masks. Face mask virus filtration is assumed to be 50%.

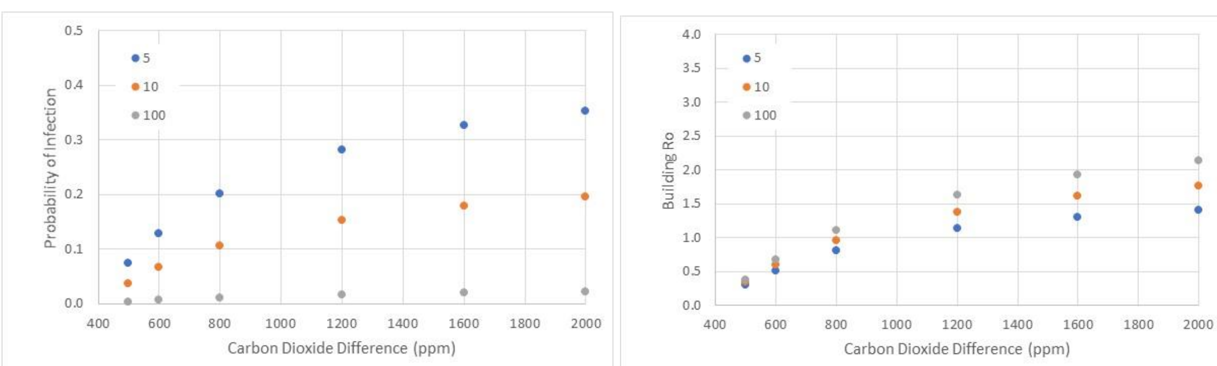


Figure 9 Infectious occupants wearing face masks with 50% exhalation virus capture and susceptible occupants wearing face masks with 50% inhalation virus filtration coupled with 25cfm per occupant of air recirculation through a MERV 13 filter reduces the chance of becoming infected and achieves building Ro of 1 (self-sustained transmission limit) at 800ppm carbon dioxide concentration.

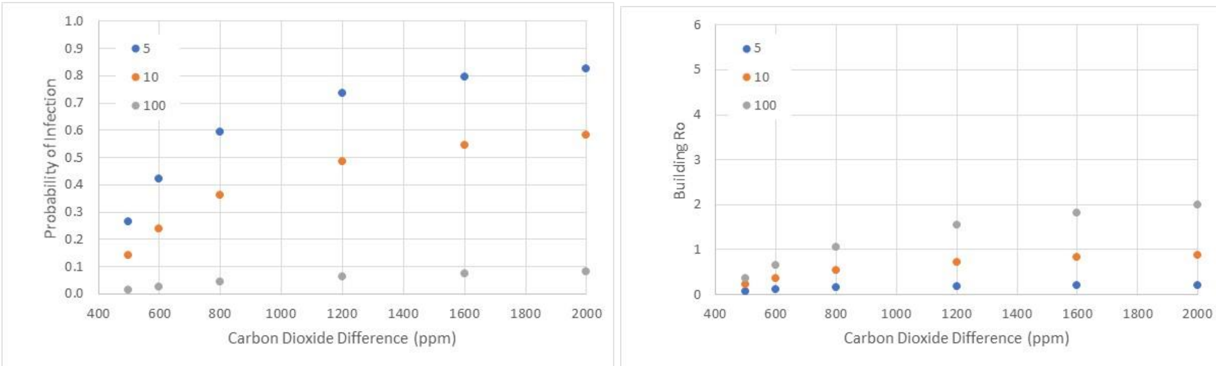


Figure 10 8 hour exposure time with air recirculation at 25cfm per person through a MERV 13 filter and 75% occupant immunity (sum of vaccinations and recovered immunities) does not impact infection probability of susceptible persons (see Figure 7, same case with no immunity). Building Rao is lowed as immunity increases, reducing the ability of a virus to propagate.

