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Evaluating The Effectiveness Of Various Infection Control Strategies In Classrooms

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Abstract— Classrooms are high-risk environments for airborne infection transmission due to dense occupancy and prolonged exposure periods. In this study, we evaluate the effectiveness of three infection mitigation strategies using the Wells-Riley model to quantify the event reproduction number (R_0) as an indicator of infection risk. The strategies examined include: (1) air cleaners, (2) disposable masks, and (3) an integrated strategy employing personal exhaust ventilation with physical barriers together with ventilation. Results from the infection risk analysis demonstrate that while air cleaner is insufficient to control pathogen spread, strategies that incorporate additional measures significantly reduce R_0. In particular, integrated personal exhaust ventilation with physical barriers yield the lowest R_0 values, indicating superior infection control performance. These findings offer valuable insights for educational institutions seeking to implement effective, evidence-based infection mitigation measures in classroom settings.

Keywords— Infection risk; Air cleaner; Disposable mask; Physical barriers; Personal exhaust ventilation.

I. INTRODUCTION

Airborne transmission of infectious diseases in classroom environments presents a significant challenge for public health, given the high density of occupants and the extended duration of indoor exposure. Numerous strategies have been proposed to mitigate the spread of airborne pathogens in such settings. Traditional approaches have focused primarily on enhancing ventilation, while more recent measures include the use of air cleaners, disposable masks, and the integration of localized control systems such as personal exhaust ventilation and physical barriers. Previous studies employing the Wells-Riley model have shown that improvements in ventilation can reduce the event reproduction number, R0, but the effectiveness of additional interventions varies considerably. For example, while disposable masks can lower infection risk by filtering exhaled and inhaled particles, their overall efficacy depends on factors such as filtration efficiency. Similarly, the use of air cleaners has been demonstrated to remove a significant fraction of airborne contaminants, yet their impact is influenced by operational parameters like clean air delivery rates. A novel approach that integrates personal exhaust ventilation with physical barriers has emerged as a promising strategy, as it directly targets the source of exhaled pathogens and limits cross-contamination among individuals. The present study aims to evaluate and compare the infection risk reduction capabilities of three distinct mitigation strategies in a classroom setting. By quantifying R_0 over the course of a typical one-hour class session, we assess the effectiveness of each strategy in controlling airborne transmission. This comparative analysis is intended to provide a robust framework for decision-makers in educational settings, helping them select interventions that most effectively reduce infection risk.

II. STUDY MODEL

The study was conducted in a typical classroom with dimensions of 9 m in length, 6 m in width, and a height of 3.3 m, accommodating 30 occupants, including students and teachers. Classes are held with each lesson lasting 45 minutes, followed by a 15-minute break. The classroom is equipped with a mechanical ventilation system operating at a flow rate of 148 Liters per second (L/s). This ensures adequate indoor air quality based on standards. Three additional infection control strategies in this study:

A. Air cleaner

The air cleaner considered in this study is a high-performance device equipped with HEPA filters, capable of removing 99.97% of particles as small as 0.3 μm [1]. It is well-suited for classroom environments, providing a Clean Air Delivery Rate (CADR) of 330 m^3/h in "High" mode [2].

B. Disposable mask

In this study, it is assumed that each occupant uses one disposable medical mask per day during class hours. The effectiveness of facial masks in reducing airborne particle transmission depends on whether the mask is worn by an infected individual or a susceptible one. Research by Ueki et al. [3] has shown that mask efficiency can vary significantly, with a worst-case efficiency of 50% for masks worn by infected individuals and 30% for those worn by susceptible persons, even if the masks are nominally identical. This discrepancy arises due to differences in droplet size and water content between emitted and inhaled droplets.

C. Integrated system of personal exhaust ventilation and physical barriers (PE+PB)

The integrated system of personal exhaust (PE) ventilation and physical barriers (PB) was specifically designed to mitigate airborne infection risks by creating localized containment around each occupant [4], [5]. Partitions were mounted on desks, with the front panel measuring 45 × 138 cm and three side panels separating adjacent occupants. These barriers were designed to fit on individual desks, ensuring effective physical separation. Each partition included a plenum box attached to the front panel, featuring a 1 cm high slot running across the table's width. This slot served as the air outlet for personal exhaust ventilation, designed to capture exhaled air directly at the source before it could disperse into the surrounding environment. Each plenum box was connected to an exhaust duct equipped with an airflow meter and an adjustable fan to control airflow. The personal exhaust system operated at a flow rate of 6 L/s per person, balanced in coordination with the main exhaust system, where the total air removed by the personal and main exhaust systems matched the air supply to the classroom.

