HHS Public Access

Author manuscript

J Occup Environ Hyg. Author manuscript; available in PMC 2023 August 30.

Published in final edited form as:

J Occup Environ Hyg. 2022 May ; 19(5): 295–301. doi:10.1080/15459624.2022.2053142.

Assessment of university classroom ventilation during the COVID-19 pandemic

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Abstract

Ventilation plays an important role in mitigating the risk of airborne virus transmission in university classrooms. During the early phase of the COVID-19 pandemic, methods to assess classrooms for ventilation adequacy were needed. The aim of this paper was to compare the adequacy of classroom ventilation determined through an easily accessible, simple, quantitative measure of air changes per hour (ACH) to that determined through qualitative "expert judgment" and recommendations from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), and the American Conference of Governmental Industrial Hygienists (ACGIH)®. Two experts, ventilation engineers from facilities maintenance, qualitatively ranked buildings with classrooms on campus with regard to having "acceptable classroom ventilation." Twelve lecture classrooms were selected for further testing, including a mix of perceived adequate/inadequate ventilation. Total air change per hour (ACH) was measured to quantitatively assess ventilation through the decay of carbon dioxide in the front and rear of these classrooms. The outdoor ACH was calculated by multiplying the total ACH by the outdoor air fraction. The classrooms in a building designed to the highest ASHRAE standards (62.1 2004) did not meet ACGIH COVID-19 recommendations. Four of the classrooms met the ASHRAE criteria. However, a classroom that was anticipated to fail based on expert knowledge met the ASHRAE and ACGIH criteria. Only two classrooms passed stringent ACGIH recommendations (outdoor ACH > 6). None of the classrooms that passed ACGIH criteria were originally expected to pass. There was no significant difference in ACH measured in the front and back of classrooms, suggesting that all classrooms were well mixed with no dead zones. From these results, schools should assess classroom ventilation considering a combination of classroom design criteria, expert knowledge, and ACH measurements.

Keywords

Air change rate; carbon dioxide; heating ventilating and air conditioning; tracer

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Introduction

Some viruses, such as SARS-CoV-2, can spread from person to person through aerosolization and indirect contact (Greenhalgh et al. 2021). Guidelines suggest physical distancing to prevent the spread of SARSCoV-2 (Kucharski et al. 2020). However, many university classrooms are designed to fit as many students as possible while complying with fire safety codes. The National Fire Protection Association (NFPA 2011) and the International Fire Code (IFC 2015) recommend a net area of 20 ft^2 per person for traditional classrooms (NFPA 2011; IFC 2015). These occupancy calculations result in, at best, 4 ft. of separation between students, not the 6 ft. minimum recommended in social distancing guidelines. Moreover, college courses last at least 50 min, with some courses lasting up to 3 hours, making ventilation a critical factor to minimize the spread of infections from airborne viruses.

Well-operating ventilation systems provide adequate intake of fresh air from outdoors, filtration, and sufficient room air change rate. Uncontaminated outdoor air pulled into a building with fans dilutes airborne hazards (Burgess et al. 2004). In school settings, common hazards include bacteria, dust, mold, and viruses (Hosseini et al. 2020). In most ventilation systems, air exiting rooms is centrally filtered, mixed with outdoor air, and returned as supply air throughout the building (ACGIH 2019). The total room air change rate, expressed as air changes per hour (total ACH), is the total airflow entering a room divided by its volume. The outdoor ACH can be calculated by multiplying the total ACH by the fraction of outdoor air supplied to the room. The higher the outdoor ACH in a room, the more dilution of contaminated air (Qian and Zheng 2018). The dilution of contaminants is complemented by filtration of particulate contaminants (including viruses).

Various organizations recommend increasing outdoor air percentage, operating with high efficiency filters, and providing adequate room ACH to help reduce the spread of COVID-19 in indoor environments. A checklist from ASHRAE, based on ASHRAE standards 55 and 62.1 for maintaining temperature and outdoor airflow, respectively, recommends increasing ventilation outdoor airflow to the maximum capacity of the system (ASHRAE 2020). A limited number of systems operate with 100% outdoor air, in which no air is recirculated. The benefit of 100% fresh air ensures any contaminated air is exhausted from a room to minimize the chance of recirculation, but it is costly to heat/cool and maintain appropriate humidity. Moving air within a building without filtering any contaminants may spread the SARS-CoV-2 virus throughout a building. For SARS-CoV-2 virus, minimum efficiency reporting value (MERV) 13 filters are recommended as a minimum for schools and universities (ASHRAE 2020). To reduce spread of the SARS-CoV-2 virus, the Industrial Ventilation Committee of the ACGIH has recommended facilities have an outdoor ACH between 6 and 12 (ACGIH 2021).

