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Indoor Environmental Quality Performance Approaches: Trending IAQ to IEQ to COVID-19 Extended Abstract

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ABSTRACT

The University of Colorado Boulder (CU Boulder) is in Boulder, Colorado USA at 5280 feet above sea level. The campus has approximately 12 million square feet of infrastructure spanning over 100 years of building infrastructure evolution. In response to the COVID-19 pandemic, the University employed a science-based approach with campus researchers including aerosol scientists and campus epidemiologist and industry standards to inform a layered risk management strategy for an on-campus learning experience during the pandemic. This strategy was applied campus wide and specifically informed higher risk activities such as singing, music, theater, dance, athletic activities, as well as lecture, labs, and maker spaces. Through contract tracing and testing the campus reported 52 positive cases, where infected students had spent time in at least one classroom. It was determined that the infected student(s) had not spread the virus to other students who had been in the classroom due to the control measures and strategy that was employed. The campus response and risk management approach are summarized in this paper, as well as, the science that informed the strategy, the infrastructure modifications applied, and lessons learned from the data that was collected such as trends for CO_2, temperature, CO_2 and particle measurements during high aerosol activities, HEPA air cleaner placement, and data collected through contact tracing. Lessons learned from the effort will also be described to help improve post pandemic operations, assist others to operate during a pandemic, and plan for future pandemic scenarios which are primarily aerosol driven

INTRODUCTION

In the early stages of the pandemic, transmission paths for COVID-19 were unknown. A group of aerosol scientist including Shelly Miller, suspected aerosol transmission paths, both short-range and long-range transmission, to be significant vectors in transmission and had written to the WHO (Morawska, Milton, 2020) to assist in gaining control over the pandemic. Early anecdotal reports of outbreaks occurring in restaurants (Li et al, 2021) and choirs (Miller et al, 2021) with poor or no ventilation, indicated a need to explore and understand this transmission path clearly to minimize airborne transmission.

In addition, CU Boulder was tasked with keeping the campus operational for core research not only for the pandemic research such as vaccines (Cech, 2021) and tracing (Marshall, 2020) but also maintaining the value of an in-person campus

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experience that included high aerosol activities such as music, theater, dance, and athletics activities. The team needed to determine quickly what operational measures could be put into place immediately to minimize risk to the campus occupants to maintain the function and mission of the University.

The University's strategy was a multi-layered risk management plan to control transmission paths both through fomites and long-range and short-range aerosol transmission paths. Essentially people are potential transmission vectors in a pandemic or the potential cause for IAQ issues in a space. It is an indoor air quality problem where the source of the potential contaminant or virus was an individual versus a source generating IAQ issues such as mold, or particulate matter in the space.

The primary strategies to improve IAQ in this scenario was to address the quantity and quality of air for all buildings across campus through containment, dilution, and duration engineering control measures. Containment was focused on preventing distribution, dilution was focused on decreasing the air concentration of the virus, and duration was focused on limiting exposure.

The following will discuss the specifics for each control measure as it relates to airborne transmission. how each control measure was informed by the emerging aerosol science as related to COVID-19 and pragmatic field tests (i.e fogging with HEPA filters to inform placement), and how each control measure performed through contact tracing data, and trend data for temperature, and CO_2 trends through the Building Automation System, coupled with validation through high resolution CO_2 and particle. Tracing and testing were employed to confirm assumptions about transmission paths and assist in validating the effectiveness of control measures.

