Evaluation of preventive measures in mitigating the risk of airborne infection of COVID-19

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Abstract: In this study, a systematic approach for estimating the infection probability under different infection control strategies is presented for several indoor cases. Increased airflow rates, ventilation schemes, air cleaning equipment, disinfection systems, and face masks are considered according to existing guidelines and standards. These strategies are implemented to care facilities, schools, and offices with varying scenarios. Infection probability calculations are conducted based on the widely used Wells-Riley model. The possible variation of the input parameters is evaluated by employing the Monte Carlo approach to increase the representativeness of the findings. Results show that the infection risk reduction of 15 to 99% is possible depending on the measure preferred.

Keywords: Indoor air quality, COVID-19, preventive measures, Wells-Riley model.

1. Introduction

The novel coronavirus COVID-19 pandemic impinged millions of people [1]. Overwhelming numbers of reported cases brought into attention the importance of preventive strategies to alleviate the propagation of extremely infectious diseases. Multiple guidelines have raised the concern on the indoor airborne transmission of COVID-19 and many recommendations have been released by organizations [2–4]. These recommendations and strategies in terms of building, room, and personal scale have been reviewed and discussed from different perspectives [5–7]. In this context, infection risk assessment is considered a useful tool that may help to quantify and compare the effectiveness of corresponding infection control measures.

Wells-Riley [8,9] and dose-response models are known as two fundamental approaches in infection risk modelling for ventilated indoor enclosures. In general, the infection risk is characterized by a probability between 0 to 1. Models preferred can provide a quantitative risk assessment to deal with the ongoing epidemic and help to comprehend possible results of varying circumstances. The Wells-Riley model is a simple and quick approach based on the quantum concept, which also considers infectivity and source strength. The infection risk prediction with the Wells Riley assumes that the pathogens are homogeneously distributed in a room. The dose-response model on the other hand can provide more precise and realistic outputs than the Wells-Riley model. Nevertheless, this model is less handy since it requires infectious dose data to construct the dose-response relationship [10,11].

The Wells–Riley model and its modifications have been extensively used for the investigation and evaluation of the infection risk of numerous ventilated environments from different perspectives [12–17]. In corresponding studies, key parameters of the Wells-Riley model like quantum generation and breathing rate are evaluated mostly as a constant. In fact, these fundamental parameters have a varying character and considering them as a constant may result in misleading conclusions. Also, the effect of preventive measures on infection risk mitigation was rarely inspected and compared in a quantitative way. Hence, the motivation of this study is to evaluate the effect of different infection preventive strategies by employing the Wells-Riley model in which the probability distributions of unknown parameters are considered. For this purpose, the stochastic Monte Carlo approach is used to broaden the representativeness of the results. The effect of displacement ventilation, standalone air cleaners, installing partition, upper room UVGI systems, and wearing N95 masks are evaluated. The findings can be used in the ongoing struggle against COVID-19 by helping to understand effective countermeasures in infection.

2. Methods

2.1 Infection risk model

The Wells-Riley equation is mainly described as follows:

$$P_0 = \frac{D}{S} = 1 - e^{-IqQ_bt/Q} \tag{1}$$

where P_0 is the probability of infection, D is the number of cases, S is the number of susceptible, I is the number of infectors, q is the quanta emission rate by one infector ($quanta/h$), Q_b is the breathing rate of the susceptible person (m^3/h), and Q is the volume flow rate of pathogen free air (m^3/h). In this study, the above version of the Wells-Riley equation is modified to include the use of N95 masks, air cleaners, displacement ventilation, partition, and UVGI system. The modified equation is given as follows:

$$P = 1 - e^{-(1-\eta_s)(1-\eta_I)\frac{IqQ_bt}{V\alpha}} \tag{2}$$

In this equation, η_s and η_I represents the mask filtration efficiency of the susceptible and infected persons respectively. V is the volume of the room (m^3) and α expresses the equivalent air change rate (given in Eq.3) which depends equivalent ventilation air change rate (λ_{vent}), inactivation rate of ultraviolet germicidal irradiation (k_{UV}), and natural inactivation (k_{inact}).

