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Research Article

Elevator Ventilation and SARS-CoV-2-Relevant Particulate Matter Removal in Three Older California Elevators

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The objective of this study was to measure particulate matter (PM) total loss rates in three older (1940s, 1960s, and 1980s) elevators in California during two phases and three low-cost intervention modes. Tracer gas decay and <2 μm aerodynamic diameter nontoxic NaCl particles (PM_2) were used to calculate PM_2 loss rates. The NaCl particles were considered surrogates for smaller particles carrying SARS-CoV-2. Empirical PM_2 loss rates were paired with modeled dynamic scenarios to estimate SARS-CoV-2-relevant PM_2 removal. Mean loss rates (hr^{-1}) ranged from 1.8 to 184. Compared to a closed-door, stationary elevator, the moving elevators had a fourfold increased mean loss rate (hr^{-1}), while an air cleaner in a stationary elevator increased the mean loss rates sixfold. In a dynamic particle removal simulation of a ten-story elevator, PM was removed 1.38-fold faster with an air cleaner intervention during bottom and top floor stops only (express ride) and 1.12-fold faster with an air cleaner during every other floor stops. The increase in removal rates due to the air cleaner was modest due to the higher moving and open-door removal rates, except during stationary phase. The half-life of PM_2 particles in a stationary elevator after all passengers have left can be 8-12 minutes following a single emission and 2-5 minutes with an air cleaner. The low particle removal rate in the stationary elevator requires an intervention so that the particle removal rate will be high to eliminate infectious aerosol. If codes permit, keeping the door open when the elevator is stationary is most effective; otherwise, an air cleaner in a stationary elevator should be used. While an air cleaner is commonly seen as a substantial improvement in reducing potential virus concentration in air, in the moving elevator scenarios, the effect is quite modest. This paper provides empirical particle loss rates inside elevators, the effectiveness of air cleaners in a dynamic elevator space, two approaches to control infectious agents while the elevator is stationary, and support for a precautionary approach towards elevator use amidst a pandemic.

1. Introduction

Ventilation and particle loss rates are relevant to mitigating transmission of SARS-CoV-2 [1–4]. It is well established that SARS-CoV-2 is transmitted through the aerosol route [5, 6] and that small particles containing the virus can remain in the air for minutes [7, 8]. Small particles carrying virus can remain airborne in a shared space after the infected individual has left [9–12]. Additionally, the observation that viral particulate matter (PM) concentrations are reduced with ventilation [4, 13, 14] implies that areas with poor ventilation pose a higher risk for transmission of SARS-CoV-2. Crowded spaces such as elevators are especially of concern for transmission and have been implicated in two documented COVID-19 outbreaks that took place in an eight-floor shopping mall in China [15] and a Korean apartment complex [16].

To reduce SARS-CoV-2, aerosol transmission workplaces have implemented building and elevator-use protocols such as vaccination requirements, indoor masking policies, passenger occupancy limits, and a six-foot distancing rule [17, 18]. More recently, there has been an easing of these protocols [19], despite ongoing subvariant concerns [20] and long COVID [21]. To date, few studies [22, 23] have collected measurements of natural ventilation and particle loss rates in elevators. No studies have investigated ventilation and PM removal within older, nonhospital, elevators in the United States that lack mechanical ventilation. Studies instead have focused on modeled ventilation in ideal conditions without considering changing ventilation rates during different elevator operating conditions [24, 25]. Multiple studies using computational fluid dynamic models (i.e., Dbouk and Drikakis [26], Shao et al. [24], and a whitepaper by Chen and Otis Worldwide [25]) showed that ventilation rates increased during moving and intervention modes but did not provide experimental ventilation measurement data. van Rijn et al. [23] experimentally investigated European hospital elevators with added mechanical ventilation of 10 ACH during all phases and open-door interventions (e.g., propping open the doors between rides), which is not feasible in elevators due to safety reasons [27, 28]. Somsen et al. [22] identified elevators as a public space with low ventilation and relatively long aerosol half-life (5 minutes) and hence a public space posing a higher risk of infection. Thus, no experimental studies to date have measured natural ventilation, particle loss rates within US elevators, and the effect of using a portable air cleaner in PM removal during elevator use.

Previous literature has shown particle deposition and natural ventilation to be strong drivers of PM removal [4, 7, 29]. Elevator intervention strategies for improved ventilation may include propping doors open between rides or inserting air cleaning devices for filtration [13, 30, 31], such as high efficiency particulate air- (HEPA-) filtered air cleaning fans to increase the effective air change rate. Previous literature suggests [30–34] that a 120 cfm air-filtered fan is a reasonable tool that can be purchased at a standard retailer for under \$200. Elevator cabins installed with permanent decontamination units showed improved viral PM removal [35]. However, the costs incurred with this method are larger than a retail-available 120 cfm portable HEPA air-filtered fan, and installation of the air purifying units fit for older elevators was not mentioned.