TRANSMISSION PATHS FOR HIGH AEROSOL ACTIVITIES THE SCIENCE

Early in the pandemic it was unclear what was the major transmission route and traditional respiratory infectious disease paradigms focused on fomite transmission. Hand washing and intense surface cleaning was emphasized. However, evidence quickly began to mount that there was an airborne transmission component by inhalation of aerosol. Several studies detected and/or cultured SARS-CoV-2 in air samples and found virus on surfaces of ventilation exhaust vents (Lednicky et al. 2020. Ong et al. 2020: Santarpia et al. 2020). Outbreak investigations reported inhalation of virus-containing aerosol to be the most plausible explanation of many exposed individuals getting infected not located directly near the index case (Miller et al. 2021). SARs-CoV-2 is an overdispersed pathogen such that as few as 10-20% of infected people transmit 80-90% of the infections; many people barely transmit (Lloyd-Smith et al. 2005). Short-range aerosol transmission (< 3 ft) is thought to drive over half of the infections due to proximity to an infectious person and high aerosol virus shedding, while long-range transmission drives many outbreaks because of elevated viral-aerosol concentrations and poor ventilation (Azimi et al. 2021)**.**

Findings for High Aerosol Generating Activities

Because of the risk of infection by inhalation of virus-containing aerosol, many activities have been modified especially those that have the potential to generate respiratory airborne particles. These include singing and theatre performances. Singing has been implicated in several outbreaks (Miller et al. 2021). A research project lead by Shelly Miller was undertaken at CU Boulder to better inform the aerosol generating potential of playing wind instruments and theatre performances and to make control recommendations for modified performance activities. The project now completed found that plumes from musical performance were highly directional, unsteady, and vary considerably in time and space. Aerosol number concentration measured at the bell of many wind instruments including the clarinet were comparable to singing. Face and bell masks attenuated plume velocities and lengths and decreased aerosol concentrations measured in front of the masks. Modeling showed differences between indoor and outdoor environments and that lowest risk of airborne COVID-19 infection occurred at less than 30 minutes of exposure indoors and less than 60 minutes outdoors (Miller preprint)**.**

CONTACT TRACING AND TESTING

CU Boulder COVID-19 response included a multi-layered mitigation approach including testing, tracing, non-pharmaceutical interventions, and environmental controls. Given the potential for a relatively high frequency of asymptomatic cases among our core age demographic (18-22 years), a monitoring testing platform (saliva-based PCR) through our academic labs to compliment the more common diagnostic testing platform offered through our student health clinic (Medical Services). In fall 2020, we required students living in residence halls and recommended off-campus students to participate in weekly monitoring testing and by spring 2021, we required anyone accessing campus facilities to test weekly. If viral signs were detected through monitoring, individuals were referred for diagnostic testing. Once an individual affiliated with CU Boulder tests positive (diagnostic), CU Boulder's case investigation and contact tracing team would issue isolation and quarantine orders in partnership with our local public health authority (Boulder County Department of Public Health). Residential students were moved to isolation spaces on-campus while off-campus students were asked to isolate in-residence. Case investigation was conducted to identify close contacts while trained student contact tracers would issue quarantine and testing guidance for close contacts. Face-coverings were required in all campus facilities and strict limitswere placed on density and capacity for events.

ENGINEERING CONTROL MEASURES

The engineering control measures were based on enhancing the quality and quantity of air via containment, dilution and duration. Regardless of the type of HVAC system for the various campus buildings creating equivalency of risk in each building is essential in minimizing transmission. With varying types of HVAC systems three primary strategies were developed and then hybrid approaches of the three were applied campus wide. The three types of systems are one hundred percent outside air systems, return air systems with minimum outside air, and naturally ventilated spaces. Increased filtration was employed along with purging the space between occupants and having breaks every ½ hour or hour depending on the activity.

Increasing the quantity of air per person was employed for all buildings through extended operational hours, extended outside air economiser operational hours, decreased density of occupants, and mask mandates as required by the state of Colorado.

Containment Engineering Control Measure

Creating the outdoor environment inside was achieved through operational modes of the HVAC systems coupled with enhanced filtration. Due to the climate in Boulder Colorado approximately 80% of the school year 100% outside air can be employed for ventilation as well as heating and cooling the building (ASHRAE 90.1,2019) (eia, HDD and CDD). Control sequences were extended to the limits of the system sizing to maximize outside air based on temperature.