Ensuring each classroom is appropriately ventilated to minimize the spread of the SARS-CoV-2 is a huge undertaking for a large academic institution. One pre COVID-19 study took 3 days to look at the ventilation quality in four locations in a 34-classroom middle school (Scheff et al. 2000). Schools may not have personnel with training in ventilation design to help make decisions on ventilation air quality during a pandemic. Facilities that do have ventilation experts are rarely equipped to inspect all designated rooms. A lack of ventilation monitoring capabilities across multiple rooms leave building managers with uncertainties about the ventilation quality, leading to slow decision making and reliance on qualitative assessments. We are unaware of research on the accuracy of assessing ventilation qualitatively by experts.

The aim of this work was to provide university leadership with information on the adequacy of ventilation in classrooms on campus during the initial phases of the COVID-19 pandemic. All classrooms on campus were qualitatively assessed into levels by facilities maintenance engineers. To help validate this qualitative assessment, we used a low-cost, simple method to measured total and outdoor ACH in classrooms from a range of levels. The conclusions drawn from these quantitative data were then compared to qualitative conclusions made by facilities maintenance engineers with detailed working knowledge of the ventilation systems.

Methods

Ranking of buildings

This study was conducted at the University of Iowa (UI) from May 2020 through August 2020. A time when no rooms were in use as classroom due to COVID-19 restrictions. The University facilities maintenance team gave the ventilation system in each building on campus with classrooms a level from 1–9 based on the building's age, HVAC system type, and degree of monitoring and building automation (Table 1). Level 1 buildings had air quality monitoring capabilities, were more recently built, and had better ventilation systems than other levels. They used variable air volume (VAV) units, which control the airflow to connected rooms, and air handling units (AHUs) used 100% outdoor air. In contrast, level 9 buildings used nonstandard heating, ventilation, and air condition (HVAC) units and had little, if any, monitoring capabilities. The buildings in which teaching concerns were most critical at the University were deemed those at levels 3, 5, and 7. Level 3 and better buildings were originally thought to have adequate ventilation for occupants during the COVID-19 pandemic. Level 5 buildings were thought to have a mix of adequate and inadequate ventilation for classrooms. Level 7 buildings were originally thought to have inadequate ventilation for occupants in a classroom setting.

Selection of classrooms

Eleven classrooms in eight of the ranked buildings were selected for quantitative investigation to represent a variety of rankings and convenience of sampling. One classroom was selected from a building assessed at level 3. Two classrooms were selected from a building that was level 7. For comparison of mechanical and natural ventilation, five mechanically ventilated classrooms were selected in four buildings. These were compared with two classrooms that lacked central forced air ventilation (they used radiators or steam-heated fan coils for heat, and open windows or a packaged terminal air conditioner, PTAC, for cooling). One of these classrooms was tested twice—once with windows closed and PTAC off and then a second time with windows open and PTAC set to its highest fan setting. One of the classrooms was examined to be representative of a large lecture hall.

In each classroom, the research team measured room dimensions, recorded the number, placement and type of supply and return points, and noted whether the return ventilation was ducted or free return. Free air return systems used the open or free space, typically above ceiling tiles and collocated with cable runs, for a conduit between conditioned spaces and the air handler. Like ducted air return, air from multiple rooms is mixed before filtration and recirculation at the AHU. The free return had variety of setups, with some classrooms having an open slot across the top of the class allowing air to flow out of the classroom from multiple locations. In other classrooms, the free return and supply ducts shared the same opening to the classroom, running the risk of poor mixing. Building age was identified from facilities maintenance building information website, and classroom capacity information was obtained from the Office of Registrar.

