Infection Prevention in Practice 3 (2021) 100170

Available online at www.sciencedirect.com

Infection Prevention in Practice

journal homepage: www.elsevier.com/locate/ipip

Evidence-based aerosol clearance times in a healthcare environment

Seth A. Hara [a], Timothy L. Rossman [a], Lukas Johnson [b], Christopher J. Hogan [c], William Sanchez [d], David P. Martin [e], Mark B. Wehde [a,*]

[a] Division of Engineering, Mayo Clinic, Rochester, MN, USA
[b] Division of Facilities Management, Mayo Clinic, Rochester, MN, USA
[c] University of Minnesota, Minneapolis, MN, USA
[d] Gastroenterology, Mayo Clinic, Rochester, MN, USA
[e] Anesthesiology and Perioperative Medicine, Mayo Clinic, Rochester, MN, USA

ARTICLE INFO

Article history:
Received 21 April 2021
Accepted 10 August 2021
Available online 14 August 2021

Keywords:
Aerosol
COVID-19

SUMMARY

Background: As researchers race to understand the nature of COVID-19 transmission, healthcare institutions must treat COVID-19 patients while also safeguarding the health of staff and other patients. One aspect of this process involves mitigating aerosol transmission of the SARS-CoV2 virus. The U.S. Centers for Disease Control and Prevention (CDC) provides general guidance on airborne contaminant removal, but directly measuring aerosol clearance in clinical rooms provides empirical evidence to guide clinical procedure.

Aim: We present a risk-assessment approach to empirically measuring and certifying the aerosol clearance time (ACT) in operating and procedure rooms to improve hospital efficiency while also mitigating the risk of nosocomial infection.

Methods: Rooms were clustered based on physical and procedural parameters. Sample rooms from each cluster were randomly selected and tested by challenging the room with aerosol and monitoring aerosolized particle concentration until 99.9% clearance was achieved. Data quality was analysed and aerosol clearance times for each cluster were determined.

Findings: Of the 521 operating and procedure rooms considered, 449 (86%) were issued a decrease in clearance time relative to CDC guidance, 32 (6%) had their clearance times increased, and 40 (8%) remained at guidance. The average clearance time change of all rooms assessed was a net reduction of 27.8%.

Conclusion: The process described here balances the need for high-quality, repeatable data with the burden of testing in a functioning clinical setting. Implementation of this approach resulted in a reduction in clearance times for most clinical rooms, thereby improving hospital efficiency while also safeguarding patients and staff.

© 2021 The Authors. Published by Elsevier Ltd on behalf of The Healthcare Infection Society. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

* Corresponding author. Address: 200 First St. SW, Rochester, MN, 55904, USA. Tel.: +507-284-2519.
E-mail address: Wehde.mark@mayo.edu (M.B. Wehde).

https://doi.org/10.1016/j.infpip.2021.100170
2590-0889/© 2021 The Authors. Published by Elsevier Ltd on behalf of The Healthcare Infection Society. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Introduction

The COVID-19 pandemic has strained the staffing and facilities resources of healthcare systems around the world. As researchers race to understand the nature of the disease and how it is transmitted, healthcare institutions must work with the knowledge at hand to treat COVID-19 patients while also safeguarding the health of staff and other patients. One aspect of this process involves mitigating aerosol transmission of the SARS-CoV2 virus.

The mechanism of transmission for the SARS-CoV2 virus is actively under investigation and aerosol transmission is a serious concern for nosocomial infection [1—5]. For that reason, known COVID-19 patients are often placed in airborne infection isolation rooms (AIIR), if available, to limit exposure to others [6]. However, there is also a risk of transmission from unconfirmed COVID-19 cases, especially when potentially aerosol generating procedures (AGP) are performed [7] [1]. While recently there has been increased interest in better quantifying aerosol production in "aerosol generating procedures," commonly the phrase refers to clinical procedures that potentially increase the risk of aerosolizing infectious particles [8—10]. When these procedures are performed, the aerosolized infectious particles that are generated must be removed from the room to prevent aerosol transmission of the virus.

As healthcare institutions seek to identify best practices, guidance on airborne contaminant (in this case, aerosolized infectious particles) removal is provided by the U.S. Centers for Disease Control and Prevention (CDC) in the form of timetables based on air exchange rate [6]. Hospital administrators can use these tables and the air exchange rate for a particular room to determine policy regarding when staff can enter said room without adhering to transmission-based precautions [11] and when the next patient can be roomed. In this way, policy can be created from a risk-assessment approach to balance infection control with patient needs. As the reality of the COVID-19 pandemic became clear, healthcare administrators relied heavily on this CDC guidance to implement infection control policies.