To address the gaps in knowledge, we conducted an empirical study with two tracer agents to determine empirical particle loss rates in elevators. We used CO_2 to estimate the natural ventilation rate and a nontoxic sodium chloride (NaCl) PM_2 as a SARS-CoV-2 surrogate to measure total particle loss rates within an elevator during normal operation and interventions. First-order particle removal rates were calculated for normal and intervention modes. In addition, a simulation model was created to investigate PM_2 removal in an elevator following successive emissions.

2. Experimental Methods

2.1. Site Description. Three San Francisco Bay Area nonhospital, nonmechanically ventilated passenger elevators manufactured in three different decades (1940s, 1960s, and 1980s) were sampled in 2020 (Table 1). The baseline, temperature (°F), relative humidity (%RH), and background CO_2 indoors (PPM) were measured at each elevator prior to sampling (Supporting Information—Table SI-1).

2.2. Continuous Real-Time Aerosol and Carbon Dioxide Monitors. We used two continuous real-time instruments to measure environmental parameters in our study. TSI Q-Traks (8525 and 8552, *TSI Incorporated, Shoreview, Minnesota, USA*) were used to measure CO_2 concentrations (PPM), relative humidity (RH%), and temperature (°F) with measurements taken every second. A TSI SidePak with a $PM_{2.5}$ cyclone (AM510, *TSI Incorporated, Shoreview, Minnesota, USA*) was used to measure $PM_{2.5}$ mass concentrations (mg/m^3) with measurements taken every second to measure particles in the size range of 0.03-2.5 μm. All instruments were calibrated, and flow rates were checked before and after each sampling run.

2.3. Experimental Setup and Description. Experiments quantified the loss rates of CO_2 during a normal stationary phase and PM during two phases (stationary and moving) and three conditions (normal operation, air cleaner intervention, and open-door intervention, the latter in stationary phase only for a total of six combinations of conditions per elevator); all experiments were repeated in triplicate. Each experiment produced a decay rate constant with the unit hr^{-1}. As shown in Table 2, these constants are as follows:

(i) $k_{nv-stat-closed}$: the natural ventilation rate as measured by CO_2 decay, when stationary with the door closed

(ii) $k_{total-stat-closed}$: the total particle removal rate when stationary with the door closed

(iii) $k_{total-moving}$: the total particle removal rate when moving including variable short periods when the elevator stopped, opened, and closed at each floor

(iv) $k_{total-stat-closed-cleaner}$: the total particle removal rate when stationary with the door closed plus an air cleaner

(v) $k_{total-moving-cleaner}$: the total particle removal rate when moving plus an air cleaner including variable short periods when the elevator stopped, opened, and closed at each floor

(vi) $k_{total-stat-open}$: the open-door natural ventilation rate when stationary with the door propped open for five minutes. Due to technical issues, the natural ventilation rate while the elevator was moving was not measured. Sampling during stationary phases occurred on different floors of the building due to site sampling limitations

2.3.1. CO_2 Removal Rate Experiments. The main first-order mechanisms of aerosol removal are natural ventilation and a combination of particle gravitational settling, impaction,

Table 1: Characteristics of elevators sampled in the San Francisco Bay Area.

Elevator #	Decade of manufacture	Number of floors	Elevator volume (m^3)	Elevator floor area (m^2)	Open-door dimensions (m^2)	Maximum passenger capacity	Wall characteristics
1	1940s	4	7.19	2.89	2.28	16	Stainless steel
2	1960s	8	6.37	2.83	2.28	20	Carpeted
3	1980s	3	9.66	3.27	2.93	23	Carpeted

Table 2: Summary description of experimental tests and associated variables.

Variable	Loss rate experiment	Door status	Measurement
C_0	Background CO_2 concentration	Closed	Mean baseline CO_2 concentration
$^*k_{nv-stat-closed}$	Normal stationary natural ventilation	Closed	Rate of decay of generated CO_2 due to natural ventilation of elevator
$k_{total-stat-closed}$	Normal particle removal in stationary elevator	Closed	Rate of decay of PM_2 due to deposition onto elevator surfaces
$k_{total-moving}$	Normal particle removal rate in moving elevator	Variable	Rate of decay of PM_2 due to removal mechanisms in a moving elevator
$k_{total-stat-closed-cleaner}$	Intervention stationary: stationary elevator+HEPA air cleaner	Closed	Rate of decay of PM_2 due to deposition onto elevator surfaces with HEPA air cleaner
$k_{total-moving-cleaner}$	Intervention moving: moving elevator+HEPA air cleaner	Variable	Rate of decay of PM_2 due to incremental removal mechanisms in a moving elevator with HEPA air cleaner
$k_{total-stat-open}$	Intervention stationary: stationary elevator+door open	Open	Rate of decay of PM_2 due to deposition onto elevator surfaces and door propped open for five minutes

