Effect of Ventilation And Filtration on Viral Infection in Residences

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What should people do in their homes regarding HVAC system operation during a pandemic? According to the CDC, "COVID-19 is thought to spread mainly through close contact from person-to-person. Some people without symptoms may be able to spread the virus. We are still learning about how the virus spreads and the severity of illness it causes."[1] The SARS-CoV-2 virus is transmitted via airborne routes[2] and has been detected in HVAC systems.[3] The risks of airborne infection for residential scenarios with an infected person can be quantified for purposes of comparing alternative HVAC approaches. In this article, an evaluation method is proposed for comparing actions to take for HVAC systems to decrease the risk of viral infection within residences using a median single-family U.S. residence with central HVAC.

The basic recommendations from ASHRAE regarding residential HVAC can be accessed on the ASHRAE website.[4] These recommendations should not be construed to replace the advice of the Centers for Disease Control and Prevention (CDC), World Health Organization (WHO) or other health authorities. A calculated relative risk of airborne infection for comparison of the effectiveness of various ventilation or filtration options is presented here. Generally, more ventilation and enhanced filtration are recommended by ASHRAE and other organizations. What is the range of impact of relatively simple low-cost interventions in a residential setting to decrease the risk of COVID-19?

COVID-19 is caused by the SARS-CoV-2 virus. According to WHO, the virus can be transmitted by "contact, droplet, airborne, fomite, fecal-oral, blood-borne, mother-to-child and animal-to-human transmission."[5] HVAC is assumed to have little to no effect on any transmission mode other than airborne. People can be infectious without showing symptoms

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(asymptomatic).[6] We examine cases when infection is known, and when infection is unknown. The risks in the home are increased without social distancing and cannot be reliably calculated. COVID-19 risks are evaluated in this paper using the tool provided by Jose Jimenez[7] that uses a modified Wells-Riley calculation.

The scenarios evaluated are presented in *Table 1*.

TABLE 1 Summary of scenarios evaluated.

Infection is Unknown	Risk in bedroom (Case 1)	Susceptible person shares a bedroom with infected person	1. Sleeping 2. Awake before and after going to sleep
	Risk in open area (Case 2)	Infected household member spends time in living room (no knowledge of infection of any household member)	6 hours
	Risk in open area (Case 2)	A visitor comes to the house (no knowledge of infection of any household member)	1. 2 hours 2. 4 hours
Infection is Known	Risk in bedroom (Case 3)	Susceptible person goes into an isolated room (negative pressure) of the infected person	Awake – caregiver spends 30 min
	Risk in rest of the house (Case 4)	Infected in isolation room 24-hour period, susceptible people are in rest of house (no direct contact)	1. Awake – 16 hours 2. Sleeping – 8 hours
	Risk in rest of the house (Case 4)	Infected in isolation room 24-hour period, susceptible people are in rest of house (no direct contact) + air cleaner in infected room	1. Awake – 16 hours 2. Sleeping – 8 hours
	Risk in rest of the house (Case 4)	Infected in isolation room 24-hour period, susceptible people are in rest of house (no direct contact) + air cleaner in rest of house	1. Awake – 16 hours 2. Sleeping – 8 hours