$$\alpha = \lambda_{vent} + k_{UV} + k_{inact} \tag{3}$$

The equivalent ventilation rate (λ_{vent}) includes the air supply rate of the HVAC system (λ_{HVAC}) and portable air cleaners (λ_{PAC}). Here, in order to reflect the imperfect mixing case in different ventilation concepts like displacement ventilation an additional ventilation parameter (ε_{HVAC}) is also included to this equation as seen below. This additional ventilation parameter is equal to one for a perfect mixing situation which is one of the main assumptions in Wells-Riley consideration. A similar factor is also employed in another modification of Wells-Riley by Sun and Zhai [14].

$$\lambda_{vent} = \lambda_{HVAC}\varepsilon_{HVAC} + \lambda_{PAC} \tag{4}$$

Air supply rate of the HVAC system (λ_{HVAC}) is composed of supplied air flow rate of outdoor air ($\lambda_{outdoor}$) and recirculated air ($\lambda_{recirculated}$). It is given in the following form:

$$\lambda_{HVAC} = \lambda_{outdoor} + \lambda_{recirculated} \tag{5}$$

where η_{filter} is the filtration efficiency of the filters.

2.2 Cases considered

Three different base cases namely an elderly nursing home, a waiting area at the doctor's office, and a classroom are evaluated. Layouts, occupancy levels, duration of stay, ventilation configurations are assigned based on literature and the most typical real practices. Definitions and details regarding corresponding cases are given in **Table 1**.

Table 1. *Settings of the studied cases.*

Space	Elderly nursing home	Waiting area at doctor's office	Music lesson in a classroom	Corridor in a school	Gym in a school
Duration of stay (min)	60	60	60	15	90
Number of total people	2	10	25	40	25
Volume of space (m^3)	3x4x2.7	4x5x2.7	5x8x3.2	30x1.25x3.2	15x27x5.5
Outdoor ventilation rate (l/s)	8.6	44	137		452.5
Quanta generation (h^{-1})	58±31	58 ± 31	970±390	251±134	492±270
Breathing rate (m^3/h)	0.3±0.2	0.3± 0.2	1.3±0.85	1.3±0.85	2.5±1.75

2.3 Model parameters

Two critical parameters in the Wells-Riley equation are quanta generation rate (q) and breathing rate(p). The quantum generation rate depends on disease type, infector activity, etc., and varies significantly [18]. In this study, the quantum generation rate is adapted from the studies of Shen et al. [19], Millet et al. [20], and Hartmann et al. [21]. Breathing rates are assigned up to the activity levels. In each scenario, only one infectious pathogen emitter exists. It is also assumed that the infectious aerosols become evenly distributed throughout the space promptly. Quantum generation and breathing rates are assumed to follow the normal distribution. Variations of these inputs are applied by using the stochastic Monte Carlo approach on the calculations. In every setup, 50,000 trials are simulated.

Minimum outdoor ventilation rates are calculated in accordance with Ashrae Standard 62.1 [22]. In these calculations space area and occupant number are taken into account as seen in the following form:

$$\lambda_{outdoor} = R_p P_z + R_a A_z \tag{6}$$

where R_p is the outdoor airflow rate required per person (L/s), P_z is the occupant number, R_a is the outdoor airflow rate required per unit area (L/s), and A_z is the net floor area (m²). Required airflow rates are determined by the minimum ventilation rates presented in Ashrae Standard 62.1 [22].

For the base cases mixing ventilation (ε_{HVAC} = 1) is applied. The fraction of outdoor ventilation on the air supply rate of the HVAC system is specified as 25% [23]. The filtration efficiency of the filters (η_{filter}) in recirculation is considered as 70% [22]. Natural inactivation is assumed to have a uniform distribution between 0 and 1 h^{-1}.