The time required to remove infectious aerosol particles from a room presents competing challenges regarding: (1) allowing adequate clearance time to ensure the safety of patients and staff and (2) reducing room downtime to improve hospital efficiency and patient care. As such, there is a strong motivation to use the most accurate and reliable information possible to balance these competing needs and ensure that enough time is allowed to provide a safe environment while also efficiently allocating the scarce resource of procedure and operating rooms for patient care.

The times provided by the CDC guideline tables are based on a single parameter—air exchange rate—whereas aerosol clearance is a complex, multi-factor phenomenon where aerosol particles may clear the air through settling and deposition in addition to ventilation [12—14]. As such, directly measuring aerosol clearance in operating and procedure rooms provides empirical evidence for the time required to reduce aerosols from a room. In this work, we present a risk-assessment approach to measuring and certifying the aerosol clearance time (ACT) in operating and procedure rooms to improve hospital efficiency while also mitigating the risk of nosocomial infection.

[1] It should be noted that "aerosol" as used in the acronym "AGP" did not derive from any specific physics related to "aerosol" as defined in aerosol science literature. This has led to significant confusion when the COVID-19 pandemic hit the medical community in early 2020. In this work, "aerosol" refers to solid or liquid particles suspended in air.

Methods

Room identification and clustering

Given that Mayo Clinic's Rochester campus has several thousand procedure and operating rooms where airborne transmission may be a concern, testing each individual room was deemed impractical and overly burdensome for the clinical setting. Testing was prioritized for areas conducting the most high-risk procedures with high patient volumes. To efficiently canvas these rooms for testing, grouping was performed using clinical and facility-based shared characteristics (Figure 1). From a clinical perspective, the various types of AGP were ranked according to relative risk (Supplemental Material, Figure 1). This was done in collaboration between specialists in infectious diseases, surgeons, and anaesthesiologists, based on the probability of aerosol generation as well as the underlying probability of contagion of the patient based on testing and symptoms. Clinical departments were then surveyed and rated each of their rooms according to the ranking system. The rooms rated medium or high risk began using the CDC guidelines to determine aerosol clearance times for all AGP occurrences and were also grouped by building and department in preparation for ACT testing. In this way, rooms served by the same types of air handling units and with similar equipment, layout, and furnishings would be grouped together. Finally, heating, ventilation, and air conditioning (HVAC) characteristics further clustered rooms to those whose and air changes per hour (ACH) were within 15%. Each cluster had one room scheduled to have three unique clearance tests conducted and another a single clearance test conducted. This approach minimized clinical disruption with the full test providing confidence in repeatability within a room and the spot test giving assurance the clustering was performed properly.

Test procedure

Aerosol concentration was measured with TSI® condensation particle counters (CPC, models 8525 and 3007, ±15% measurement uncertainty), chosen for their portability and capability to detect a range of particle sizes (0.01 to >1.0 um). Although virus-containing bioaerosols also contain larger particles (0.2—100 μm), it was critical to capture particles in this range since they are known to be generated through normal respiratory processes at high concentrations and are more likely to remain suspended in an aerosol than larger particles [3,6,15]. To generate non-toxic polydisperse aerosols that mimic bioaerosols, a 2% (by weight) sodium chloride solution was dispersed into the air with one or two consumer-grade ultrasonic humidifiers (number depending on room size and airflow). These aerosol generators dispersed large amounts of aerosol particles (1.00 μm geometric mean, 1.38 μm geometric standard deviation) in short periods of time, allowing initial