Residences

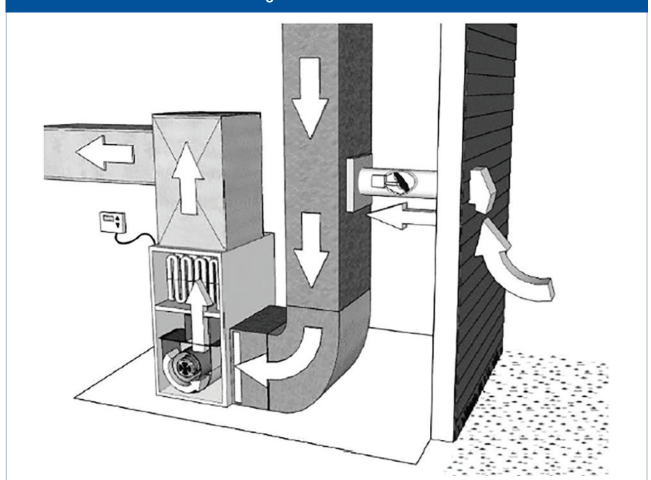
In the U.S.[8] as of 2017, residential structures were comprised of 86 million single-family, 29 million multifamily and 7 million other types of dwellings (including manufactured, trailer, RV, boat, etc.). For this evaluation, a single-family residence is considered. Other structures would be expected to have similar risk graphs, but different risk numbers. Generally, more infected people present, longer exposure time or smaller enclosed spaces will result in higher risks.

Many construction types in the U.S. exist for single-family residences, and many options exist for HVAC. For the same square footage a wide range of number of rooms may exist. Some houses are one month old, and some are more than 100 years old. An estimated median house is evaluated here. More specific evaluations may be performed by engineers for any specific structure using the process presented here. The model assumes uniform mixing throughout the house unless a space is intentionally converted to an isolation room.

The area of a single-family residence is assumed to be 2,200 ft^2 (204 m^2). It is assumed there is a central heating and air-conditioning system and that windows are operable. An air change rate per hour (ach) of 0.35 with the outdoors is assumed. This rate is representative of a system that would comply with the minimum ventilation required by ASHRAE Standard 62.2-2019. In this evaluation, a central system is assumed to supply well-mixed air in the spaces. A ventilation rate of 1 ach is illustrated for comparison and will require larger fans and perhaps greater HVAC system capacities. 1 ach may also be achieved by opening windows, but determining how much opening is required is beyond the scope of this evaluation.

For illustration of an up-to-date HVAC system, it is assumed that the ventilation air is brought in through the air handler and is filtered by the HVAC filter as illustrated in *Figure 1*. Other configurations of ventilation in residences will not affect the outcome, as the outdoor air is assumed to be free of SARS-CoV-2 viruses (i.e., filtration has no effect on zero concentration).

FIGURE 1 Residential HVAC configuration.[9]



When climate conditions permit, open windows will usually provide more ventilation than residential mechanical systems. In many parts of the U.S. for many months of the year, however, open windows do not allow the heating and cooling systems to provide comfortable conditions. Because ventilation through open windows is climate limited and natural ventilation rates are highly variable depending on open area, wind velocity and temperature differentials, open windows are not evaluated here as an independent option.

HVAC System Characteristics

For central HVAC systems, the fan can be run continuously by switching to fan-on mode on the thermostat. If not switched to "on," the fan runs when heating or cooling is needed based on the thermostat setting (unless it is programmed to run on a schedule). Because the HVAC is a protection system, for this evaluation assume the fan runs 100% of the time to obtain maximum benefit of the filter. The fan with the filter is like the mask for your house; it doesn't work if it's not on.

Filters

The level of filtration can be improved by purchasing higher-rated filters. In the U.S., filters are rated by MERV[10] ranging from MERV 4 to MERV 16, with higher numerical ratings indicating better filtration. Typical residential filters are MERV 4. Better filters commonly available to consumers include MERV 7, MERV 8 and MERV 11. Filters higher than MERV 11 are specialized and may not be suitable for installing in many residential HVAC systems because of higher pressure drop (resistance to airflow that cannot be overcome by the fan). In this case, we assume that the filter face velocity is 250 fpm (1.3 m/s) for which MERV 8 and MERV 11 filters are available with an initial pressure drop of 0.1 in. w.c. (25 Pa) or lower.

Many residential central HVAC systems have a total fan pressure capacity of 0.5 in. w.c. (125 Pa),[11] which must include the filters, coils and ductwork. Some low pressure drop filters rated higher than MERV 11 may be available; however, caution is advised since pressure drop is velocity dependent, and filter face velocity in residential HVAC can range from 160 fpm to 500 fpm (0.8 m/s to 2.5 m/s).[12] A hypothetical example for a MERV 14 filter is illustrated in case one can find such a filter with acceptable pressure drop. The filter efficiency is taken from Stephens[13] based on the size distribution of viral particles and shown in *Table 2*.