Appendix A - Derivation of Infection Probability and Building Reproductive Number Relation

Pollutant concentration inside a building or building space with filtration and air sanitation of a pollutant as shown in Figure 3 can be formulated as:

$$C_R = \frac{(1-f_m f_s)S + C_a V_{iv}(1-n_{fs})(1-n_{uvs}) + C_a V_{ib}(1-n_{fb}) - D}{V_e + V_{r1}(1-(1-n_{fr1})(1-n_{uvr1})) + V_{r2}(1-(1-n_{fr2})(1-n_{uvr2}))}$$

Where

C_R = general room contaminant concentration (eg, ppm, particles/vol, mass/vol)

C_a = outdoor ambient contaminant concentration

D = disappearance rate of contaminant (eg, deposition, decay, absorption, etc)

S = generation rate of contaminant

V_e = exhaust and exfiltration air flow rate (eg, cu ft per minute, liters per second)

V_{iv} = fresh air ventilation flow rate

V_{ib} = fresh air infiltration flow rate

V_{r1} = system 1 air recirculation flow rate

V_{r2} = system 2 air circulation flow rate

f_m = fraction of room occupants wearing facemasks

f_s = facemask exhalation filtration efficiency

n_{fs} = fresh air filtration efficiency

n_{uvs} = fresh air UVGI single pass kill efficiency

n_{fb} = inherent building infiltration filtration efficiency

n_{fr1} = system 1 air recirculation filtration efficiency

n_{uvr1} = system 1 air recirculation UVGI single pass kill efficiency

n_{fr2} = system 2 air recirculation filtration efficiency

n_{uvr2} = system 2 air recirculation UVGI single pass kill efficiency

Applying the generalized steady state relation for carbon dioxide from human respiration, steady state carbon dioxide concentration in an indoor space can be derived. Note that typical air filtration and air sanitation (UVGI) do not affect carbon dioxide. Carbon dioxide concentration can only be reduced by dilution with infiltration and fresh air ventilation.

$$C_{RCO2} = \frac{S_{CO2} + C_{aCO2}(V_{iv}+V_{ib})}{V_e}$$

Where

C_{RCO2} = room carbon dioxide concentration (ppm)

C_{aCO2} = outdoor ambient carbon dioxide concentration = 400ppm

S_{CO2} = carbon dioxide generation rate

V_e = V_{iv} + V_{ib}

And,

$S_{CO2} / V_e =$ (10775ppm-cfm per Met) x ($N \times M / V_e$) (cfm=cubic feet/minute)

Or,

$S_{CO2} / V_e =$ (5064ppm-lps per Met) x ($N \times M / V_e$) (lps=liters/second)

M = Met per person (see Table 2 for metabolic rates)

N = Total number of people (no other sources of CO_2 assumed)

Therefore, expressions for indoor carbon dioxide concentration (in English and SI units) can be found. The expressions assume a reference level of 1.2 Met per person. Indoor activity levels of 1.2 to 1.5 Mets for daytime activities are typical, resulting in 1000 to 1200ppm indoor carbon dioxide concentration with 20cfm per person (9.4l/2 per person) fresh air flow.

$$C_{RCO2} = (10775\text{ppm-cfm per Met}) \times (N \times M / V_e) + C_{aCO2}$$

$$C_{RCO2} = (5064\text{ppm-cfm per Met}) \times (N \times M / V_e) + C_{aCO2}$$

An infectious dose density (quanta per volume) expression can be similarly derived from the generalized, steady state concentration expression.

$$C_{Rq} = \frac{(1-f_m f_{se})S_q \times N_i - D_q}{V_e+V_{r1}(1-(1-n_{fr1})(1-n_{uvr1}))+V_{r2}(1-(1-n_{fr2})(1-n_{uvr2}))}$$

Where

C_{Rq} = infectious dose (quanta) per volume

S_q = quanta shedding per hour per infectious person

N_i = number of infectious persons

D_q = decay and deposition rate of infectious dose (quanta per hour)

f_m = fraction of room occupants wearing facemasks

f_{se} = face mask exhalation filtration efficiency

Substituting indoor carbon dioxide concentration relation into infectious dose density relation results in an expression between infectious dose density (quanta per volume) and carbon dioxide (ppm), shown in English units and SI units.

$$C_{Rq} = \frac{((1-f_m f_{se})S_q \times N_i - D_q)\ (1\text{hr}/60\text{min})}{10775\text{ppm-cfm per Met} \times NxM/(C_{RCO2}-C_{aCO2})+V_{r1}(1-(1-n_{fr1})(1-n_{uvr1}))+V_{r2}(1-(1-n_{fr2})(1-n_{uvr2}))}$$

= quanta per cubic ft

Where air flow rate terms are in cfm

$$C_{Rq} = \frac{((1-f_m f_{se})S_q \times N_i - D_q)\,(1hr/3600sec)}{5064ppm\text{-}lps \text{ per Met} \times N \times M/(C_{RCO2}-C_{aCO2})+V_{r1}(1-(1-n_{fr1})(1-n_{uvr1}))+V_{r2}(1-(1-n_{fr2})(1-n_{uvr2}))}$$

= quanta per liter

Where air flow rate terms are in liters per second

The probability of infection, following Rudnick and Milton (1), is described by amount of infectious dosage inhaled by a susceptible person.