$^*k_{nv-stat-closed}$ is assumed to be present in all observed results.

and diffusion onto surfaces [4, 7, 29]. The baseline natural ventilation of the elevator ($k_{nv-stat-closed}$) was measured during stationary and closed elevator door phases by rapidly increasing the concentration of the CO_2 tracer gas, mixing the air, and observing the decay of the tracer gas according to the ASTM E471 concentration decay linear regression method [36, 37]. To generate CO_2, we placed a reaction vessel in a closed elevator with approximately 220 grams of sodium bicarbonate and three liters of vinegar. We allowed it to react for five minutes to generate >5,000 ppm CO_2; a fan mixed the air with the elevator doors closed. After five minutes, the reaction vessel was removed, the mixing fan was turned off, and the elevator door was closed to measure the escape of CO_2 from the elevator. Natural ventilation is assumed to be present during all elevator phases, so all observed results incorporate natural ventilation [3, 7].

2.3.2. Total Particle Removal Rate Experiments. During the experiments to determine the total particle removal rates, a surrogate SARS-CoV-2 inert sodium chloride (NaCl) PM_2 aerosol was measured with continuous real-time monitors. The particle decay experiments used an inert NaCl polydisperse nebulizer (Salter Aire Elite nebulizer) to generate polydisperse NaCl PM_2 at a height of 7 feet (Supporting Information—Figure SI-1). The use of PM_2 is relevant for continuous breathing emissions and coughing events because the majority of emitted virus is found in the particle fraction less than 5 μm in aerodynamic diameter [8, 38–43]. For each of the particle decay experiments, we followed the same basic method of particle generation. We placed the nebulizer in the elevator and allowed it to generate aerosol particles for five minutes, then turned it off, and measured PM decay for several minutes to determine the decay rates. The air cleaner interventions used the stand-alone HEPA filtered, air cleaner set at 120 cfm by IQAir as used in Bennett et al. [44].

2.4. Tracer Gas and PM_2 Decay Rate Calculations. The loss rates (hr^{-1}) were calculated from the concentration time series based on the Equation (1) model:

$$C(t) = C_0\left(e^{-kt}\right), \tag{1}$$

where $C(t)$ is the observed concentration of CO_2 or PM_2, k is the decay rate constant in hr^{-1}, and C_0 is the baseline concentration at time = 0. In the regression, the rate constant corresponds to the slope of the regression line for $\ln[C(t)]$ versus t. The decay rate was calculated beginning at 20-120 seconds after ceasing production of CO_2 or PM_2 and ending above the baseline concentration inside the elevator (Supporting Information—Figure SI-2).

2.5. Statistical Analysis. Data were analyzed using R statistical software (*v.3.6.1, Vienna, Austria*) in R Studio Development Environment (*v. 1.3.959*) and Microsoft Excel (*v. 2102, Microsoft, Seattle, Washington*). The R tidyverse package was used with dplyr, ggplot2, hms, and zoo packages. To determine the relationship between the total PM_2 removal rates in the different elevator experiments, a nonparametric Kruskal-Wallis test was paired with Dunn's test for multiple comparisons using the Benjamini-Hochberg adjustment to determine if the median total particle removal rates were significantly different across the four total particle removal experiments. $k_{\text{nv-stat-closed}}$ was not considered for analysis. The null hypothesis of the Kruskal-Wallis test is that there is not a significant difference between medians for the experiments by elevator. Significant associations were determined at $p < 0.05$.

2.6. Dynamic Particulate Matter Removal (DPMR) Model with Successive Emissions. The DPMR model was used to estimate the concentration of PM that remains suspended inside the elevator during frequent and infrequent stops with and without an aerosol reduction measure applied. The dynamic elevator model incorporates the overall aerosol removal rate and emissions from breathing and coughing to generate outputs of PM concentration over time during a series of events (Equation (2)).

$$C(t + \Delta t) = C(t)e^{-k\Delta t} + \frac{(NE_B)}{Q}\left(1 - e^{-k\Delta t}\right) + \frac{N_C E_C}{V}\left(e^{-0.5k\Delta t}\right), \quad (2)$$

where $C(t + \Delta t)$ is the new concentration at $t + \Delta t$ in particles/m^3, $C(t)$ is the concentration of PM at time (t) in particles/m^3, k is the rate constant for the decay of PM in hr^{-1}, t is the time in hr, N is the number of people inside the elevator, E_B is the average particle emission rate due to exhalation (particles/m^3), N_C is the number of people who are coughing, E_C is the number of particles emitted in a cough (particles), and Q is the dilution air flow rate in m^3/min.The cough is treated as a discrete emission and occurs at the midpoint of the time difference interval (Δt). The output provides particle concentration (particles/m^3) over time during normal and intervention elevator modes.