TABLE 2 Assumed filter efficiency by MERV. This filter efficiency assumes the following particle size distribution: 15% are 0.3 μm – 1 μm, 25% are 1 μm – 3 μm, and 60% are 3 μm – 10 μm.

MERV	0.3 μm – 1 μm	1 μm – 3μm	3 μm – 10 μm	DROPLET NUCLEI-WEIGHTED η_{FILTER}
4	1%	9%	15%	11%
7	17%	46%	50%	44%
11	30%	65%	85%	72%
13	70%	90%	90%	87%
14	80%	90%	90%	89%
15	90%	90%	90%	90%
16	95%	95%	95%	95%
HEPA	99.90%	99.90%	99.90%	99.90%

Ventilation

Ventilation for residences is specified by ASHRAE Standard 62.2-2019.[14] Ventilation may be provided by mechanical ventilation, exhaust systems, infiltration or a combination. The relevant effect on exposure in this case is air changes with the outdoors with an implicit assumption that no infectious particles are brought in from the outdoors. The term "air change" is the variable used in the model and will be used to describe ventilation.

Portable Air Cleaning

Stand-alone portable air cleaning devices are rated in terms of clean air delivery rate (CADR) by the Association of Home Appliance Manufacturers (AHAM).[15] Certified ratings are similar to those used in commercial applications such as AHRI or AMCA. Manufacturer's claims about effective square foot coverage are not the same as a certified CADR. CADR rates the measured **system** effectiveness, which is often not the same as an assumed cfm multiplied by an assumed filter efficiency. Filters or devices without MERV or CADR ratings are not recommended because no basis exists for comparison or assurance of performance. For more information on residential filtration, including information on ozone and other "purifiers," please refer to the "ASHRAE Position Document on Filtration and Air Cleaning,"[16] the "EPA brochure Residential Air Cleaners,[17] and EPA web pages.[18,19,20]

Infection Risk

One often-used approach to estimate the risks associated with airborne transmission of respiratory diseases is the Wells-Riley model. The Wells-Riley model is based on a concept of "quantum of infection," whereby the rate of generation of infectious airborne particles (or quanta) can be used to model the likelihood of an individual in a steady-state, well-mixed indoor environment being exposed to the infectious particles and subsequently succumbing to infection. In this work, we used the COVID-19 aerosol transmission estimator tool developed and published by Jose Jimenez of the University of Colorado-Boulder.[7] The calculator is calibrated to COVID-19 per recent literature on quanta emission rates. The model does not include droplet or contact/fomite transmission and assumes that 6 ft (2 m) social distancing is respected. This model does not include transmission to the people present when they are in locations other than the one analyzed here.

Results

We show the results of infection risk in absolute numbers (top of the graph or tables), and we explored trends in risk reductions for each case using a measure of relative risk as shown in the bar charts. Relative risk values use the baseline of the HVAC system not running (case where thermostat is satisfied), no ventilation, no filtration, no infiltration. Each relative risk is calculated as the probability of infection with a particular filter installed and for a certain ach divided by the probability of infection for the baseline. For example, a relative risk of infection of 0.8 provides 20% reduction of risk over the baseline.

The following improvement over baseline is considered for the different scenarios: HVAC system running 100%, 0.35 ach and 1 ach and MERV 4, MERV 7, MERV 11 and MERV 14. For some scenarios, we explore masks and portable air cleaners' effect on risk reduction. We are assuming people will not wear masks at home when no known infection exists (Case 1 and Case 2). In all cases the highest risk of infection is in the space with the infected person (the source). The risks for other than those spaces addressed are not the same.