$P = 1 - \exp(B\, C_{Rq}\, t\, (1 - f_m f_{si}))$

Where

C_{Rq} = infectious dose (quanta) per volume
B = breathing rate (volume per time)
t = exposure time
f_m = fraction of room occupants wearing facemasks
f_{si} = face mask inhalation filtration efficiency

Also, following Rudnick and Milton (1), the building reproductive number is expressed as:

$R_{ao} = (N_s + (1-e_v)N_v)P / N_i$

R_{ao} = building reproductive number
N_s = susceptible (unvaccinated) building occupants
N_v = vaccinated building occupants
N_i = infectious building occupants
N_r = recovered (assumed immune) building occupants
e_v = vaccine efficacy

The total number of building occupants is related to the sum of infectious, vaccinated, recovered and susceptible persons.

$N = N_i + N_v + N_r + N_s$

Total occupants = sum of infectious, vaccinated, recovered (immune) and susceptible

Appendix B – Estimate of Virion Shedding Rate

Lednicky, et al (22) provide information on airborne infectious viral particles contained in a hospital room with two SARV-CoV-2 patients. The general pollutant concentration relation can be used to estimate the virus shedding rate from the patients, providing insight to the relation between virus concentration and infectious dosage.

Rearranging the pollutant concentration relation, we can solve for the virion respiratory shedding rate per infectious person for the hospital room.

$$S_q \times N_i = C_{Rq} \times V_e \times [1 + (V_{r1}/V_e) \times (1-(1-n_{fr1})(1-n_{uvr1}))] \sim C_{Rq} \times V_e$$

Total air flow is described as 6ACH (Air Changes per Hour) (22), which is estimated to be 212cfm (100liter/second) based on estimated room dimensions. 90% of the air exchange rate is recirculated, passing through high efficiency filtration and UVGI, with an estimated kill and removal level of 100%. Fresh air flow is the remaining 10% of the total airflow.

Lednicky et al (22) measured up to 74 infectious viral copies per liter of room air. If one patient is not shedding virus, then all viral copies are from the other. If both patients are equally shedding virus, then half of the captured virus particles are from each patient.

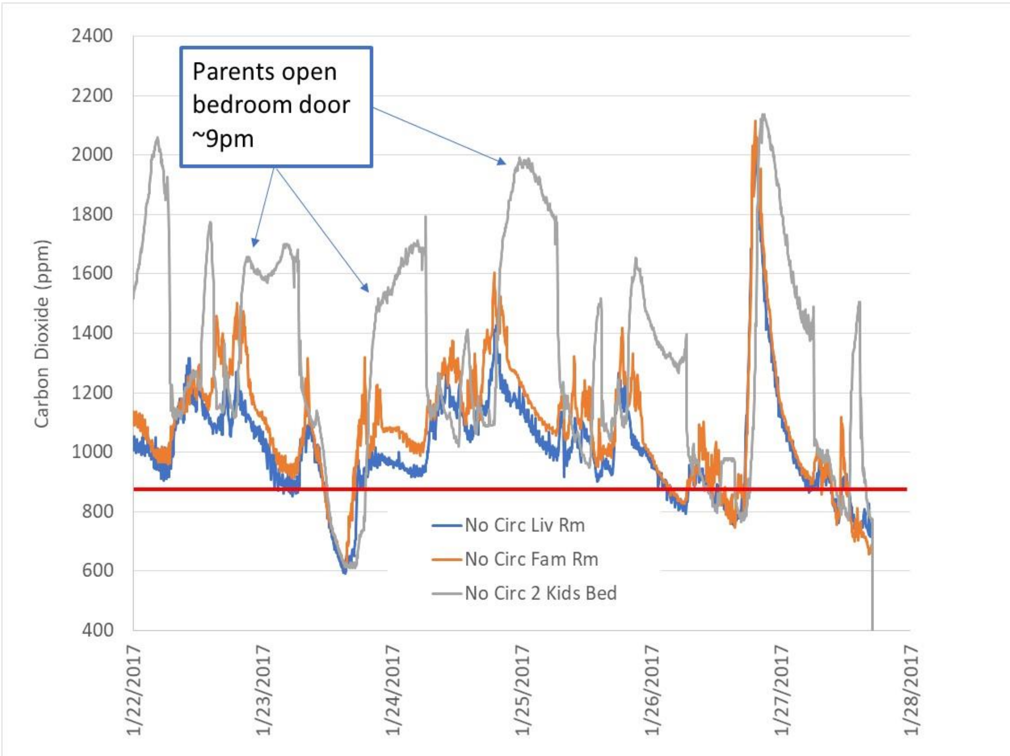
The above relation estimates 740 viral copies per second are released into the room. For two patients equally shedding virus, viral shedding is 370 copies per second, and if only one is shedding virus, shedding is 740 copies per second, with the actual shedding per patient between these bounds if both are shedding at differing rates.