Measurement of air exchange rate by CO_2 tracer

Following Escombe (2006), total ACH was measured with carbon dioxide (CO_2) as a tracer gas. The CO_2 concentrations in the classroom were measured with two direct-reading monitors (Q-Trak, Model 8554, TSI, Shoreview, MN). One monitor was placed on a student desk in the rear of the room, and the other was placed on a desk near the front of the room. The monitors were set to record concentrations every minute. Background concentrations were recorded for at least 10 min, and then a class B and C fire extinguisher was discharged throughout the classroom to produce elevated concentrations of CO_2. The room was vacated and left unoccupied when both monitors read higher than 4,000 ppm CO_2. In the largest classroom, a fan was used to mix the CO_2 for 10 min. Tests continued until concentrations were below 500 ppm on both monitors or until the test reached 4 hours, whichever came first. The CO_2 monitors were calibrated once a month, following manufacturer's protocol.

Three methods were used to estimate the percentage of outdoor air, $OA\%$. Where possible, was calculated from historical temperature data (mixed air, return air, and outdoor air) archived by the building ventilation system as:

$$OA\% = \frac{T_{RA} - T_{SA}}{T_{RA} - T_{OA}} \times 100\%, \quad (1)$$

where T_{RA} is the temperature of return air, T_{SA} is the temperature of supply air (the air after the return air is mixed with outdoor air), and T_{OA} is the temperature of outdoor air (TSI 2022). The second method used logged data of the outdoor airflow, and AHU fan speed from the buildings historical data to calculate $OA\%$ as:

$$OA\% = \frac{Q_{OA}}{\left(\frac{SF}{100}\right) \times Q_{RF}}, \quad (2)$$

where Q_{OA} is the outdoor airflow pulled into the AHU, SF is the supply fan speed, and Q_{RF} is the supply fan speed rated airflow. The last method used a thermal anemometer (Velocalc, Model 9545, TSI, Shoreview, MN) to measure the mean air velocity of the AHU at the outdoor air supply, V_{OA}, and the air return, V_{RA}. $OA\%$ was then calculated as:

$$OA\% = \frac{(V_{OA} \times A_{OA})}{(V_{OA} \times A_{OA}) + (V_{RA} \times A_{RA})}, \quad (3)$$

where A_{OA} and A_{RA} are the area of the outdoor air supply vent and the return air vent, respectively. The naturally ventilated classrooms with open windows were assumed to have 100% outdoor air and the naturally ventilated classrooms with closed windows were assumed to have 0% outdoor air.

Data analysis

Background CO_2 concentrations were averaged and subtracted to create time series of the increment of CO_2 above background. The total ACH was determined as the slope of the line of best-fit linear regression of the natural log of CO_2 concentrations measured during the decay by time. We assumed the CO_2 was well-mixed, and there was no recirculation of CO_2 into the classrooms. The assumption of no CO_2 recirculation was valid because the buildings were unoccupied, and each classroom occupied only a small fraction of the total area covered by the air handler. A Shapiro–Wilk test was used to determine if the total ACH measured in the front and rear of classrooms were normally distributed using a specialized spreadsheet (IHSTAT, v. 237, American Industrial Hygiene Association). A two-sample variance F-test and a matched paired two-sample t-test was performed with Minitab 19 (Minitab v.19.2020.2 LLC, State College, PA) to compare total ACH measured in the front to that in the rear of classrooms.

For each classroom, outdoor ACH was calculated as the mean of the two total ACH measurements (front and rear of classroom) multiplied by the percentage of outdoor air. These quantitative values were compared to recommendations from ASHRAE and ACGIH. Following ASHRAE (2004), recommended outdoor ACH was determined for “lecture classrooms” by adding the outdoor airflow rate needed per person (7.5 cfm/person) to the outdoor airflow rate needed per classroom area (0.06 cfm/ft^2) found in Table 6–1 of the ANSI/ASHRAE 62.1 2004 standards. The number of people in the classroom was assumed as the maximum student capacity defined by the university registrar prior to COVID-19 plus one for a teacher. Following the ANSI/ASHRAE standard 62.1–2004, the ASHRAE recommended total ACH was determined as a minimum exhaust rate 0.7 cfm/ft^2 from Table 6–4 (ASHRAE 2004). ACGIH recommends a minimum of six ACH of virus-free air, which can be achieved by using outside air or “sufficiently filtered recirculated air” (ACGIH 2021). Sufficiently filtered recirculated air is poorly defined. However, recirculated air typically passes through two banks of filters. If the filters are rated MERV 13, which has a minimum efficiency of 50% for particles from 0.3 μm to 1.0 μm (ASHRAE 52.2–2017), then the recirculated air may be considered sufficiently filtered for practical purposes. We took a conservative approach and interpreted the ACGIH recommendation as outdoor ACH.