Case 1: Susceptible Person Shares a 200 ft^2 (18.6 m^2) Bedroom With Infected Person (Infection is Not Known)

What is the risk to the susceptible household member?

Scenario 1: Sleeping—8 hours.

1. Resting (Oral Breathing) = 2 quanta/hour

Scenario 2: Awake before and after sleeping—2 hours

1. Resting (Speaking) = 9.4 quanta/hour
2. Standing (Loudly Speaking) = 65.1 quanta/hour

Results: *Figure 2* shows the relative risk of airborne infection from sleeping in a bedroom with an infected person (Scenario 1). Merely running the fan on the air-conditioning system lowers the risk by one-third.

FIGURE 2 Relative risk of infection in bedroom, sleeping for 8 hours. Data labels show the comparison relative to the baseline case (no HVAC system running, no ventilation, no filtration, no infiltration).

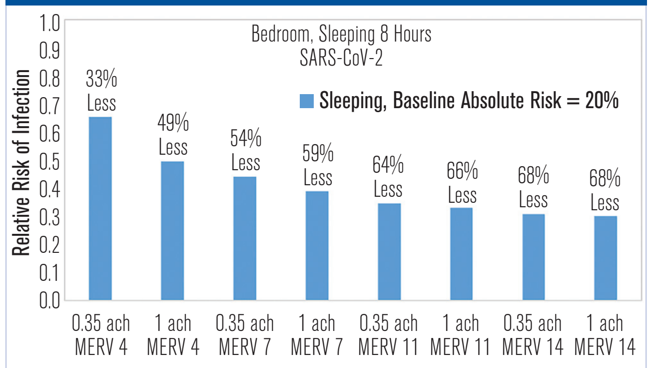
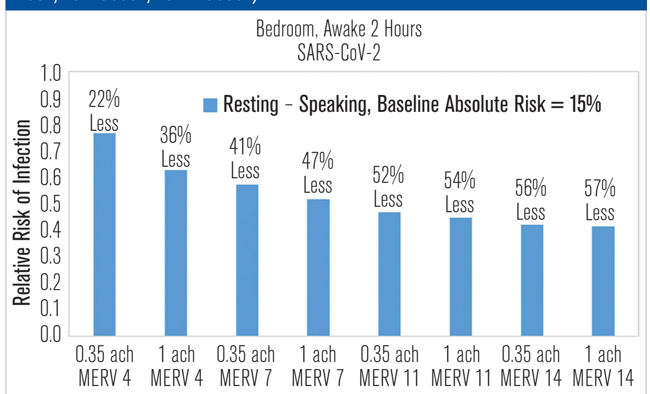


FIGURE 3 Relative risk of infection in bedroom, awake for 2 hours. Data labels show the comparison relative to the baseline case (no HVAC system running, no ventilation, no filtration, no infiltration).



Improving the filtration in the system can lower the risk by two-thirds.

Figure 3 shows the effect of awake time in the bedroom (Scenario 2). In this case the infected person is assumed to be speaking during the two-hour time period. Improvements in filtration can cut the risk in half.

The baseline risk of not running the HVAC system at all is 20% for sleeping for 8 hours and 15% for talking for 2 hours. More activity by the infected person increases risk. In this case talking loudly in the bedroom for 2 hours would increase the risk to 67%—or more than four times higher risk to the well person than normal talking.

Case 2: Infected Person Spends Time With Other Household Members or a Visitor in a 500 ft^2 (46 m^2) Open Area (Infection is Not Known)

What is the risk to the other household members? Open or common areas are in most houses built in the last 50 years, and they usually feature the kitchen opening into a family room or a living room. The open area is assumed to be 500 ft^2 (46 m^2) although it could be larger or smaller.

Scenarios: Time spent = 6 hours, simulating a stay-at-home or school-from-home scenario.