The 1980s elevator measurements and empirical PM removal rates were used to estimate PM concentration over time during two scenarios modeling typical elevator modes within a 10-floor office building. These determine how rapidly the PM is removed. In both scenarios, the elevator is in continuous use in a 10-story building; in the first scenario, there are stops only at the ground and 10$^{\text{th}}$ floor per trip (2 total stops), while in the second scenario, there are stops on every other floor per trip (5 total stops). Each scenario was modeled with and without an air cleaner. These stops incorporated stationary elevator and open-door time when passengers exited. To model these scenarios, we assumed that the elevator was a well-mixed space, that there were four passengers inside the elevator with breathing emissions and cough emissions of a single person emitting PM$_2$, that breathing and cough emissions were constant values, and that passengers were unmasked. We used particle counts (particles/m^3) instead of mass counts (mg/m^3) as the mass would favor larger particles and the majority of emitted virus is found in the particle fraction less than 5 μm in aerodynamic diameter as previously mentioned [8, 38–43]. All passengers were assumed to exhale 786 (particles/min) as found by Fabian et al. [45] for rhinovirus patients (assuming 32 particles per liter, one breath every 2.5 seconds); the cough was treated as a discrete emission from a symptomatic passenger, and a mean cough produced 75,400 particles per cough as found by Lindsley et al. [46] for influenza-infected patients. Cough produces a polydisperse aerosol [46, 47], and we assumed PM sized 2 μm [7]. Compared to the PM$_2$ particle size used in the DPMR model, the polydisperse cough particle counts from Lindsley et al. [46] had a wider range of aerodynamic sizes including larger particles that are removed more quickly through gravitational settling [7]. PM larger than 2 μm were not considered for this simulation model. This assumption is based upon previous literature that suggested that some of the larger PM rapidly decrease in aerosol diameter due to water loss to create droplet nuclei and more PM$_2$ by count [7, 47]. The model incorporated measured door use times from the 1980s elevator with doors open for 10 seconds, a stationary phase of 5 seconds, and between-floor time movement of 5 seconds.

3. Results

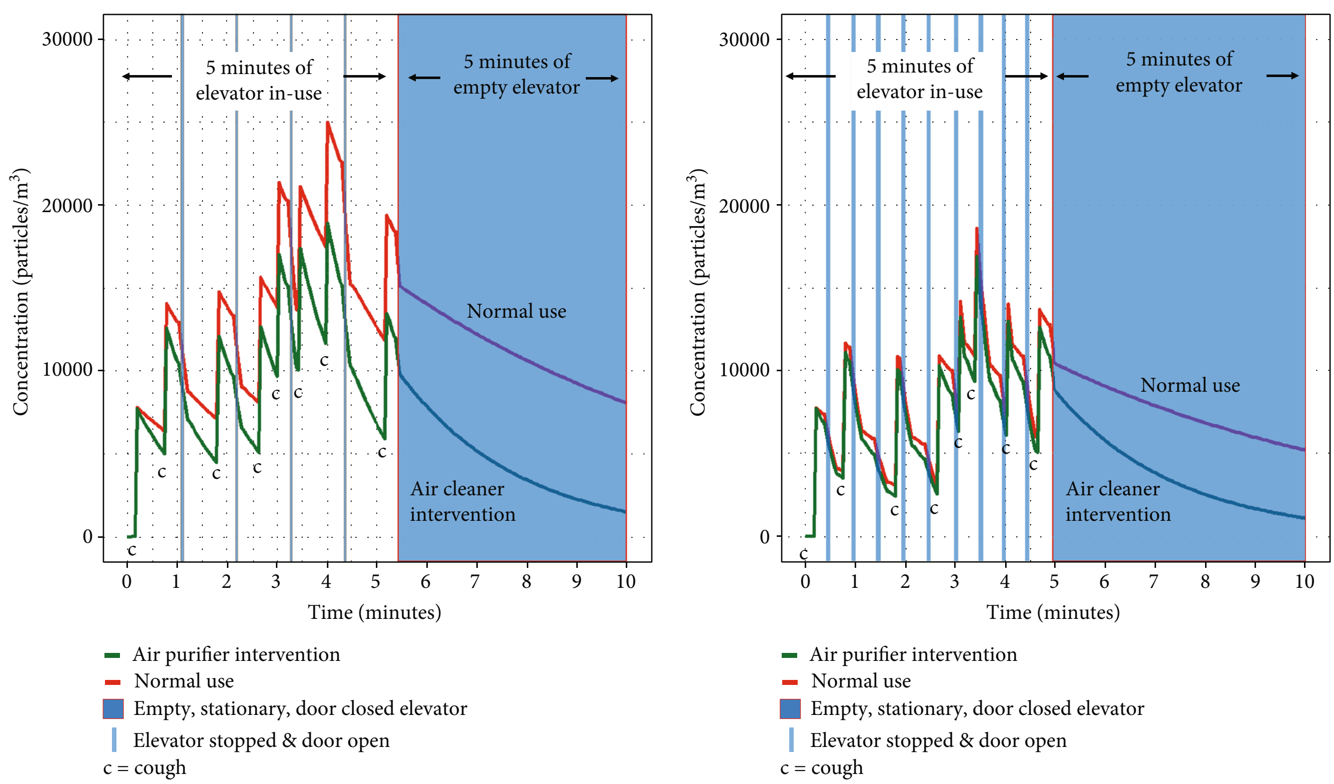
Table 3 presents the experimental loss rate constants for the six tests in each elevator. The lowest mean loss rate was due to natural ventilation when the elevator was stationary with the door closed (mean = 2.40 hr^{-1}). The overall particle loss rate when the elevator was stationary with the door closed (mean = 4.60 hr^{-1}) was 1.9-fold higher and reflected added particle removal by deposition mechanisms. The overall particle loss rate when the door was held open (mean = 120 hr^{-1}) was 26-fold higher than when the door was closed and the elevator was stationary. The overall particle loss rate when the elevator was moving was 4.9-fold higher than when the elevator was closed and stationary. This higher loss rate likely reflects increased natural ventilation associated with elevator movement, although the natural ventilation air exchange rate when the elevator was moving was not measured. The increase in the overall particle loss rate achieved by the air cleaner was similar in the stationary elevator with door closed (31.7 hr^{-1} – 4.6 hr^{-1} = 27.1 hr^{-1}) versus the moving elevator with the door closed (49.4 hr^{-1} – 22.6 hr^{-1} = 26.8 hr^{-1}). The air change rate increase due to the air cleaner was expected in a well-mixed space. The air cleaner was operated at 120 cfm, or 204 m^3 per hour. Dividing the latter quantity by the volume of the three elevators (7.19 m^3, 6.37 m^3, and 9.66 m^3) gives similar values, respectively, 28.4 hr^{-1}, 32.0 hr^{-1}, and 21.1 hr^{-1}, for which the average is 27.2 hr^{-1}.This result provides confidence that our measurements were reasonable.