Results

Eleven classrooms or lecture halls were assessed in eight buildings (Table 2). Experts from the facilities and maintenance department on campus qualitatively assessed the buildings as level 3, 5, or 7. Level 3 qualitative assessment was assumed to have sufficient ventilation for pandemic use because these were designed to ASHRAE 62.1–2004 or later standards and had a building automation system (BAS) and fault detection and diagnostics (FDD) monitoring. Level 5 qualitative assessment also had BAS and FDD, but were designed prior to ASHRAE 62.1–2004. Therefore, University personnel suggested spot checks using CO2 tracer testing and measurement of supply, return, and OA%. Level 7 qualitative assessment also had BAS and FDD, but had “non-standard” HVAC. For the specific cases tested, nonstandard HVAC was radiator or steam-coil heat, and a combination of PTAC and windows for cooling. These rooms were assumed by ventilation professionals as unsuitable for use during the pandemic, particularly during the heating season; however, testing data could help inform campus leaders as they weighed pros and cons of a number of pandemic response strategies.

Measured total ACH ranged from 0.4–7.7. The lowest ACH values were measured in rooms without mechanical ventilation and windows closed. The highest ACH values were measured in the same rooms when they had windows open and PTAC units operating with a minimum of recirculation. A scatter plot comparing the total ACH measured in the front and back of the classroom is shown in Figure 1. This plot was prepared without ACH data from CPHB #1, in which a fan was used to promote mixing of the CO_2. The linear regression comparing the total ACH measured in the front to the rear of the classrooms showed high correlation ($R^2 = 0.98$). The largest difference in ACH between front and rear of the classrooms was 14.5%. ACH measured in the front and rear of the classroom were normally distributed (Shapiro–Wilk $p = 0.93$). There was no statistical or substantial difference between ACH means between front and rear of classrooms ACH (Matched Paired Test, t-test $p = 0.16$; Two-sample Variance, F-test $p = 0.92$).

As shown in Table 3, measured ACH values were compared to recommended values from ASHRAE (outdoor air ACH and total ACH) and ACGIH (outdoor ACH > 6). Recommended ASHRAE ACH for outdoor air ranged from 1.2–4.8, whereas that for total ACH ranged from 3.2–4.9. Measured total ACH was greater than or equal to ASHRAE recommendations in seven of the 12 cases. Measured outdoor ACH exceeded the ASHRAE recommendation in only three of 12 cases. Compared to the higher ACGIH recommendation of 6 ACH of outdoor (or sufficiently filtered recirculated) air, measurements exceeded the recommendation only in one of the 12 cases.

Discussion

Recommendations from ASHRAE and ACGIH for air exchange in classrooms during COVID-19 are difficult to meet. Measured outdoor ACH was equal to or greater than recommendations from ASHRAE in only three of the 12 cases (Table 3). Outdoor ACH was high in NH when the windows were open (7.7 ACH) and low when closed (0 ACH). It was, however, unexpected that the naturally ventilated classroom would have the lowest and highest total ACH, depending on whether the windows were open or closed. Total ACH targets were easier to pass with eight of the 12 cases passing ASHRAE recommendations. Total ACH measured in NH Open exceeded the minimum recommended by ASHRAE by more than 3 ACH. Two of the failed classrooms were close with EPB #2 and VAN #1 ≤1.1 ACH away from their ASHRAE total recommendations. However, the naturally ventilated classroom with 0% outdoor air were more than 3 ACH away from their target values. Only one case passed the ACGIH recommended outdoor ACH minimum of 6 (Table 2). This naturally ventilated classroom with open windows (NH Open) exceeded the recommended exchange rate by 1.7 ACH.

Carbon dioxide tracer testing is reasonably easy to implement and is valuable as an independent qualitative check on conclusions made by facilities engineers. Persily and Dols (1990) identified the effectiveness of CO_2 decay and other tracer gases in office buildings. Thus, carbon dioxide is not a novel tracer gas nor is the method of using it to measure ACH. However, fire extinguishers provide a cheap and easy to use source of high CO_2 concentrations, allowing ACH to be determined without disrupting normal supply and exhaust configurations. This was a major benefit of this study during the pandemic with limited access to new resources.