1. Resting (Speaking) = 9.4 quanta/hour
2. Resting (Loudly Speaking) = 60.5 quanta/hour

Results: *Figure 4* shows a significant increase in risk from greater activity. As in the bedroom scenario, the risks are reduced by just running the HVAC fan with a MERV 4 filter. With more infectious quanta expelled into the air with the higher activity, the HVAC system cannot have as much beneficial effect.

To quantify the impact of different activities for the same exposure time, we run the model for an exposure time of 2 hours doing the following:

1. Resting (Speaking) = 9.4 quanta/hour
2. Resting (Loudly Speaking) = 60.5 quanta/hour
3. Light Exercise (Loudly Speaking) = 170 quanta/hour
4. Heavy Exercise (Loudly Speaking) = 408 quanta/hour

Results: *Figure 5* illustrates the increases in risk from more activity over a 2-hour period. This could be a neighbor who is socializing or friends of household members talking. The volume of the speaking depends on the friends, their ages or local norms. Light exercise could be dance practice, singing or cheerleading. Heavy exercise could result from some sort of major repair work or a serious workout. *Figure 5* illustrates the baseline risk from no HVAC system running and with the HVAC running at 0.35 ach and with MERV 11 filters. These risks are shown as percent absolute risk and illustrate that higher quanta emissions result in significantly higher risks. Visit https://tinyurl.com/yxer2364 to see the values that are input to achieve one of the absolute risk values illustrated in *Figure 5* using the Jimenez spreadsheet. The increase in quanta overwhelm the beneficial ventilation dilution and cleaning of the recirculated air. In the extreme situations, residential HVAC cannot overcome the intensity of the infectious quanta in the air (i.e., one is more likely than not to become infected). However, in all cases it is beneficial to have the HVAC running.

FIGURE 4 Relative risk of infection in open area.

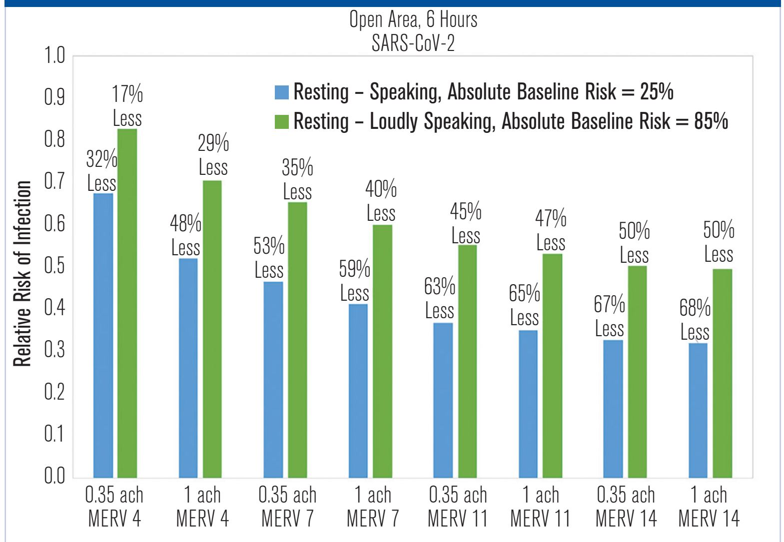


FIGURE 5 Absolute infection risk comparing different activities.