We observed statistically significant differences in medians between the moving elevator with air cleaner ($k_{\text{total-moving-cleaner}}$) and the stationary elevator with doors closed ($k_{\text{total-stat-closed}}$) and open door ($k_{\text{total-stat-open}}$) and stationary elevator with doors closed ($k_{\text{total-stat-closed}}$).

3.1. Dynamic Particulate Matter Removal (DPMR) Model with Continuous Emission. The DPMR is a simulation of the dynamic concentration of PM after a series of coughs in an elevator with an air cleaner (green) and without an air cleaner (red) during a series of express elevator runs with stops at ground and top floors for a total of 2 stops in a 10-story building per trip (Figure 1(a), scenario 1) and

Table 3: Mean loss rates (hr^{-1}) ± standard deviation for the three elevators. All rates except $k_{nv-stat-closed}$ are based on the use of NaCl.

	Rate constant	Experimental description	Elevator 1 (1940s) (hr^{-1})	Elevator 2 (1960s) (hr^{-1})	Elevator 3 (1980s) (hr^{-1})	Mean elevator air change rate ± SE (hr^{-1})
Normal	$k_{nv-stat-closed}$	Natural ventilation stationary elevator+closed door based on CO_2 decay	1.9 ± 0.31	1.8 ± 0.06	3.4 ± 0.17	2.40 ± 0.26
	$k_{total-stat-closed}$	Total particle removal in stationary elevator+closed door	5.4 ± 0.64	3.6 ± 0.52	4.9 ± 0.90	4.60 ± 0.33
	$k_{total-moving}$	Particle removal rate in moving elevator	29.7 ± 0.91	15.4 ± 1.06	22.6 ± 0.81	22.6 ± 2.09
Intervention	$k_{total-stat-closed-cleaner}$	Intervention: stationary elevator +air cleaner	39.3 ± 0.13	31.3 ± 0.83	24.6 ± 0.30	31.7 ± 2.13
	$k_{total-moving-cleaner}$	Intervention: moving elevator +air cleaner	53.8 ± 3.58	46.3 ± 0.72	48.2 ± 6.04	49.4 ± 1.62
	$k_{total-stat-open}$	Intervention: stationary elevator +open door	38.3 ± 0.87	184 ± 34.2	140.7 ± 2.13	121.0 ± 22.3



(a) (b)