Increased filtration consisted of installing MERV 13 and higher in all air handling units, Fan Coil Units, and recirculated units. The MERV 13 filters captures the COVID virus size (Marr, 2020) and it has been shown that improved filtration can reduce aerosol airborn infection risk (Azimi, Stephens, 70). See dilution and duration measures below to address smaller particle sizes not addressed by containment.

In spaces where natural ventilation via operable windows are the primary means of ventilation, portable HEPA cleaners were deployed. The portable air cleaners added filtration and capture opportunities in spaces that did not have the benefit of mechanical systems to capture the virus from being re-circulated in spaces. HEPA's airflow placement and performance were informed by fogger tests conducted by the team. In spaces where MERV13 filters could not be installed and were 100% recirculated, these units were turned off.

Dilution Engineering Control Measure

In addition to employing outside air economizer modes and minimizing return air and capturing the virus through filtration principles, distancing allowed for more outside air per person in occupied spaces. Distancing measures were recommended to be at least 2 m. On average most systems were sized for a 10% of outside air per person rate. With decreased densities HVAC systems had approximately 70% to 100% more outside air per person than the HVAC system was designed for.

Duration Engineering Control Measure

In addition to the containment and dilution control measures, smaller aerosol particles potentially not captured by HEPA or MERV 13 filters or increased outside air were managed by limiting the duration of activity as was informed by the emerging science of Shelly Miller performers aerosol study (Miller preprint).

Summary

FIGURE 1 Is a summary (Horn, 2020) of the layered control measures implemented at CU Boulder and how they have contributed to increased quantity and quality of the air in the occupied environment compared to Pre-COVID**.**