III. **METHODS**

The Wells-Riley model was used to determine the probability of infection risk for students in the classroom based on their varied activities [7]. Quanta emission rate (E) introduces the viral load released in the Wells-Riley model. Each student's sitting, light movement, and speaking during lectures have been assumed for this study. Weighted averages of E therefore equal 58 quanta/h. At the start of the first lesson, the quanta concentration is zero (QC0), and it rises over time until the student leaves the classroom. Equation (1) provides the time evolution of the average quanta concentration QC(t) (quanta/m3) in the classroom.

$$QC_{(t)} = \frac{E \cdot I \cdot (1 - \eta_i)}{V \cdot \lambda} + \left(QC_0 - \frac{E \cdot I}{V \cdot \lambda}\right) \cdot e^{-t \cdot \lambda} \tag{1}$$

The variables V, I, ηi, and λ indicate the room volume (m^3), infected persons, facial mask efficiency, and first-order loss rate coefficient, respectively. Quanta is lowered by factors such as facial mask efficiency, ventilation ($\lambda\nu$), filtering (kf), deposition (λ_{dep}), and airborne viral decay (k). Therefore, λ is defined as the combined effects of these values (eq. 2).

$$\lambda = \lambda v + \lambda_{dep} + k + k_f \tag{2}$$

This study considers 532.8 m^3/h mechanical ventilation, therefore $\lambda\nu$ will be 3 h^{-1} considering the volume of the classroom. Previous research has indicated a surface deposition loss rate of 0.31 h^{-1} [8], while airborne viral decay is believed to be 0.63 h^{-1} [9]. The filtration removal rate, kf, can be computed as CADR/V. CADR (m^3/h) is the clean air delivery rate attained by portable air cleaners equipped with HEPA filters, as stated in study model. When two air cleaners were used, the filtration removal rate for one air cleaner assumed in this investigation was 330 m^3/h with kf =1.85. The infection risk R(t) represents the likelihood of infection in a closed space of susceptible individuals at a given time (t). It can be calculated using equation (3), which is based on the Wells-Riley model [10] R(t) and enhanced by Gammaitoni-Nucci [11]. Infection risk is determined by the inhalation rate (Q_i) of susceptible individuals, which has been calculated to be 0.71 m^3/h for each student based on their classroom activities. When all susceptible students wear masks, the efficiency of the facial mask (ηs) decreases the amount of air inhaled. A perfect mixing of indoor air with a continuous source was assumed to use the calculated average, $QC_{(t)}$, which grows over time.

$$R(t_1) = n(1 - e^{-Q_i(1-\eta_s)\int_0^{t1} QC_{(t)}dt}) \tag{3}$$

R(t) reflects the average quantum concentration when there is uniform mixing over space. The use of local ventilation alters the distribution of pathogens in the vulnerable person's breathing zone. This study explores a proportional relationship between the quantum concentration and the aerosol concentration in the revised Wells-Riley model, which may be utilized to quantify the SARS-CoV-2 infection risk under varied airflow patterns [12]. A feasible probability level for the classroom can be specified using the reproduction number **R0**, which is derived as the ratio of new infections to original infectious persons. To control the epidemic effectively, **R0** should remain below 1, with an optimal recommended value of 0.5.

IV. RESULTS AND DISCUSSION

Infection control effectiveness is evaluated by the event reproduction number, R0, defined as the ratio of new infection cases to the initial number of infectors. To effectively control an epidemic, a value of R0<1 is recommended, with R0=0.5 considered optimal. This threshold serves as a benchmark for assessing the ability of each mitigation strategy to limit infection spread within a classroom. The results have shown in Figure 1. Air cleaners show a high increase in R0, which approaches 0.75 by the end of the hour. The addition of air cleaners provides a moderate reduction in airborne contaminants, although it does not achieve the ideal condition for epidemic control. Using disposable masks reduces the growth of R0, keeping it around 0.45 after an hour. Masks offer significant mitigation by reducing both the inhalation and emission of infectious particles. Integrated personal exhaust ventilation and physical barriers achieve a substantial reduction, with R0 stabilizing around 0.36 by the end of the hour. This localized strategy, which focuses on controlling the immediate environment around each individual, provides a high level of infection prevention among the tested cases, well below the recommended threshold.

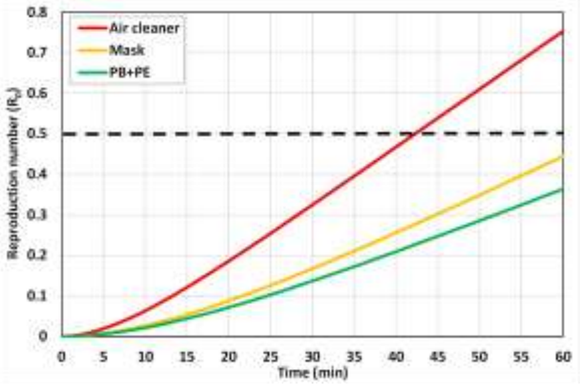

Fig. 1. Temporal variation of event reproduction number for different infection control strategies in a classroom setting - Dashed line exhibits the recommended threshold.

V. CONCLUSIONS

This study evaluated the effectiveness of various infection control strategies in classroom settings by quantifying infection risk using the Wells-Riley model. Three mitigation strategies were compared: air cleaners, disposable masks, and an integrated strategy employing personal exhaust ventilation with physical barriers together with ventilation. The analysis demonstrated that air cleaner is insufficient to control the spread of airborne pathogens, as evidenced by higher event reproduction numbers. In contrast, strategies that incorporate local control measures substantially reduce the event reproduction number. Our results indicate that the disposable masks achieve low reproduction number, demonstrating robust infection control. Notably, the integrated strategy with personal exhaust ventilation and physical barriers shows the most effective infection risk reduction. These findings suggest that local approaches offer strong potential for mitigating infection risk in classroom environments. Overall, the study underscores the importance of adopting infection mitigation measures that extend beyond basic ventilation. Future research should focus on further validating these findings in real-world scenarios and exploring additional factors that influence infection risk in dynamic classroom environments.

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