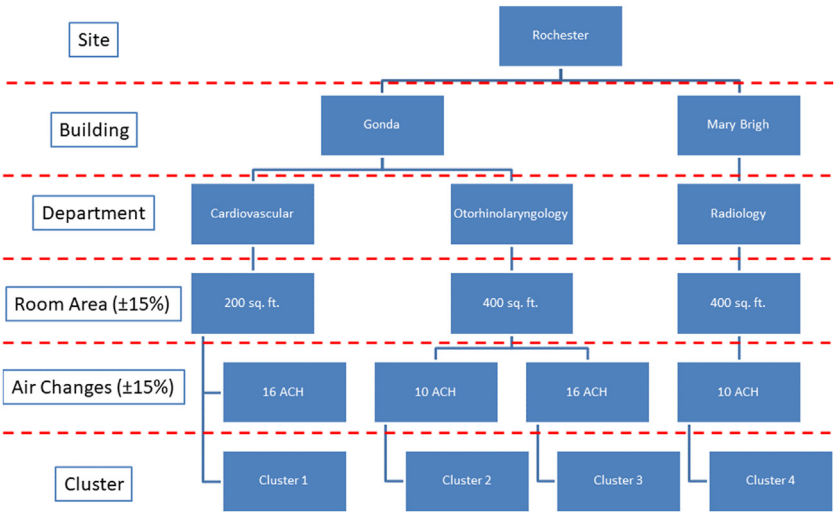

Figure 1. Example flowchart of room cluster breakdown. "ACH" stands for "air changes per hour."

particle concentrations to be reached even in high air exchanges per hour (ACH) rooms.

The field tests were performed by initially visually surveying the room for clinical use and air supply/return points to determine the generator and CPC placement. HVAC systems were held at steady-state and at their minimum airflow settings in order to evaluate the worst-case scenario for aerosol removal. The aerosol generators were placed where the AGP source would occur (typically a bed or chair). Two CPCs were co-located and positioned along a line equidistant between the generator and an air return grille (Supplemental Material, Figure 2). Multiple CPCs allowed for detection of instrument problems in real-time, minimizing further clinical disruption from retesting. Each CPC first measured the background particle count present in the circulating air. The count was recorded and later used to baseline the particle counts measured during the clearance test (i.e. background counts were subtracted when determining clearance times). While background concentrations varied from room to room, they were typically of the order 10^2 particles per cm^3. Testing began by operating the aerosol generators until the room reached a particle count of $\sim$10,000 particles per cm^3. The generators were then stopped and the peak concentration was noted. Concentrations were recorded every 60 seconds until 99.9% of the peak particle concentration was removed from the room air (see Supplementary Materials for example calculation). Particle concentration was recorded until 99.9% clearance was directly measured, as opposed to determining the clearance rate with a subset of data points and extrapolating clearance time using linear regression on the log-transform of those points. While the latter is a conventional approach to determination of air change rate, this method was selected to account for any transients or irregularities that may occur during testing and ensure that true clearance was directly observed. For the duration of the clearance time, personnel movement in the room was minimal and all entryways were closed. Whenever possible throughout testing, the room air supply flow rates were verified and continuously monitored in the HVAC control system.

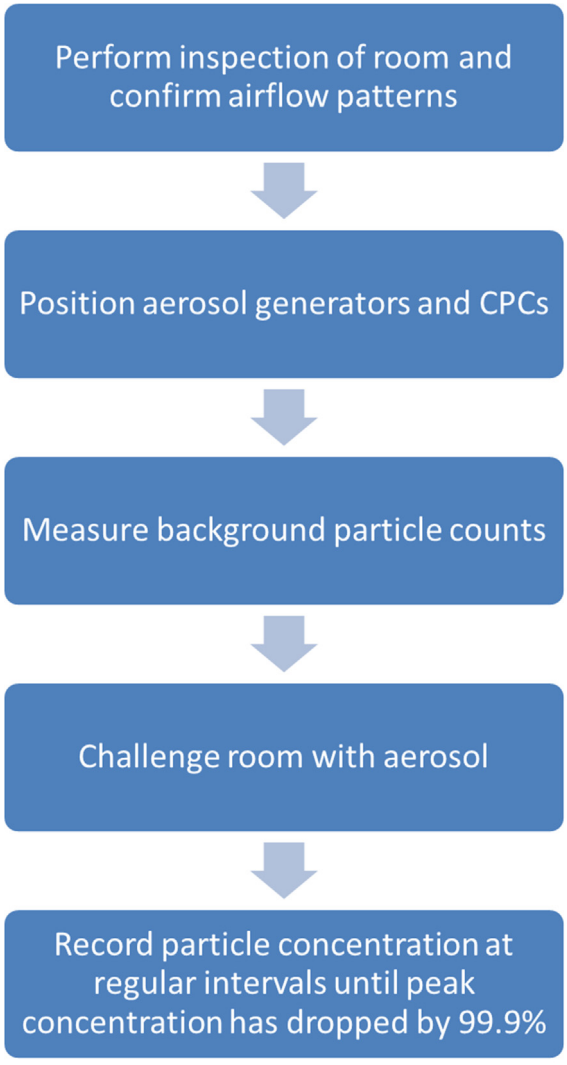

Figure 2. Aerosol clearance test procedure.