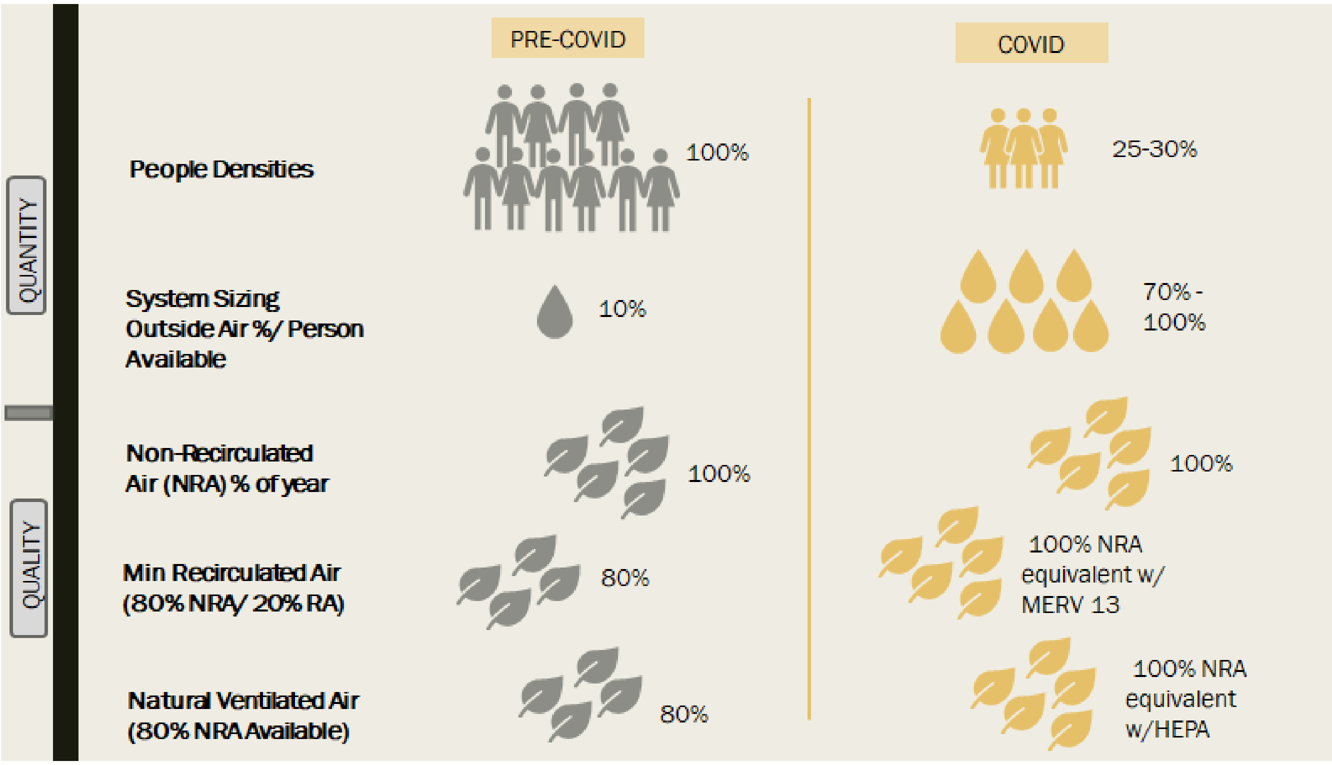

Figure 1 graphical summary of the layered mitigation approach implmenetd by CU Boulder

FINDINGS

The benefit of working at a University is the ability to understand how effective the control measures are, the application of Science and discovering other variables that were potentially unknown. Temperature and CO_2 were monitored and trended across campus where available to determine how effective the control measures and indoor conditions correlated to any outbreaks that occurred across campus. Due to the accuracy of CO_2 sensors installed in several buildings and how quickly these sensors loose calibration, additional or higher grade 3M^{TM} EVM 7 Advanced Particulate and Air Quality Monitors were employed to validate the quality of the air. These measurements are still ongoing but preliminary results indicate that containment and dilution were contributing factors resulting in zero transmission of the virus in classroom spaces. By July of 2021 the team will have completed collecting data to confirm these preliminary findings from the spring Semester. The indoor environment was better than the outdoor environment based on particles and CO_2 levels respectively.

Through campus case investigation and contact tracing, we were not able to identify COVID-19 transmission in our classrooms. The vast majority of transmission arose off-campus through in-person gatherings where no engineering control measures were employed.

The team also discovered that temperature has a correlation with CO_2 and could be used as another indicator to determine if spaces are poorly ventilated. This could be considered another option when CO_2 sensors are not available.

CONCLUSION

Aerosol transmission both long-range and short-range have been determined to be factors in the transmission and subsequent COVID-19 infection. Addressing the quality and quantity of air for the indoor environment are essential through containment, dilution and duration control measures. Additional critical strategies are mask mandates and distancing coupled with tracing and testing. These measures include increased outside air, increased filtration to reduce particulate matter and viral load in the space and shortening the duration of high aerosol activities to limit the amount of viral load accumulation in a space. Viral load was also minimized by factoring the amount of time needed to purge a space with change in occupancy.

Correlation of temperature and CO_2 can be used as indicators of the quality of the indoor environment. Correlating temperature to CO_2 and environmental quality could be an option used to determine risk level of any space when CO_2 or particulate counters are not an option.

A comprehensive multi-layered approach is essential for determineing the effectiveness of control strategies as well as minimizing the risk of transmission for air borne infectious diseases**.**

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REFERENCES

ASHRAE. 2019. ANSI/ASHRAE/IES Standard *90.1-2019 Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta: ASHRAE

Azimi, P., Keshavarz, Z., Laurent, J. G. C., Stephens, B., Allen, J. G. 2021. Mechanistic Transmission Modeling of COVID-19 on the Diamond Princess Cruise Ship Demonstrates the Importance of Aerosol Transmission. *PNAS 118* (8). https://doi.org/10.1073/pnas.2015482118.