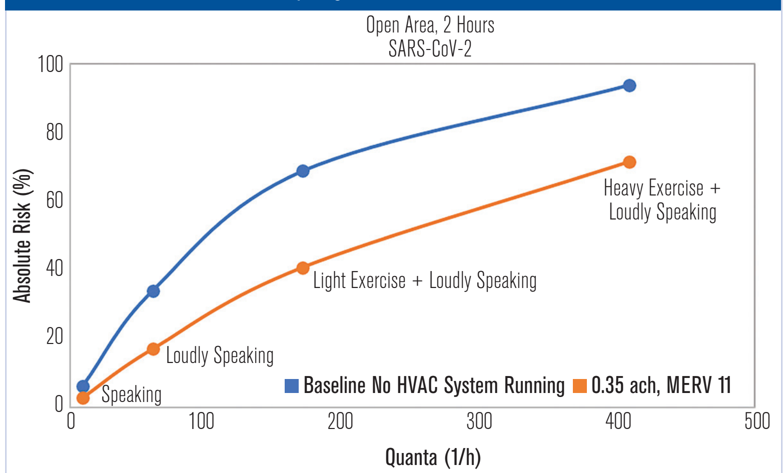
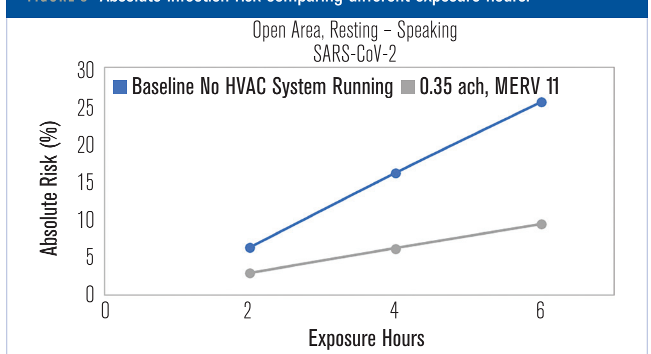


FIGURE 6 Absolute infection risk comparing different exposure hours.



As expected, spending less time with an infected person will decrease the risk of exposure. *Figure 6* shows a comparison between different times of exposure (2 hours, 4 hours, and 6 hours). *Figure 6* illustrates the baseline risk from no HVAC system running and with the HVAC running at 0.35 ach and with MERV 11 filters. These risks are shown as percent absolute risk and illustrate that higher exposure time results in significantly higher risks. All risks decrease when adding ventilation and filtration. For the cases evaluated (including all the filtration/ventilation options), doubling the exposure time from 2 hours to 4 hours leads to a 2.2 times increase in risk. Compared to the risk at 2 hours, 6 hours leads to about 3.4 times increase in risk.

FIGURE 7 Relative risk of infection when infected in isolation room, Resting – Speaking.

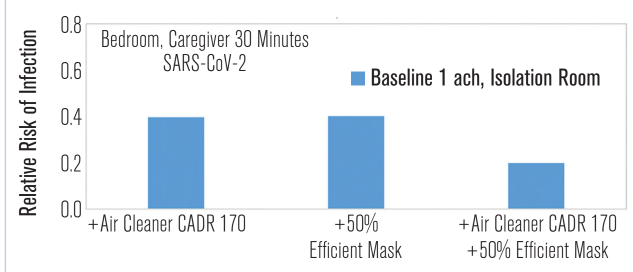
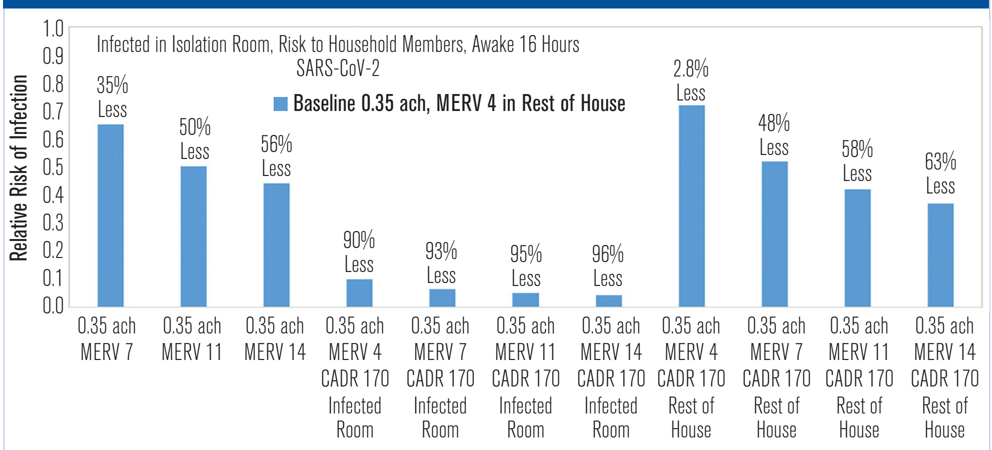


FIGURE 8 Relative risk of infection in rest of house.