Data analysis

For each room cluster, the test runs from the full test room and spot test room were inspected to ensure consistent decay rates visually when graphed on a semi-log chart, otherwise the room(s) were re-tested. If deemed consistent, the average ACT from the full test room was compared to the spot test ACT. Provided the variation of the clearance times was within 15%, the longer of the two ACTs was selected for the room cluster, thereby providing the more conservative ACT for the cluster. If the variation was larger, the HVAC conditions in the tested rooms were verified (i.e., supply/return airflows checked and/or room clustering was reviewed). If HVAC conditions were correct, another spot test room was added to the cluster to confirm cluster ACT. If unacceptable variation still remained that could not be explained solely from HVAC differences, additional action was undertaken on a case-by-case basis, such as retesting all rooms in the cluster or further breaking the cluster into smaller clusters having acceptable variation. This verification step helped ensure that the clustering and sampling process properly captured the characteristic behaviour of the rooms within the cluster. Once the test data were verified, they were compared to the ACT recommended by the CDC guidelines. If the measured ACT was within 15% of the CDC guidance-based ACT, no change was implemented. If the measured ACT was less than the CDC guidance-based ACT by 15% or more, the certified ACT was reduced. If it was instead greater than the CDC guidance-based ACT by 15% or more, the certified ACT was increased. Certified times were communicated with clinical leadership and informed clinical policy decisions. Occasionally, rooms were certified to longer ACTs than were measured to simplify clinical operations and reduce confusion amongst staff by aligning with nearby rooms measured with longer ACTs.

Results

Within the Mayo Clinic — Rochester campus, over 560 operating and procedure rooms were identified by clinical staff as high risk for AGPs, and over 160 of those were tested to determine their ACT. These rooms were grouped into 113 clusters, as described above, with 1—44 rooms in each cluster. The test process provided empirical evidence for the certification of ACTs of high risk AGP rooms across the Clinic.

Approximately 77% of the rooms tested showed the opportunity to reduce clearance times an average of 38%. Of the remaining rooms, 15% showed ACTs that were comparable to the CDC-recommended guidelines and 8% of the rooms required longer times to achieve the target clearance. The measured ACT distribution shifted dramatically lower (Figure 3), with 31% of the rooms clearing 99.9% of aerosols in 19 minutes or less and 67% clearing in 29 minutes or less (compared with only 7% and 40% of rooms, respectively, when using CDC guidance).

Based on the test results, a total of 521 operating and procedure rooms were considered for revised clearance times (excluding the room clusters where mitigation measures were implemented). Of these, 449 rooms (86%) were issued a decrease in ACT relative to CDC guidance, 32 (6%) had their ACTs increased, and 40 rooms (8%) remained at guidance. The average ACT change of all rooms assessed was a net reduction of 27.8%. Generally, the largest clearance time reductions came in rooms with the longest CDC guidance-based ACTs (Figure 4), with the ≥60 minutes group experiencing an average reduction of 44%. In contrast, the room groups with CDC guidance-based ACTs from 10-19 minutes and 20—29 minutes experienced the least benefit from direct measurement of ACT (18% reduction).

Typical aerosol clearance test data are shown in Figure 5. The peak concentration reached during this aerosol challenge