Figure 1: PM removal simulation during continuous use of a 10-story elevator for five minutes, during which there are eight coughs and then the elevator empty and stationary with the door closed for five minutes. (a) Scenario 1: express transit between top and bottom floors only. (b) Scenario 2: stops every other floor. y-axis is the concentration of particles per cubic meter inside the elevator, and the x-axis is the time in minutes during normal use (red) and with air cleaner intervention (green). C = discrete cough emission of 75,400 particles [46] in an elevator. Narrow blue regions are when the elevator stops on a floor and the door opens to let out passengers ($t = 0$ to 5 minutes), and large blue regions outlined in red are when the elevator is empty and stationary and the door is closed waiting for passengers ($t = 5$ to 10 minutes). Open-door times for stops on floors were 10 seconds at every floor stop.

elevator stops at every other floor for a total of 5 stops in a 10-story building per trip (Figure 1(b), scenario 2). Coughs in Figure 1, scenario 1 occurred at $t = 0.25$, 0.83, 1.88, 2.71, 3.08, 3.5, 4.04, and 5.25 minutes while the elevators were moving. Coughs in Figure 1 (scenario 2) occurred at $t = 0.25$, 0.83, 1.88, 2.71, 3.13, 3.46, 4.08, and 4.71 minutes while elevators were moving. Gray regions in the graph represent when the elevator was moving with passengers. Thin blue regions are when the elevator stops on a floor and the door opens to let out passengers. These occur during the first 5 minutes of the graph. Large blue regions with red outline are when the elevator is empty, stationary, and doors closed. These occur during the subsequent 5 minutes of the graph. PM is removed faster with more open-door time during frequent stops; a portable air cleaner also reduces PM, especially during an empty, door closed, stationary elevator.

The results from the DPMR, which was posed as a possible worst-case scenario, allows assessing differences in concentrations in terms of relative fold changes. The DPMR model demonstrated modest effectiveness of the air cleaner intervention during "in-use" operation in both the express and every other floor stop elevator. The express top to bottom stops had a mean 1.38-fold reduction for air cleaner compared to no air cleaner (Figure 1, scenario 1, 0 to 5.5 minutes) and a mean 1.12-fold reduction for every other floor stops (Figure 1, scenario 2, 0 to 5.0 minutes). The peak concentration without air cleaner during bottom to top floor stops for scenario 1 (24,974 particles/m^3) was 1.34-fold higher than that for scenario 2, stops every other floor (18,607 particles/m^3). With the air cleaner, the difference between peak concentrations for scenario 1 (18,910 particles/m^3) was 1.12-fold higher than that for scenario 2 (16,916 particles/m^3). However, the air cleaner has much more impact in reducing the concentration during the five minutes the elevator is empty, door closed, and not in operation: particle concentration without the air cleaner remains quite high even after five minutes (7,700 particles/m^3), but the air cleaner reduces this more than 6-fold to 1,263 particles/m^3 or an 83% reduction.

4. Discussion

This paper reports measurements of respirable particle total loss rates in older, nonhospital, and nonmechanically ventilated US-located elevators. Inert NaCl PM_2 served as a surrogate for SARS-CoV-2 to estimate the airborne particle loss rate for small particles (less than 2 μm) during moving and stationary phases with and without an air cleaner intervention. In turn, based on these loss rates, we were able to model PM_2 removal over time during continual elevator use for five minutes followed by five minutes of nonuse. Significantly different medians were observed between a moving elevator with air cleaner ($k_{\text{total-moving-cleaner}}$) and a stationary closed-door elevator ($k_{\text{total-stat-closed}}$) and between an open-door elevator ($k_{\text{total-stat-open}}$) and a stationary closed-door elevator ($k_{\text{total-stat-closed}}$).