If the viral shedding rate results in an infectious dosage of 100quanta per hour, which we do not know but assume in the spirit of understanding order of magnitude relation between viable virus shedding rates and infectious dosage rates, we find 13,000 to 26,000 viral copies per quanta.

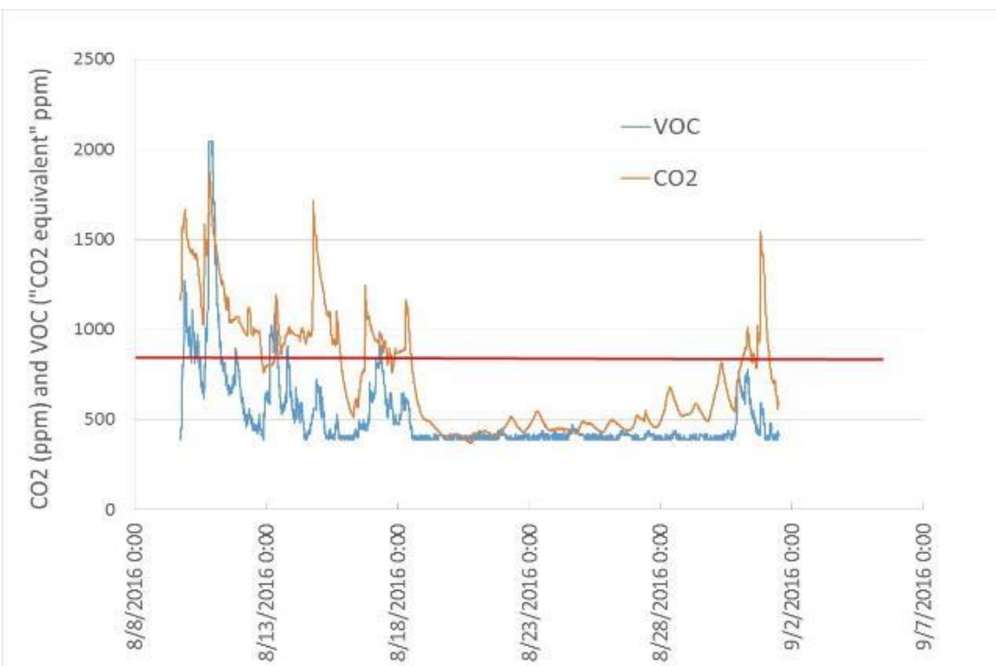
Appendix C – Photos of carbon dioxide concentration in a variety of indoor environments.

Carbon dioxide concentration readings in several venues. Do you think your nose can tell you which ones have sufficient fresh air? Are you willing to risk your health on it?