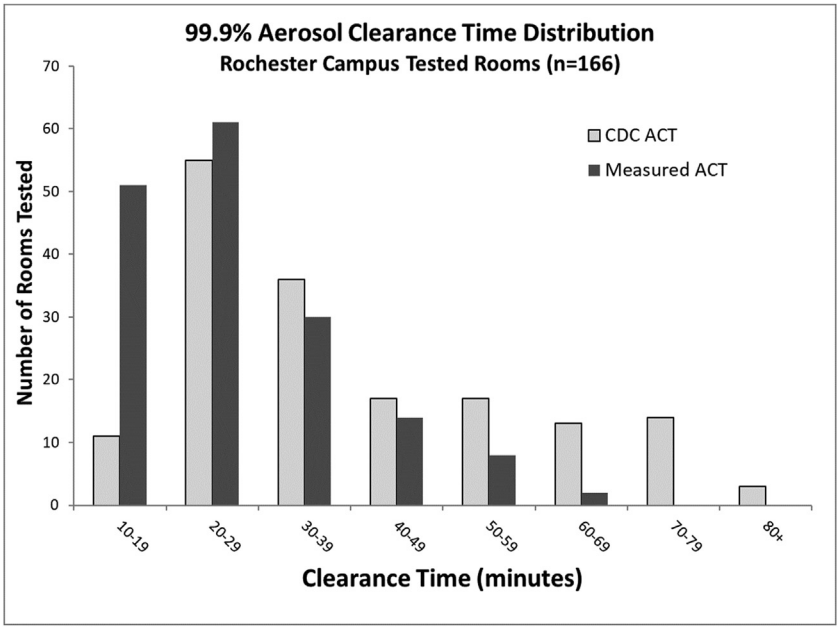

Figure 3. Comparison of time distributions for tested rooms to achieve 99.9% aerosol clearance.

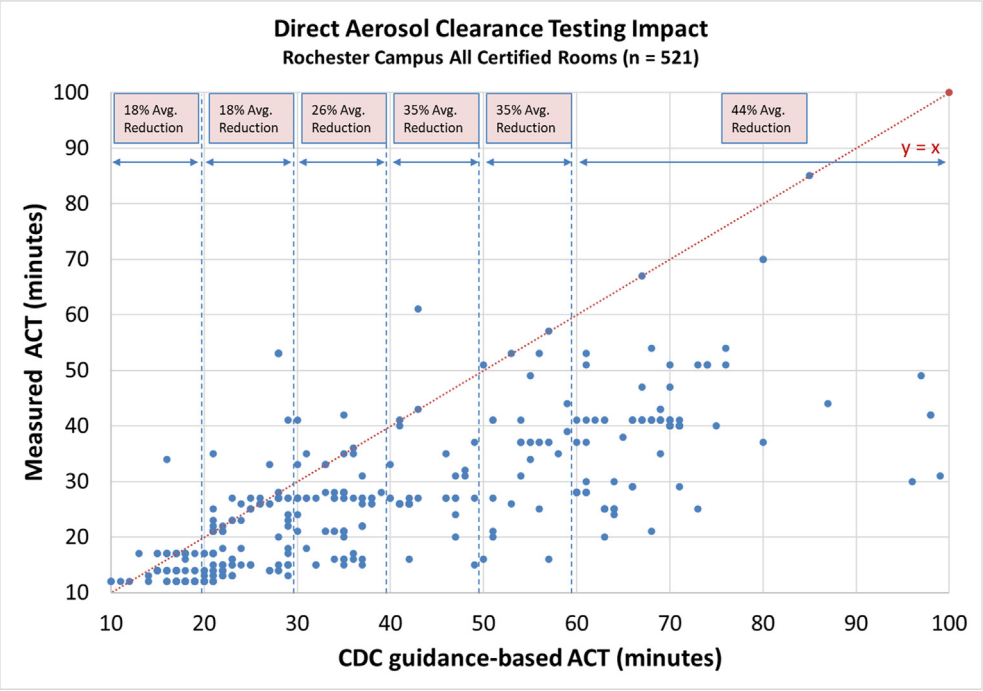

Figure 4. Impact of ACT testing on all rooms certified by this method. The y=x line is overlayed to indicate where measurements would lie in the event of perfect alignment with CDC guidance. The average reduction in ACT for rooms grouped according to CDC guidance-based ACTs is noted at the top of the graph.

was slightly above 10,000 pt/cm^3, resulting in a 99.9% clearance concentration of 295 pt/cm^3 after accounting for the background concentration of 284 pt/cm^3. The three tests in this room exhibited repeatable results with 99.9% clearance times of 21, 20, and 24 minutes, yielding an average clearance time of 22 minutes when rounded to the next largest minute