CU Boulder COVID Research Solutins for Campus (Webinar Series). August 6, 2020. "Webinar #1 Aersols, HVAC Buildings & Classrooms." Slide Deck, Slide 9. Accessed April 20, 2021 https://www.colorado.edu/researchinnovation/sites/default/files/attached-files/covidsolutions-webinarslides-aug6.pdf

CU Boulder Today. March 17, 2021. "The magic of RNA: From CRISPR to Coronavirus Vaccines" with Nobel Laureate Tom Chech." Accessed April 20, 2021. https://www.colorado.edu/today/2021/03/01/nobel-laureate-explore-gene-editing-covid-19-vaccines-march-17-talk

Eia, U.S. Energy Information Admisnstration. 2019 Heating and Cooling Degree day Calculators. Accessed April 20, 2021 https://www.eia.gov/energyexplained/units-and-calculators/degree-days.php

Li, Y.; Qian, H.; Hang, J.; Chen, X.; Cheng, P.; Ling, H.; Wang, S.; Liang, P.; Li, J.; Xiao, S.; Wei, J.; Liu, L.; Cowling, B. J.; Kang, M. Probable Airborne Transmission of SARS-CoV-2 in a Poorly Ventilated Restaurant. *Building and Environment* **2021**, *196*, 107788. https://doi.org/10.1016/j.buildenv.2021.107788

Lednicky, J.A., Lauzardo, M., Fan, Z.H., Jutla, A., Tilly, T.B., Gangwar, M., Usmani, M., Shankar, S.N., Mohamed, K., Eiguren-Fernandez, A., Stephenson, C.J., Alam, M.M., Elbadry, M.A., Loeb, J.C., Subramaniam, K., Waltzek, T.B., Cherabuddi, K., Morris, J.G., Wu, C.-Y., 2020. Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. *Int. J. Infect. Dis*. 100, 476-482. https://doi.org/10.1016/j.ijid.2020.09.025

Marshall, Lisa. April 10, 2020. "Scientist developing COVID-19 test that knows you're sick before you do." Accessed April 20, 2021. https://www.colorado.edu/today/2020/04/10/scientists-developing-covid-19-test-knows-youre-sick-you-do Miller, S. L.; Nazaroff, W. W.; Jimenez, J. L.; Boerstra, A.; Buonanno, G.; Dancer, S. J.; Kurnitski, J.; Marr, L. C.; Morawska, L.; Noakes, C. Transmission of SARS-CoV-2 by Inhalation of Respiratory Aerosol in the Skagit Valley Chorale Superspreading Event. *Indoor Air* **2021**, *31* (2), 314–323. https://doi.org/10.1111/ina.12751

Miller preprint. https://scholar.colorado.edu/concern/articles/hq37vp75r

Morawska,Lidia, Milton, Donald K. 2020 "It Is Time to Address Airborne Transmission of Coronavirus Disease 2019 (COVID-19) July 6, 2020. IDSA. Accessed April 20, 2021 https://academic.oup.com/cid/article/71/9/2311/5867798

Ong, S.W.X., Tan, Y.K., Chia, P.Y., Lee, T.H., Ng, O.T., Wong, M.S.Y., Marimuthu, K., 2020. Air, Surface Environmental, and Personal Protective Equipment Contamination by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) From a Symptomatic Patient. *JAMA* 323, 1610. https://doi.org/10.1001/jama.2020.3227

Santarpia, J.L., Rivera, D.N., Herrera, V.L., Morwitzer, M.J., Creager, H.M., Santarpia, G.W., Crown, K.K., Brett-Major, D.M., Schnaubelt, E.R., Broadhurst, M.J., Lawler, J.V., Reid, S.P., Lowe, J.J., 2020. Aerosol and surface contamination of SARS-CoV-2 observed in quarantine and isolation care. *Sci. Rep.* 10, 1–8. https://doi.org/10.1038/s41598-020-69286-3