Case 3: Infection is Known, and The Infected Person is in an Isolated Room (Bedroom 200 ft^2 [18.6 m^2]) Per ASHRAE COVID-19 Recommendations. a Caregiver Goes Inside the Infected Person's Room for 30 Minutes

What is the risk to the caregiver when entering the isolation room? This would be isolation according to the CDC. Assuming the bedroom is set up per the recommendations of ASHRAE for an isolation space, the risks to the noninfected individual(s) improve by isolating the room from the HVAC system and exhausting the room.

Scenarios: Time spent = 30 minutes

1. Resting (Speaking) = 9.4 quanta/hour
2. Resting (Speaking + 50% Efficient Mask) = 4.7 quanta/hour
3. Resting (Speaking + Air Cleaner With CADR 170) = 9.4 quanta/hour
4. Resting (Speaking + 50% Efficient Mask + Air Cleaner With CADR 170 = 4.7 quanta/hour

Results: *Figure 7* illustrates a comparison of decrease in risk when adding a portable air cleaner that has a CADR of 170 to the infected person's room and/or using 50% efficient masks. For the baseline, we assume a separate HVAC system is used for the isolation zone. Any grille connecting the isolation space to the rest of the home is sealed. The space includes a private restroom with an exhaust fan; that fan is running continuously at high speed. We estimate an air exchange rate of 1 ach: a 25 cfm (12 L/s) bathroom fan will provide about 1 ach for the bedroom assuming air is exhausted directly through the attached bedroom and other exhaust air pathways are closed. The HVAC in the rest of the house is always on.

In the case of the portable air cleaner, it is added to the infected person's room. Although it may be counterintuitive to clean the bedroom air, it does seem logical to contain the infectious particles at or near the source. The air cleaner is assumed to have a flow of 191 cfm (90 L/s) and an efficiency of 89%.

The results show using a portable air cleaner in the infected person's room will halve the risk. Wearing a 50% efficient mask will have the same impact as operating a portable air cleaner with a CADR of 170. Operating a portable air cleaner and wearing a mask will decrease the risk by four times. This emphasizes that even with isolation modifications, additional protective actions including face coverings are essential to protecting the caretaker from airborne aerosols. More information is on the CDC website (see "Caring for Someone Sick at Home," https://tinyurl.com/y3u6w3kq).

Case 4: Infection is Known, and the Infected Person is in an Isolated Room (Bedroom 200 ft^2 [18.6 m^2]) Per ASHRAE COVID-19 Recommendations

What is the risk to the other household members (the effect on the quantity of infected particles that could be transmitted to other parts of the house)?

Scenario 1:

Time Spent = 16 hours

1. Awake (Resting)
2. Awake (Resting + Air Cleaner With CADR 170 in Infected Room)
3. Awake (Resting + Air Cleaner With CADR 170 in Rest of the House)

Scenario 2:

Time spent = 8 hours

1. Sleeping (Resting)
2. Sleeping (Resting + Air Cleaner With CADR 170 in Infected Room)
3. Sleeping (Resting + Air Cleaner With CADR 170 in Rest of the House)

It is assumed that the quanta generated for Awake (Resting) is 9.4 quanta/hour, the same as Awake (Speaking), and that the quanta generated for Sleeping is 2 quanta/hour.

Similar to Case 3, the ach in the infected room is 1. We assume leakage to the rest of the house is 1 cfm (0.5 L/s) during the day and 0.3 cfm (0.1 L/s) during the night. The assumption is that even though the isolation room is under negative pressure from a bathroom fan, the isolation room will leak 1 cfm (0.5 L/s) into the other rooms in the house from inadequate sealing and leakage from doors opening. A study by Lawrence Berkeley National Lab and California Department of Health Services[21] showed that for a negatively pressurized smoking room the volume of air from opening and closing a door (door pump) was 672 L or 24 ft^3 [0.7 m^3].