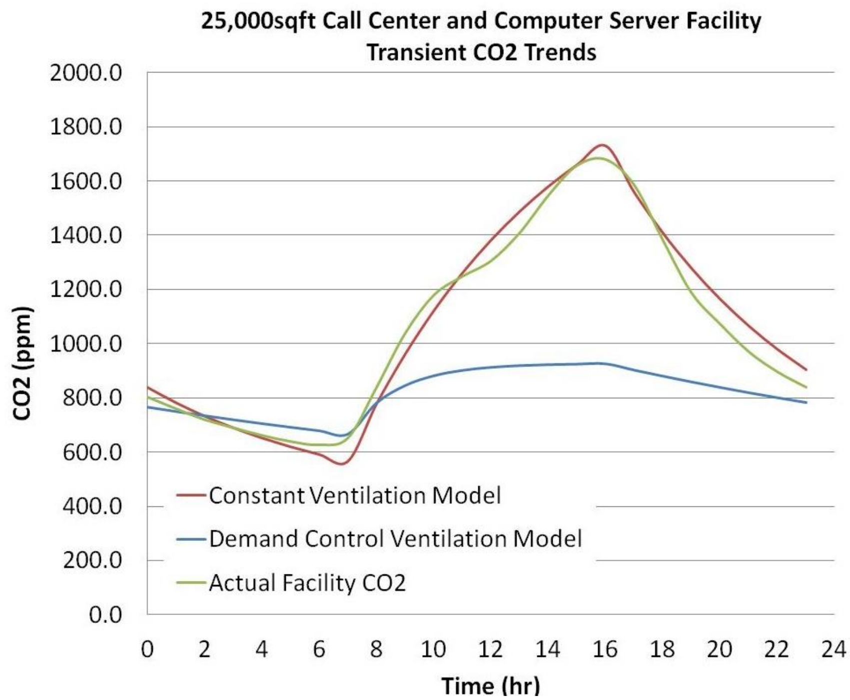
Appendix D – Carbon Dioxide Field Data for Several Situations Collected by the Author



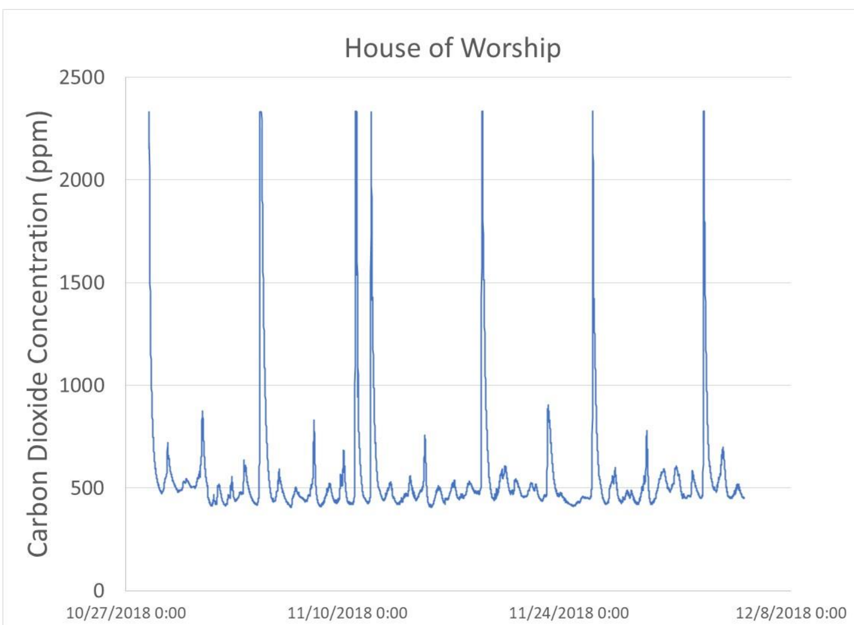
Carbon dioxide concentration in “leaky”, 1950s era house is too high, especially in bedrooms.



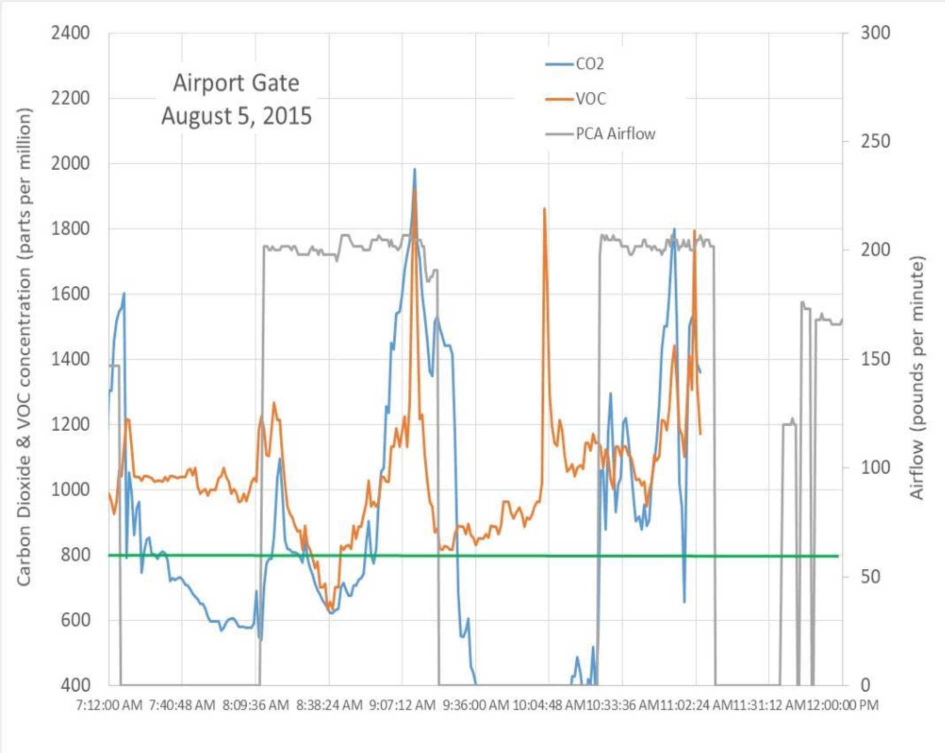
Carbon dioxide in certified Passive House is just as poor as in the leaky, 1950’s house because of inadequate ventilation standards (0.3ACH). Excessive pollutants when occupied and over-ventilated when unoccupied.