Our results suggest a lack of dead spots across student and instructor areas over a wide range of ventilation setups. "Dead spots mean the air is stagnant, and little/no mixing of incoming air" (Mundhe et al. 2019). In the CO_2 decay testing, a dead spot near a monitor would have been represented by the lack of CO_2 decay compared to the other monitor. For COVID-19, a dead spot could allow the SARS-CoV-2 virus to accumulate and potentially spread to others. However, the ACH determined from CO_2 monitors placed in the front were similar to those determined from monitors placed in the rear of the classroom (Figure 1). Moreover, a linear regression with a good fit and no significant difference between the front and back of classrooms showed there was a good mixing where students or faculty would sit.

Expert knowledge alone may be insufficient to assess whether a classroom meets ASHRAE and ACGIH recommendations. The CPHB classrooms were qualitatively assessed by experts as a level 3 building designed to ASHRAE 62.1 2004 standards. One classroom (CPHB #2) passed ASHRAE total and outdoor ACH recommendations, whereas the other classroom did not (CPHB #1; Table 3). Neither of the classrooms passed the ACGIH minimum recommendation. With neither classroom close to passing the ACGIH recommendation, it is not recommended to rely on a building's design criterion to judge the ventilation quality. The level 7 classrooms, thought by experts as some of the worst ventilated on campus, were also split with one classroom (VAN #2) passing and one classroom (VAN #1) failing their ASHRAE total ACH. Both VAN classrooms failed their recommended ASHRAE outdoor and ACGIH ACHs. The level 5 classrooms thought to be a mix of adequate and poor ventilated buildings was the most accurate prediction with 62% of the classrooms passing their ASHRAE total ACH and 25% passing their ASHRAE outdoor ACH. Mixed results were expected for the level 5 classrooms.

Other observations are worth noting. Sealed-off classrooms with no natural ventilation are not to be used during pandemic and are likely to spread respiratory illness. Classrooms with open windows are difficult to predict how well-ventilated they are without testing or monitoring of some sort. The finding that the level 3 building assumed suitable for the pandemic had some failures is concerning. Follow up is warranted to inform policy and new construction. As expected, mixed results were obtained in classrooms tested in level 5 buildings with some having sufficient total airflow, but insufficient outdoor air. Finally, buildings assessed as level 7 failed on both total and outdoor air despite being mechanically ventilated and housing one of the universities largest lecture halls.

There are some limitations to this work. We only tested 12 classrooms in eight buildings on a campus that has over 30 buildings with classrooms and specialty spaces. None of our tests included specialty spaces like laboratories, libraries, or recreation centers. A fan was used in the largest classroom to promote mixing of air and CO_2. If a fan is not used during normal use of this space, our results could overestimate the ventilation rate and miss dead space zones. For this reason, we removed the data from this room for comparing front and rear classroom measurements. Future work should be completed without a mixing fan unless it is part of normal operations. We used a conservative approach to interpret recommendations from ASHRAE and ACGIH as outdoor ACH. However, virus-free air can be achieved by filtering return air instead of relying on outdoor air solely (ACGIH 2021). Future work should investigate the type of filters that are adequate for this purpose and establish appropriate cleaning schedules.

Conclusions

Carbon dioxide tracer testing is reasonably easy to implement and is valuable as an independent qualitative check on conclusions made by facilities engineers. Outdoor and total ACH targets recommended by ASHRAE and ACGIH for COVID (ASHRAE 2020; ACGIH 2021) are difficult to meet. Out of 11 classrooms tested with the CO_2 tracer method, only three met ASHRAE and one met ACGIH targets. Our results suggest a lack of dead spots across student and instructor areas over a wide range of ventilation setups. The original design criteria of a building should not be exclusively used to make a final decision on the effectiveness of a ventilation system. Additionally, expert knowledge of the ventilation systems is inadequate to determine the adequacy of ventilation. Ultimately, a combination of expert knowledge and ventilation data should be used to assess classroom ventilation quality for occupancy. Future studies of university ventilation should include increased testing of expert knowledge compared to classroom ACH measured qualitatively. A larger range of classroom and building levels should be evaluated to better assess if expert knowledge is enough to determine ventilation adequacy.