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At first, infection probability is calculated for the base cases. Then, six different mitigation strategy is applied, and the effect of these strategies is evaluated individually. Proposed strategies are as follows:

- Increased outdoor ventilation rate is analysed by employing 100% outdoor air.

- Air distribution patterns affect the ventilation factor (ε_{HVAC}) considerably. Displacement ventilation has the potential to reduce the exposure in the breathing region so it is considered with a factor of 1.2 to 2 [24].

- Installing partition is considered by a factor of 1.1 – 3 [24].

- Portable air cleaners are becoming popular recently. The use of such air cleaners is assumed to supply clean air with a rate of 12 m³/h per square meter, which is suitable with the current EPA guide [25].

- Proper use of an upper room UVGI system is assumed to provide an air change rate of 2 to 6 h^{-1} [26].

- N95 masks can filter the droplets significantly. Filtration efficiency for both susceptible and infected persons is assumed as between 70% to 95% [27,28].

3. Results and discussion

The calculated infection rates for the base cases are shown in **Table 2**. The infection probabilities over 10% are considered as high risky spaces and these values are bolded. As it is observed, infection rates indicate a large variation in considered cases. The least risky space is found as the waiting area at the doctor's

Table 2. *Infection probabilities for base cases.*

Space	Infection probability (%)	
	Mean	SD
Elderly nursing home	14	11
Waiting area at doctor's office	3.4	2.8
Music lesson in a classroom	40	23
Corridor in a school	32	22.6
Gym in a school	24	18.4

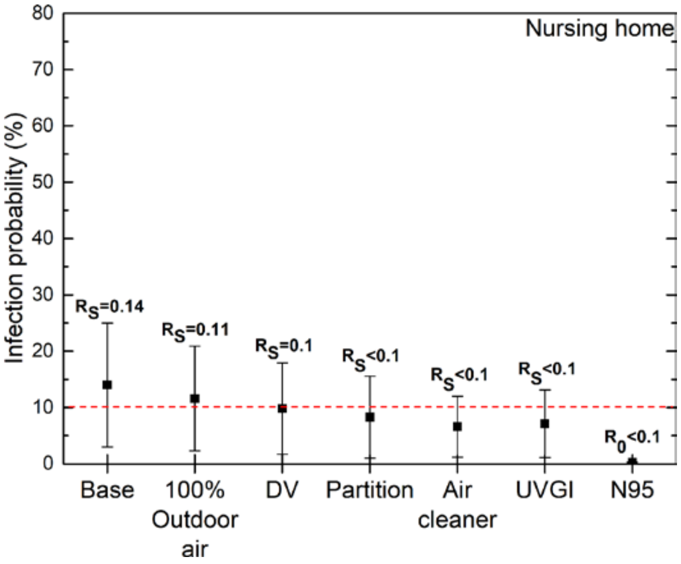

Figure 1. Infection risk predictions for the nursing home.

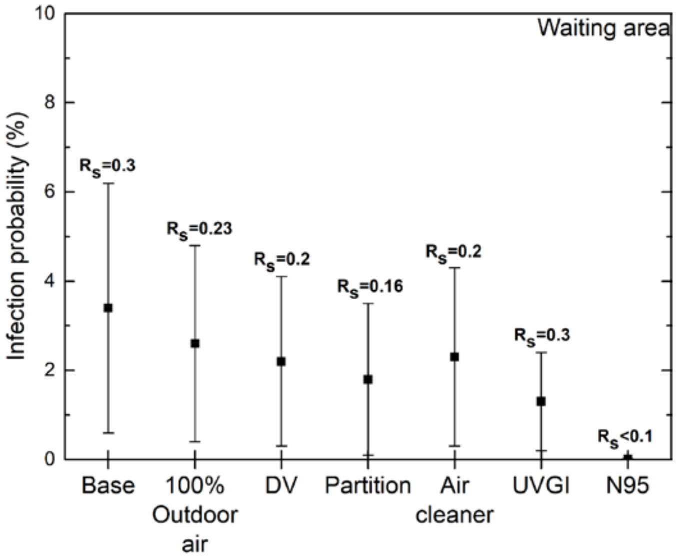

Figure 2. Infection risk predictions for the waiting area.