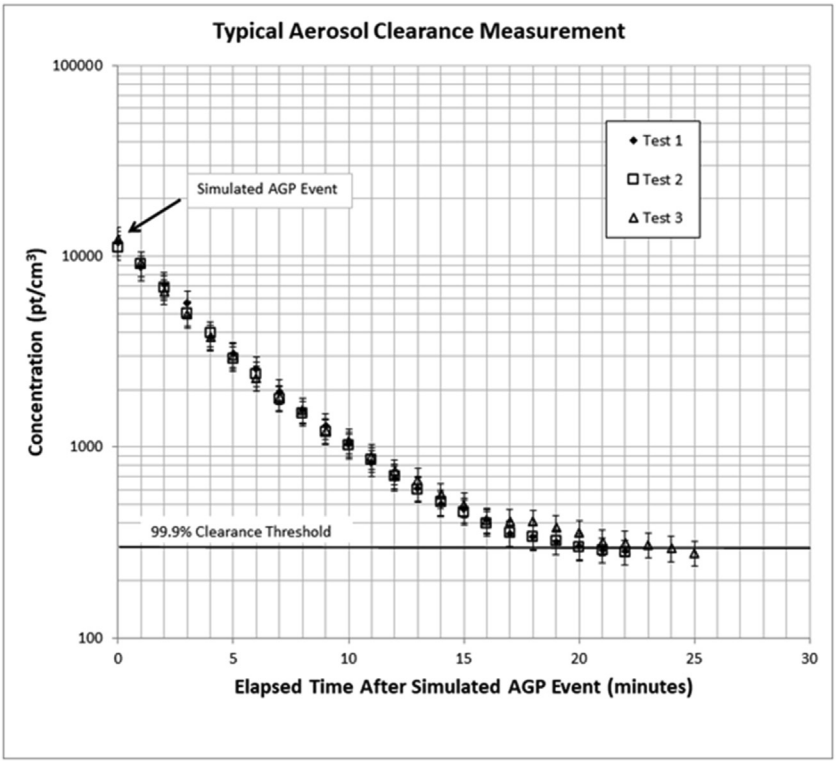

Figure 5. Sample aerosol clearance measurement data plot. The 99.9% clearance threshold was calculated with consideration of the background particle concentration measured prior to the simulated AGP event. Error bars represent the ±15% uncertainty of the CPCs.

interval. The other room making up this two-room cluster had a clearance time of 19 minutes, meeting the 15% variation allowance allowing the rooms to be certified with an ACT of 22 minutes (the larger of the two times).

Discussion

Clinical impact

As a result of this testing, a total of 6,494 minutes was reduced from the aggregate clearance time of 521 operating and procedure rooms, an overall reduction of 33%. These reductions benefited clinic operations in multiple ways over the course of the pandemic and the heightened precautions for aerosolized infectious particles. For example, with reduced ACTs, staff could clean and prepare rooms for subsequent patients sooner and without using valuable personal protective equipment (PPE). These measures complemented risk-mitigation measures, such as mandatory masking on campus, and contributed to Mayo Clinic's ability to serve more than 1.3 million patients in the year 2020 [16].

The clinical impact at Mayo Clinic has been tangible and the process described here could be similarly beneficial for other institutions. Recognizing that not all institutions can or want to replicate this work, some recommendations for doing so are given in the Supplemental Material.

Additional benefits of testing

In addition to the data gathered supporting decreases in ACTs for most operating and procedure rooms, some unexpected benefits from this process arose. As detailed above, 6% of the rooms evaluated (32 rooms) were certified at a longer ACT compared to the time indicated by CDC guidance. Of those 32 rooms, 11 were issued an increase in ACT for administrative purposes, as discussed earlier. Excluding those rooms, 4% of rooms evaluated demonstrated a need for an increased ACT. This indicated that the procedure outlined here captured instances where the generalized CDC guidance was not sufficient and clinical policy could be adjusted accordingly to ensure staff and patient safety. That is not to say that the CDC guidance itself is not worthwhile. On the contrary, the data suggest it is solid guidance. The ACT recommended by the CDC guidance was greater than or equal to the measured ACT 96% of the time, thereby providing a safe clinical environment for patients and staff.

Furthermore, this testing highlighted differences between certain HVAC system designs and components, which will be considered in future construction projects. For example, it was observed that ducted return air systems generally performed better than plenum return air systems, filtration levels that are typically applied in fan coil units were found to underperform compared to centralized air handling systems, and displacement ventilation systems generally did not meet expected clearance times. Perhaps the most generalizable learning in this area was that airflow balancing to ensure accurate return airflow was critical to minimize ACT variation within room clusters. Many of the rooms that were found to need an increase in ACT compared to the CDC guidance-based time were found to have at least one of these characteristics.