Acknowledgments

The authors wish to thank facilities maintenance of the University of Iowa for the expert support and access to all classrooms and HVAC systems during the COVID-19 shutdown. Contributions of DR were supported by a Training Grant (T42OH008491) from the Centers for Disease Control and Prevention.

Funding

This work was supported by National Institute for Occupational Safety and Health.

Data availability

Data are available upon reasonable request by contacting the corresponding author.

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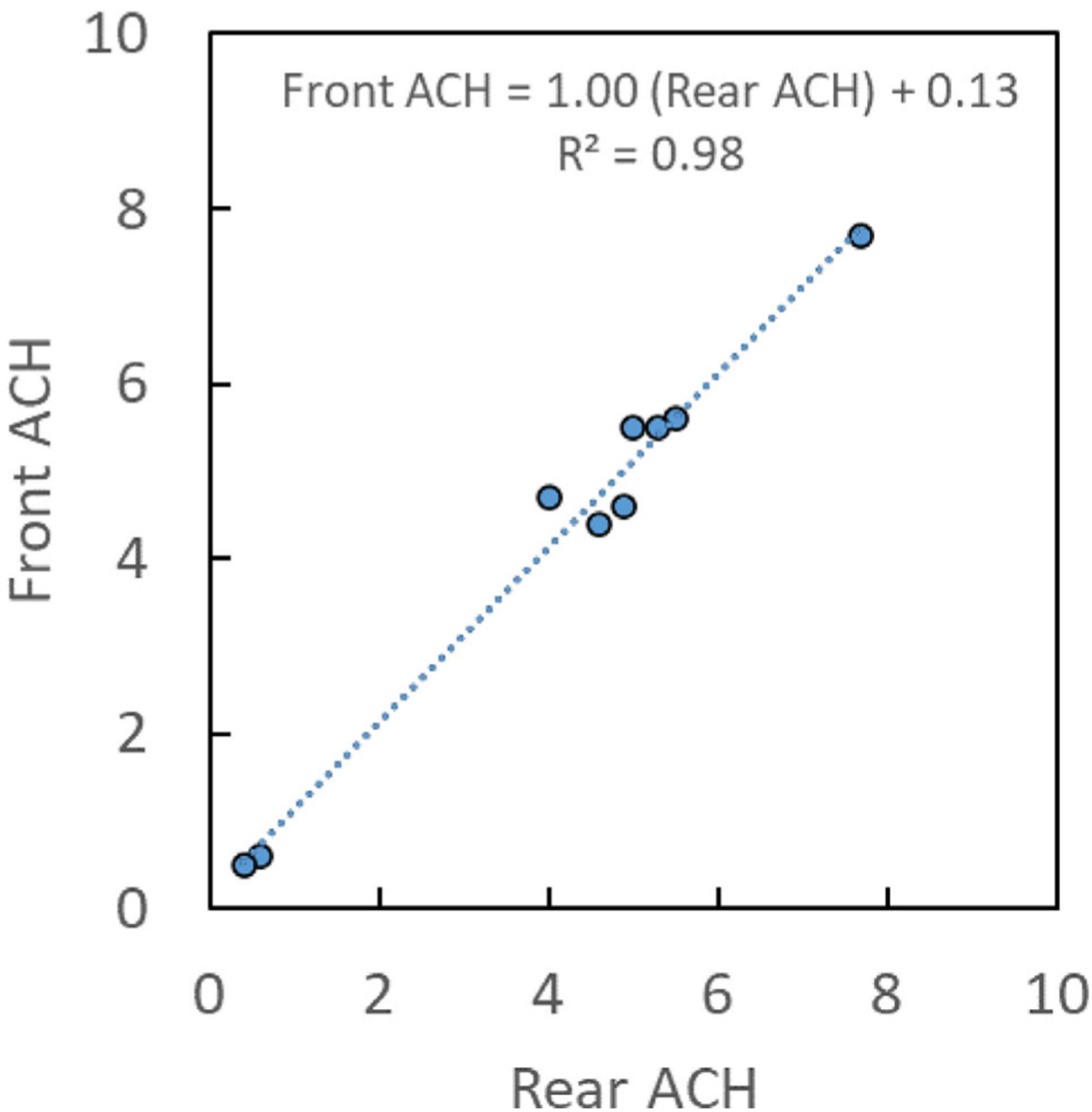

Figure 1.
Regression analysis comparing air changes per hour (ACH) measured in the front of the classroom compared to those measured in the rear of the classroom. Data measured in CPHB#1 was removed from this analysis as it was the only room where a mixing fan was used.