Other than for a stationary elevator with the door closed, these estimated particle loss rates are substantially greater than those pertaining to most commercial and residential spaces [3, 14, 48, 49] and nominally suggest that elevator cabins are not high-risk environments for inhalation transmission of an infectious agent. However, following a single cough that emits hundreds of respirable virus-containing particles, the airborne virus concentration in the cabin can be high, and the relatively short duration of cabin occupancy does not permit a significant reduction in the airborne virus concentration during occupancy. For example, consider a situation in which 7000 active viruses, say, are carried by thousands of particles < 5 μm in diameter emitted in one cough into a 10 m^3 elevator cabin, such that the initial virus concentration is 700 per m^3. If the elevator is stationary with the door open for the next 5 seconds as a passenger enters the elevator, the estimated airborne virus concentration when the door closes is about $700\,\text{viruses/m}^3 \bullet e^{-((120/3600\,\text{s})\bullet 5\,\text{s})} = 593\,\text{viruses/m}^3$, a 15% reduction. If the elevator subsequently moves between one and two floors in 10 seconds, the estimated airborne virus concentration at the end of the transit is about $593\,\text{viruses/m}^3 \bullet e^{-((22.6/3600\,\text{s})\bullet 10\,\text{s})} = 557\,\text{viruses/m}^3$, a 6.1% reduction. If the elevator subsequently opens to let out passengers for 5 seconds, the estimated airborne virus concentration is about $557\,\text{viruses/m}^3 \bullet e^{-((120/3600\,\text{s})\bullet 5\,\text{s})} = 471\,\text{viruses/m}^3$, a 15% reduction. If the elevator subsequently becomes emptied and is stationary for 10 seconds with the door closed waiting for the next passenger, the estimated airborne virus concentration is about $471\,\text{viruses/m}^3 \bullet e^{-((4.60/3600\,\text{s})\bullet 10\,\text{s})} = 465\,\text{viruses/m}^3$, a 1.3% reduction. Instead, if the elevator remains empty, stationary, and with the door closed waiting for the next passenger for a longer duration of 5 minutes, the estimated airborne virus concentration is about $471\,\text{viruses/m}^3 \bullet e^{-((4.60/3600\,\text{s})\bullet 300\,\text{s})} = 321\,\text{viruses/m}^3$, a 32% reduction; that is, two-thirds of the airborne viruses remain after 5 minutes. In contrast, an air cleaner contributing an added 27 hr^{-1} loss rate would provide a 90% reduction during that 5-minute waiting period, from 321 to 34 virus per m^3, although the air cleaner's effectiveness is more modest when the elevator is in service and moving, when it would change the respective numbers from 557 to 516 virus per m^3 at the end of transit, but drastically more during stationary 465 to 431 virus per m^3 (10 seconds). Of course, the longer the time spent with the cabin door open or in transit, the greater the overall reduction in the airborne virus concentration, if there are no additional emissions during transit. Because loss of infectivity of airborne SARS-CoV-2 has a half time of approximately one hour [50], the potential for ongoing presence of airborne infective virus is concerning in these small, high-traffic environments.

A previous study in the Netherlands by van Rijn et al. [23] investigated elevator ventilation and PM removal in mechanically ventilated hospital elevators that had a 10 ACH fan running during operation but turned off after 1-2 minutes of stationary time. They found that compared to a stationary elevator, in-operation was approximately twofold faster and open door was sixfold faster. Their results were similar to ours as they observed particle concentrations decaying much faster while in motion and with an open door. However, it was not disclosed if their elevator had open doors on both sides of the elevator, which is typical in hospitals or if the hospital building was pressurized. We found a fourfold increased removal for moving compared to stationary and with open door a twenty-six-fold increased removal compared to stationary.

A previous intervention study of Ereth et al. [35] investigated complex and costly interventions, e.g., increased elevator mechanical ventilation and installation of a purifying units, but showed similar removal rates as our measurements and modeled results. Ereth et al. [35] investigated PM removal rates with an air purification unit paired with a mechanically ventilated fan providing 27 ACH and observed an eightfold increase in PM mass concentration removal for PM_2 ($2\,\mu g/m^3$ during control experiments to approximately $0.25\,\mu g/m^3$ during intervention experiments). In contrast, we found that the air purifier intervention increased the removal rate sixfold during stationary-door-closed phase ($31.7\,hr^{-1}$ compared to $4.6\,hr^{-1}$) and twofold during the moving-door-closed phase ($49.2\,hr^{-1}$ versus $22.6\,hr^{-1}$) (Table 3). The purifying unit in Ereth et al. [35] was estimated to cost upwards of $4000, which might be cost prohibitive if air purifiers are needed for multiple elevators. However, purifiers with similar but slightly lower performance used in this study improve PM loss rates and cost less than $200 for similarly performing units (120 cfm) available at retail stores.

The DPMR model for the PM removal further demonstrated the effectiveness of using an air-cleaner during all phases of elevator use to decrease the concentration of particles. However, when the elevator was in use with passengers and with doors opening every other floor (Figure 1, scenario 2), concentrations of PM_2 continued to accumulate, but at a slower rate compared to express runs between bottom and top floor stops (Figure 1, scenario 1). The air cleaner provided only moderate improvements in decay rates because removal rates during the open-door and moving-elevator phases were high.

The PM removal rate in the stationary open-door phase varied widely among the three elevators $38.3\,hr^{-1}$, $184\,hr^{-1}$, and $140.7\,hr^{-1}$, respectively, for the 1940s, 1960s, and 1980s elevators. The PM reduction by the open-door intervention was an order of magnitude lower in the 1940s elevator compared to the 1960s and 1980s elevators. These observed differences during open-door intervention may be due to sampling on different floors of the building during the stationary phases, perhaps introducing a stronger stack effect [51]. Although an effective intervention in reducing particle concentration, leaving doors open between runs is not feasible because hard-wired elevator safety features [27] and safety codes [28] prohibit doors remaining open continuously. However, maximizing door opening times within normal elevator use may significantly improve elevator ventilation as demonstrated by Figure 1 (scenario 2).