HVAC remediation strategies

Rooms that were found to have inadequate ACTs (e.g., rooms found to have ACTs longer than CDC clearance times) were addressed with various HVAC remediation strategies. In areas where there was additional capacity in the existing infrastructure, the air flow was increased to successfully improve clearance. Occasionally, filters in fan coil units could be replaced with filters with higher minimum efficiency reporting value (MERV) ratings to adequately improve ACT. However, many environments did not have infrastructure that allowed for these sorts of minor modifications. In those instances, portable recirculating high efficiency particulate air (HEPA) filter units were often successfully employed to reduce clearance times. Although effective, this remediation strategy is less desirable since it is an active remediation and relies on clinical staff to activate the unit. While seemingly trivial, this extra step introduces the possibility for human error, especially in the clinical environment where additional procedures are already in place to address the risk of nosocomial infection. For situations where floor space was unavailable or more permanent remediation was desired, ceiling-mounted HEPA filter units were installed.

Discrepancy with CDC guidance

To comprehensively understand the discrepancy between the ACT measurements and the clearance times recommended by the CDC tables, a robust analytical study must be conducted. As that was not the intent and outside of the scope of the present work, only a few hypotheses are offered here. Some physical phenomena that are not adequately accounted for with air exchange rate are particle dispersion and deposition. Airborne particles disperse and deposit on surfaces, thereby removing them from the air without being carried away by air circulation [12,14]. This is especially true in rooms with increased surface areas due to furniture and equipment, as is the case in operating and procedures rooms [13]. In fact, the data collected in this work showed that rooms with lower air exchange rates showed more of a reduction of ACT when compared to CDC guidance than rooms with higher air exchange rates. This is consistent with particle deposition becoming a more significant factor when there are longer settling times and less air movement. A second possibility is that the position of the supply diffusers and return grilles created faster clearance rates for particles generated from specific points. This would certainly vary room-to-room and would require detailed study of airflow patterns in each room to better characterize.

Limitations of study

The primary goal of the work was to improve clinical care and safety, not to study aerosol clearance. As such, compromises were made that would not have been necessary in an experimental setting. One such limitation is the sample size used for each cluster. The two rooms tested for each cluster are not necessarily a representative sample size. However, a risk-based decision was made to minimize the clinical burden of testing while making all possible efforts to ensure the collected data was meaningful and useful.

Another limitation was the use of two CPCs in a single location. While the two units provided redundancies to account for instrument failure, this procedure did not capture any possible "dead zones" in the room where aerosols may stagnate and linger. Initial testing across various room types and layouts indicated that clearance throughout the rooms was comparable and the effect of "dead zones" would be minimal. Therefore, to ease the burden of testing to the clinical schedule, a single test location was used for this study.

The procedure described here attempts to capture a room's ability to clear aerosols by measuring all airborne particles present in the air. The instruments cannot distinguish between particle types, but respond identically to the particles emitting from the aerosol generators as they do to particles that may be naturally present in the environment. Precautions were taken to minimize environmental noise factors such as air quality changes near building air intakes, fluctuations in ventilation rate, or even particle shedding from equipment or personnel in and around the room being tested. This proved particularly challenging with positive pressure and negative pressure rooms since the source and destination of particles are difficult to track with the present setup.

Conclusion

The process described here provides a risk-assessment approach to evaluating aerosol clearance times for operating and procedure rooms in a healthcare environment. It was designed to balance the need for high-quality, repeatable data with the burden of testing in a functioning clinical setting. Our team successfully implemented this process within the Rochester campus of Mayo Clinic, testing over 160 operating and procedure rooms and using that data to certify over 500 rooms. The data collected provided a solid foundation to reduce the aerosol clearance times of the majority of the rooms evaluated, while also highlighting rooms that were not performing as expected so that any faults could be addressed. We believe this process is a pathway to determining aerosol clearance times based on empirical evidence in order to ensure a safe environment while also wisely allocating the scarce resource of procedure and operating rooms for patient care.

Credit author statement

Seth Hara: Conceptualization, Methodology, Formal Analysis, Writing — Original Draft. Tim Rossman: Conceptualization, Methodology, Formal Analysis, Writing — Review and Editing. Lukas Johnson: Conceptualization, Methodology, Formal Analysis, Writing — Review and Editing. Christopher Hogan: Conceptualization, Methodology, Formal Analysis, Writing — Review and Editing. William Sanchez: Conceptualization, Methodology, Formal Analysis, Writing — Review and Editing. David Martin: Conceptualization, Methodology, Formal Analysis, Writing — Review and Editing. Mark Wehde: Conceptualization, Methodology, Formal Analysis, Writing — Review and Editing, Project administration, Funding Acquisition.