If the door is opened twice per hour or if the sealing of the residential bedroom is not as good as the lab then a 1 cfm (0.5 L/s) leak would be conservative. When 1 cfm (0.5 L/s) leaks back into the house from the isolated bedroom, the quanta released to the house will be dependent upon the concentration of quanta in the bedroom. The quanta in the bedroom are the highest because the source is in the bedroom. Even if the leakage rate is doubled, tripled or quintupled because the tape came off the supply air grille or someone left the door open, placing the capture device nearer the source improves the risks in other areas of the house. We assume that the AHU in the rest of the house is always on.

Results: *Figure 8* (Page 43) illustrates a risk of infection relative to a baseline risk of 0.35 ach and a MERV 4 filter in the rest of the house when awake (Scenario 1). Results show that adding an air cleaner in the infected room will lead to significantly less risk than placing an air cleaner in the rest of the house due to a lower quanta. As shown before, improving the central filtration level decreases the risk of infection. At 0.35 ach, a MERV 7 filter is more effective than an air cleaner with CADR 170 + MERV 4 filter.

The results are the same for sleeping scenario (Scenario 2).

A Process for Engineers to Evaluate a Specific House

To evaluate a specific house for the optimal investment or modifications for reducing infection risk, the following process is recommended.

1. Evaluate the actual pressure capability of the fan system in the residential HVAC system. If the original fan curve for the system is not available, ASHRAE Research Project, RP-1299[12] includes a method for field constructing a fan curve.
2. Determine natural ventilation capacities and limitations. This is easier said than done. Information is available in the *2017 ASHRAE Handbook—Fundamentals*, Chapter 16.[22]
3. Get the ratings from an ASHRAE Standard 52.2-2017 test report, not just a MERV number. An ASHRAE Standard 52.2 test report provides performance curves and pressure drops.
4. Evaluate the effect of filter loading on filter efficiency. Some filters increase in efficiency upon loading and some decrease in efficiency.[14]
5. Determine the actual filter face velocity for each system evaluated.
6. Determine the acceptable pressure drop from the filter.
7. Select the highest efficiency filter at the particle sizes of interest (0.3 µm to 1 µm, 1 µm to 3 µm, 3 µm to 10 µm) that will perform over the filter lifetime at an acceptable pressure drop.
8. Determine the airflow patterns in the residence and consider using a multizone model[23] to analyze exposure.
9. Consider increased particle capture and removal efficiency techniques for infected person isolation rooms based on airflow pathways.[24]
10. Select which infection to model and choose an appropriate q value (disease generation rate); e.g., influenza will be different from COVID-19.
11. Evaluate the potential health effects of the exposure resulting from different options considered using the modified Wells-Riley equation as presented in Jose Jimenez.[7]

Conclusions

When sleeping in a bedroom with an infected person, running the fan on the air-conditioning system lowers the risk by one-third, and improving the filtration in the system can lower the risk by two-thirds. MERV 14 filters are preferred; however, they may not be readily available in a size with a low enough pressure drop for some residential systems. In that event, a MERV 11 filter provides protection within a few percentage points of a MERV 14. For the cases evaluated (including all the filtration/ventilation options), doubling the exposure time from 2 to 4 hours leads to 2.2 times increase in risk. Compared to the risk at 2 hours, 6 hours of exposure leads to about 3.4 times increase in risk. If the infected person is isolated and the isolation room is modified per the specifications provided by ASHRAE, it appears that installing a stand-alone air cleaner of 170 CADR in the isolation room and running the whole house HVAC fan 100% of the time with a MERV 14 filter results in the lowest practical achievable risk of infection to others.

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