A limitation of this study is the use of a NaCl PM_2 SARS-CoV-2 surrogate aerosol. Ideally, a wider range of PM aerodynamic diameters would have been used. However, a $2\,\mu m$ particle can remain suspended in air far longer period than, say, a $25\,\mu m$ particle, and the majority of emitted respiratory tract virus has been found in particles $< 5\,\mu m$ in diameter [8, 43]. Future studies should focus on a wider aerodynamic diameter size range of PM to investigate loss rates inside elevators.

Future studies should investigate more recently built elevators and the effectiveness of adjustable mechanical ventilation built in the cabins that older ones lack [23, 25]. Our study focused on quantifying ventilation rates, PM total removal, and feasible interventions in older, nonmechanically ventilated elevators in the San Francisco Bay Area.

From discussions with elevator technicians, the variability observed among elevators is likely based on the decade of construction, which reflects the building regulations of that period [27]. Additional variability in the environmental aspects of elevators (e.g., temperature, humidity, number of floors, and passenger movement) likely exists, which may also contribute to variation in elevator particle decay rates. This study investigated three elevators in Northern California that are expected to be typical for their construction age and location.

5. Conclusions

While air cleaners generally increase PM removal inside static spaces [32–35], this paper provides empirical evidence of the substantial effectiveness of air cleaners in a stationary elevator and the modest effectiveness when the elevator is moving or the door open. Nontoxic PM_2 was used as a surrogate for particles containing SARS-CoV-2. No live virus was used in this study. The particle removal rate in the stationary elevator ($4.6\,hr^{-1}$) with the door closed requires an intervention. If codes permit, the door should be kept open when the elevator is stationary at a floor (for which the average removal rate was $121\,hr^{-1}$); otherwise, an air cleaner in elevator should be used (for which the average removal rate was $31.7\,hr^{-1}$). An intervention is required because once passengers exit the cabin, the particle removal rate should be high to reduce potentially infectious aerosol remaining in the cabin due to emission from passengers who had just exited. This paper provides support for a layered approach of limiting passenger numbers inside the elevator, maximizing allowable door opening times, and using an air cleaner to reduce the probability of SARS-CoV-2 and other PM_2 relevant bioaerosol transmissions. Older elevators that lack mechanical ventilation should maximize open-door time and use a portable air cleaner to improve effective ventilation rates. Newer built elevators should include mechanical ventilation or an air cleaner to improve the total effective ventilation rate inside the elevator. This study can immediately contribute towards elevator-use protocols amidst a pandemic and towards future studies that investigate the risk of infection with emerging SARS-CoV-2 variants [20] for different elevator use scenarios. The PM_2 surrogate (NaCl) was removed within minutes inside the elevator only when the elevator was moving, the doors were open, or when an air cleaner was used; particles with SARS-CoV-2 would behave similarly.

Data Availability

Data are available upon request.

Additional Points

Practical Implications. This study provides data on elevator particle loss rates from 1940s-, 1960s-, and 1980s-built elevators. With concerns over transmission of SARS-CoV-2 in crowded spaces, this study improves the understanding of the persistence of PM inside elevators. The results from this study can inform current elevator practices by demonstrating the effectiveness of an air cleaner during stationary phases and future exposure assessment and infection risk studies involving crowded and dynamic spaces.

Conflicts of Interest

The authors report no known conflicts of interest.

Authors' Contributions

Michael Kado contributed to the conceptualization, data curation, investigation, methodology, project administration, and visualization; wrote the original draft preparation; and wrote, reviewed, and edited the manuscript. Kelsi Pertula contributed to the conceptualization, formal analysis, methodology, and visualization and wrote, reviewed, and edited the manuscript. Elizabeth Noth contributed to the conceptualization, formal analysis, data curation, and methodology and wrote, reviewed, and edited the manuscript. David Moore contributed to the conceptualization and wrote and reviewed the manuscript. Patton Nguyen contributed to the conceptualization, data curation, and investigation and wrote, reviewed, and edited the manuscript. Charles Perrino contributed to the conceptualization and investigation. Mark Nicas contributed to the conceptualization and methodology and wrote, reviewed, and edited the manuscript. S. Katharine Hammond contributed to conceptualization, methodology, project administration, resources, and supervision and wrote, reviewed, and edited the manuscript.

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Supplementary Materials

Table SI-1: measured elevator environmental conditions on day of sampling. Figure SI-1: particulate matter sizes produced from Salter Aire nebulizer to generate the inert NaCl PM_2 SARS-CoV-2 surrogate. The particle diameter is physical particle diameter measured by a particle aerosol spectrometer. Figure SI-2: decay graph visual where x-axis is time in hh:mm:ss and y-axis in ln Concentration. 1, start generation of CO_2 or PM; 2, turn off CO_2 or PM generation source after a sufficient concentration reached; 3, observe the decay of CO_2 or PM after 20-120 seconds after the door closes; and 4, decay rate constant (hr^{-1}) (k). *(Supplementary Materials)*

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