Acknowledgements

This work would not have been possible without the leadership and technical guidance of Mr. Tom Halvorsen. Additionally, the authors thank team members in the Division of Engineering, Division of Facilities Management, clinical operations, and clinical leadership at Mayo Clinic for their contributions to this work. During this study, Christopher Hogan received compensation as a consultant to Mayo Clinic.

Conflict of interest statement

None.

Funding source

Funding for was provided internally by the Mayo Clinic Midwest Clinical Practice Committee.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.infpip.2021.100170.

References

[1] Tang S, Mao Y, Jones R, Tan Q, Ji J, Li N, et al. Aerosol Transmission of SARS-CoV-2? Evidence, Prevention and Control. Environ Int 2020;144:106039. https://doi.org/10.1016/j.envint.2020.106039.

[2] Edwards DA, Ausiello D, Salzman J, Devlin T, Langer R, Beddingfield BJ, et al. Exhaled aerosol increases with COVID-19 infection, age, and obesity. Proc Natl Acad Sci USA 2021;118:e2021830118. https://doi.org/10.1073/pnas.2021830118.

[3] National Academies of Sciences E and Medicine. Airborne transmission of SARS-CoV-2: proceedings of a workshop—in brief. Washington, DC: The National Academies Press; 2020. https://doi.org/10.17226/25958.

[4] Prather KA, Marr LC, Schooley RT, McDiarmid MA, Wilson ME, Milton DK. Airborne transmission of SARS-CoV-2. Science 2020;370:303—4. https://doi.org/10.1126/science.abf0521.

[5] Lednicky JA, Lauzardo M, Fan ZH, Jutla A, Tilly TB, Gangwar M, et al. Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. Int J Infect Dis 2020;100:476—82. https://doi.org/10.1016/j.ijid.2020.09.025.

[6] (545922006-001) Guidelines for environmental infection control in health-care facilities. 2003. https://doi.org/10.1037/e545922006-001.

[7] Berges AJ, Lina IA, Ospino R, Tsai H-W, Brenner MJ, Pandian V, et al. Quantifying Viral Particle Aerosolization Risk During Tracheostomy Surgery and Tracheostomy Care. JAMA Otolaryngol Head Neck Surg 2021. https://doi.org/10.1001/jamaoto.2021.1383.

[8] Brown J, Gregson FKA, Shrimpton A, Cook TM, Bzdek BR, Reid JP, et al. A quantitative evaluation of aerosol generation during tracheal intubation and extubation. Anaesthesia 2021;76:174—81. https://doi.org/10.1111/anae.15292.

[9] Nestor CC, Wang S, Irwin MG. Are tracheal intubation and extubation aerosol-generating procedures? Anaesthesia 2021;76:151—5. https://doi.org/10.1111/anae.15328.

[10] Dhillon RS, Rowin WA, Humphries RS, Kevin K, Ward JD, Phan TD, et al. Aerosolisation during tracheal intubation and extubation in an operating theatre setting. Anaesthesia 2021;76:182—8. https://doi.org/10.1111/anae.15301.

[11] Siegel JD, Rhinehart E, Jackson M, Chiarello L. 2007 Guideline for Isolation Precautions: Preventing Transmission of Infectious Agents in Health Care Settings. Am J Infect Control 2007;35:S65—164. https://doi.org/10.1016/j.ajic.2007.10.007.

[12] Lai AC K, Nazaroff WW. Modeling indoor particle deposition from turbulent flow onto smooth surfaces. J Aerosol Sci 2000;31:463—76. https://doi.org/10.1016/S0021-8502(99)00536-4.

[13] Thatcher TL, Lai ACK, Moreno-Jackson R, Sextro RG, Nazaroff WW. Effects of room furnishings and air speed on particle deposition rates indoors. Atmos Environ 2002;36:1811—9. https://doi.org/10.1016/S1352-2310(02)00157-7.

[14] Particle deposition indoors: a review. Indoor Air 2002;12:211—4. https://doi.org/10.1046/j.0905-6947.2002.1r159a.x.

[15] Gregson F, Watson N, Orton C, Haddrell A, Mccarthy L, Finnie T, et al. Comparing Aerosol Concentrations and Particle Size Distributions Generated by Singing, Speaking and Breathing Comparing Aerosol Concentrations and Particle Size Distributions Generated by Singing, Speaking and Breathing. Aerosol Sci Technol 2021. https://doi.org/10.1080/02786826.2021.1883544.

[16] Furst J. Meeting the challenges of a historic year: 2020 mayo clinic performance highlights. Mayo Clinic News Net 26-Feb-2021.