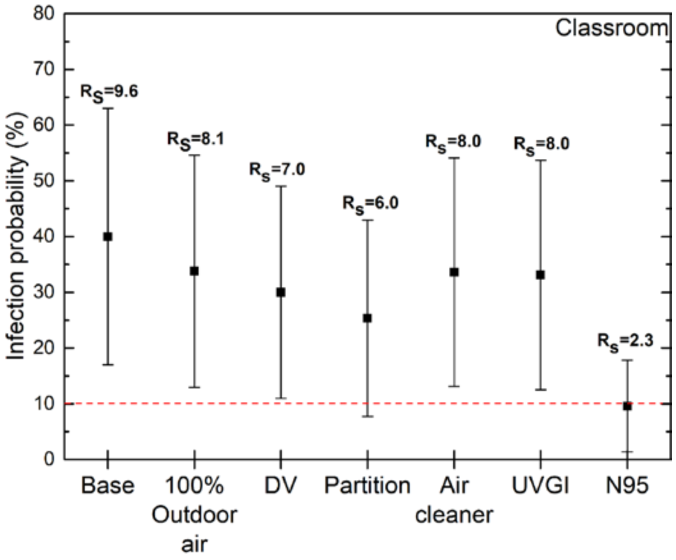

Figure 3. Infection risk predictions for the classroom.

office. As a result of the excessive quanta generation rate the music class configuration shows the highest infection risk potential (40%) among evaluated scenarios. As a result, it can be said that without any mitigation strategy all the cases apart from the waiting area show a considerable risk in terms of infection probability.

Infection risk probabilities under different mitigation measures for the nursing home, waiting area, classroom, corridor, and gym are depicted in **Figure 1, Figure 2, Figure 3, Figure 4, and Figure 5** respectively. Mean value of the situational reproduction number ($R_S = P \cdot S$) [28] in each case is also given in these figures. R_S points out the infection spreading in community. If $R_S > 1$ it is considered that an epidemic occurred.

In general, it is seen that all the measures help to decrease the infection probability to some extent. For the nursing home shown in **Figure 1**, the average infection probability decreases about 17% when the supply air is 100% outdoor originated. Nevertheless, in this case, the average infection risk is still higher than the threshold level with an 11.6% infection probability. All the other measures help to reduce the infection risk between 30% to 98%. In all these cases average infection risk is reduced to below 10% and the limit is met. Also, since the $R_S > 1$ in all cases the spread of the disease is unlikely for the nursing home.

As seen in **Figure 2**, in the case of the waiting area considered measures alleviated the infection probability in the range of 23-99%. In this case, the lowest risk reduction is obtained with the use of 100% outdoor air, and the highest reduction is with the N95 face masking as expected. Both the values of infection probability and R_S point out that the lowest risk is obtained for the waiting area at doctor's office.

Infection risk predictions for the classroom, corridor and the gym are given in **Figure 3**, **Figure 4** and **Figure 5** respectively. It is deduced from the findings that the evaluated measures are not adequate in terms of attaining the threshold limit mostly. In all three cases high reproduction number ($R_S > 1$) points a risk of serious outbreak. In every evaluated configuration, the use of N95 masks meets the threshold value and stands as the only solution for the lowest infection probability. Still, it should be noted that it might not