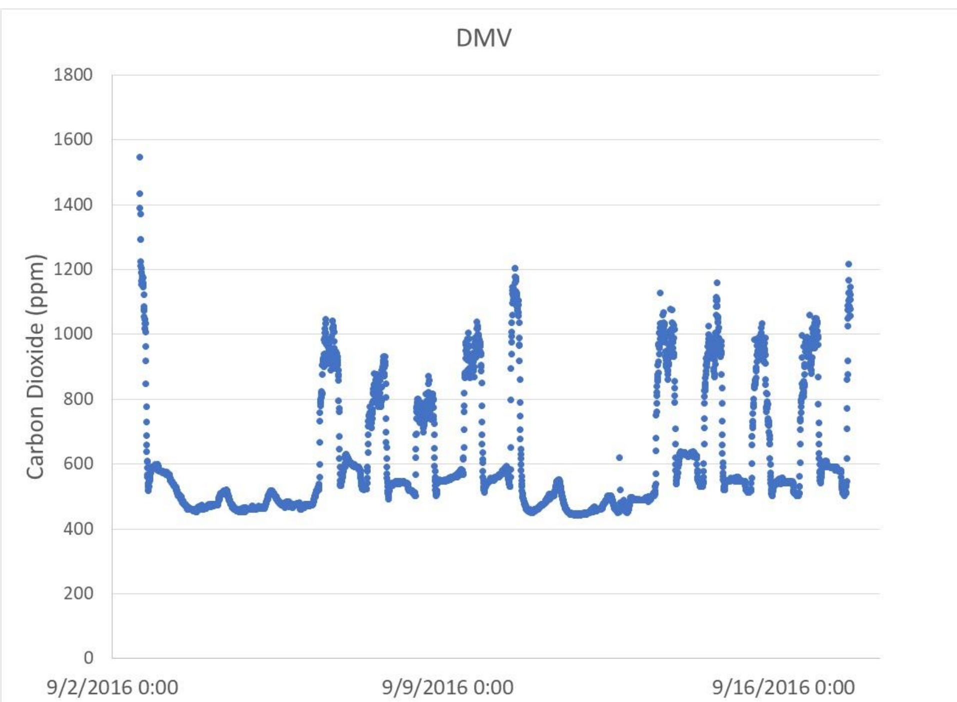
Average of 5 weekday carbon dioxide measurements from 6 monitoring stations located in the 25,000 square foot office environment business. Improved ventilation the maintains 800-900ppm carbon dioxide concentration are estimated to decrease sick day cost by an amount equivalent to annual utility cost, improve productivity by a value 10 times annual utility costs, and have <u>no</u> impact on annual utility costs and not require significant capital cost.



House of worship gatherings are often not designed for proper ventilation during worship services, resulting in Covid-19 super-spreading. Furthermore, clergy are frontline workers who frequently interact with people in high risk environments such as nursing homes, hospitals and prisons.



Airline boarding bridges, such as this one at a major US airport, often have very poor ventilation. Loading has worse IAQ than unloading periods.



An Illinois Department of Motor Vehicles (DMV) building with DCV (Demand Control Ventilation) that increases fresh air when carbon dioxide concentration increases above 1000ppm.