Table 1.

Building levels used in qualitative ranking.

Building level	System details	% of university classroom space	Flagged by FM for audits
1	VAV with 100% outdoor air	22	None
2	VAV with mixed air and MERV 13+	6	None
3	ASHRAE 62.1 2004 compliant VAV (or 100% outdoor air) with BAS and FDD	13	None
4	ASHRAE 62.1 2004 compliant VAV with BAS but no FDD	2	Half
5	VAV with BAS and FDD, but prior to ASHRAE 62.1 2004	34	Half
6	VAV with BAS, but prior to ASHRAE 62.1 2004, no FDD	11	Half
7	Nonstandard HVAC with BAS and FDD	3	All
8	Nonstandard HVAC with BAS but no FDD	6	All
9	Spaces without BAS (e.g., older houses converted to office space, some warehouse-type buildings)	3	All

HVAC – heating, ventilation, and air conditioning.

FDD – fault detection and diagnostics analysis software.

BAS – building automation system.

VAV – variable air volume.

Table 2.

Building characteristics, expert ranking, and classroom measurements.

Building and room #	Ventilation type	Room volume, ft^3	Building level ranked by expert	Outdoor air %*	Total ACH, front/rear
NH open	Open windows and PTAC as fan	4,800	7	100^{D}	7.7/7.7
VAN #2	Mechanical	6,500	7	11^{B}	6.2/N/A
EPB #1	Mechanical	6,500	5	11^{C}	5.6/5.5
PC	Mechanical	7,700	5	12^{B}	5.5/5.0
SH	Mechanical	6,500	5	14^{A}	5.5/5.3
CPHB #2	Mechanical	5,700	3	54^{A}	4.4/4.6
EPB #2	Mechanical	9,600	5	11^{C}	4.7/4.0
PBB	Mechanical	6,200	5	53^{A}	4.6/4.9
VAN #1	Mechanical	4,700	7	11^{B}	3.5/N/A
CPHB #1	Mechanical	26,100	3	48^{A}	1.6/1.6**
MH	Natural, Windows Closed, PTAC off	6,700	7	0^{D}	0.6/0.6
NH closed	Natural, Windows Closed, PTAC off	4,800	7	0^{D}	0.5/0.4

* Outdoor air % estimated as follows: A – historical temperature data; B – historical airflows and fan speed; C – thermal anemometer; D – assumed values for natural ventilation.

** Fan used in large lecture hall to mix CO_2.

PTAC – packaged terminal air conditioner.

Table 3.

Classroom measurements compared to expert ranking and minimum ACH recommendations from ASHRAE and ACGIH.

		Measured		ASHRAE criteria		
Building/Room #	**Ranking level**	**Total ACH**	**Outdoor ACH**	**Total ACH**	**Outdoor ACH**	**ACGIH Recommendation outdoor ACH > 6***
NH open	7	7.7	7.7	**4.4**	1.3	**Pass**
VAN #2	7	6.2	0.7	**4.4**	3.8	Fail
EPB #1	5	5.6	0.6	**4.7**	4.8	Fail
PC	5	5.3	0.6	**4.7**	1.2	Fail
SH	5	5.4	0.8	**3.9**	2.5	Fail
CPHB #2	3	4.5	2.4	**4.4**	**2.4**	Fail
EPB #2	5	4.4	0.5	4.9	4.4	Fail
PBB	5	4.8	2.5	**4.7**	2.8	Fail
VAN #1	7	3.5	0.4	4.6	3.6	Fail
CPHB #1	3	1.6	0.8	3.2	3.6	Fail
MH	7	0.6	0.0	3.9	3.1	Fail
NH closed	7	0.5	0.0	4.4	1.3	Fail

*The ACGIH recommendation is 6 ACH of outside air OR sufficiently filtered recirculated air. However, as only buildings with ranking level 1–2 had MERV 13þ filtration prior to the pandemic, we interpret the ACGIH recommendation in these cases as 6 ACH of outdoor air.

Bolded values indicate that measured values meet or exceed the criteria.