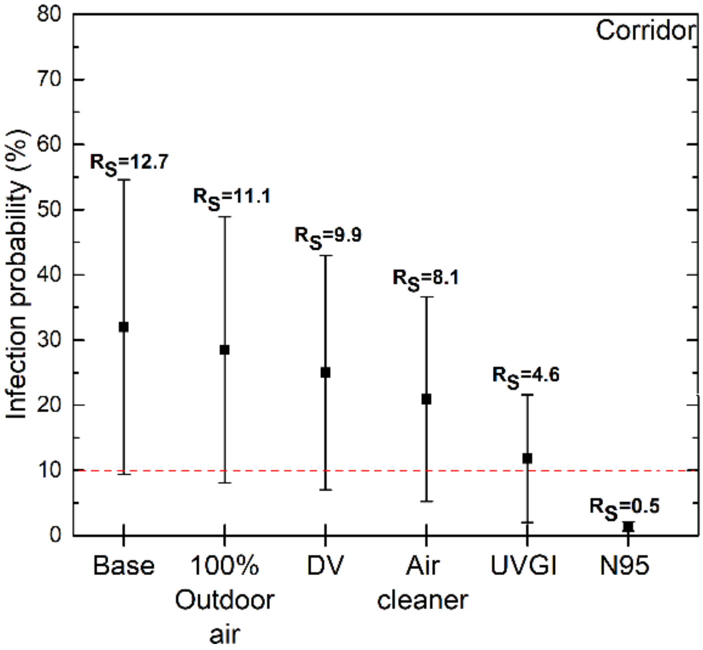

Figure 4. Infection risk predictions for the corridor.

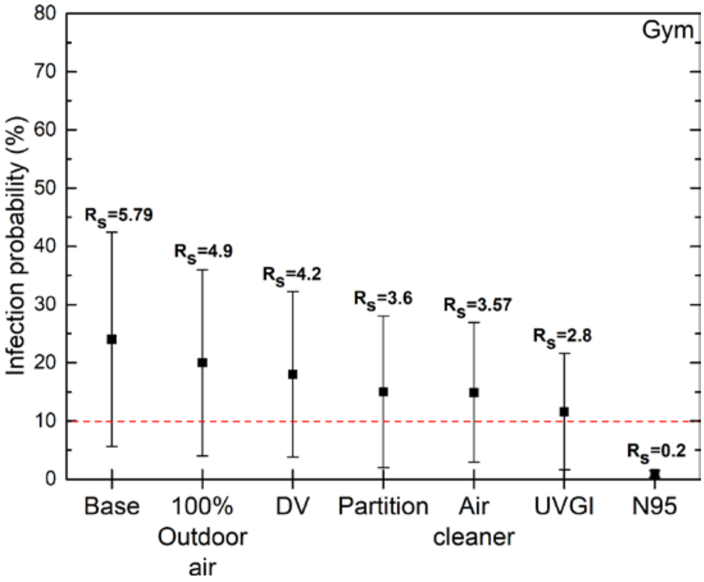

Figure 5. Infection risk predictions for the gym.

be a feasible solution in a music class. Also, for a deeper analysis of the mask efficiency leakage during inhalation and exhalation can be considered in terms of personal protection related factor [28]. For an efficient reduction of the infection risk, the combined effect of the multiple measures can also be evaluated with including feasibility and cost considerations.

4. Conclusions

In the present paper, possible infection preventive measures were analysed for five different settings by employing the well-known Wells-Riley model. Increased outdoor ventilation rate, displacement ventilation, installing partition, portable air cleaners, UVGI systems, and N95 face masks were evaluated. Related model parameters were determined based on the literature and practices. The stochastic Monte Carlo approach was used in calculations in order to include the variations of the input parameters. Future studies can evaluate the combined effect of different risk-mitigating factors from a feasibility and cost standpoint.

Important outcomes are summarized below:

- Predicted infection risk values show a deviating figure depending on the boundary conditions of the cases.
- Based on the evaluated measures risk reduction is possible between 15.5 to 99%.
- Infection risk-mitigating measures lower the probability although this may not be sufficient to achieve the predetermined limit for some cases.
- The use of N95 masks may reduce the infection risk remarkably. This potential can be considered as an easy option for complicated cases at first instance. ■

5. Acknowledgement

This study is supported by The Federal Institute for Research on Building, Urban Affairs and Spatial Development with funding code of SWD-10.08.18.7-20.02.

6. References

Please find the full list of references in the original article at https://proceedings.open.tudelft.nl/clima2022/article/view/299