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Mitigation of Aerosols Generated During Exercise Testing With a Portable High-Efficiency Particulate Air Filter With Fume Hood



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BACKGROUND: The role of portable high-efficiency particulate air (HEPA) filters for supplemental aerosol mitigation during exercise testing is unknown and might be relevant during COVID-19 pandemic.

RESEARCH QUESTION: What is the effect of portable HEPA filtering on aerosol concentration during exercise testing and its efficiency in reducing room clearance time in a clinical exercise testing laboratory?

STUDY DESIGN AND METHODS: Subjects were six healthy volunteers aged 20 to 56 years. In the first experiment, exercise was performed in a small tent with controlled airflow with the use of a stationary cycle, portable HEPA filter with fume hood, and particle counter to document aerosol concentration. Subjects performed a four-stage maximal exercise test that lasted 12 min plus 5 min of pretest quiet breathing and 3 min of active recovery. First, they exercised without mitigation then with portable HEPA filter running. In a separate experiment, room aerosol clearance time was measured in a clinical exercise testing laboratory by filling it with artificially generated aerosols and measuring time to 99.9% aerosol clearance with heating, ventilation, and air conditioning (HVAC) only or HVAC plus portable HEPA filter running.

RESULTS: In the exercise experiment, particle concentrations reached $1,722 \pm 1,484/L$ vs $96 \pm 124/L$ ($P < .04$) for all particles ($>0.3 \mu\text{m}$), $1,339 \pm 1,281/L$ vs $76 \pm 104/L$ ($P < .05$) for smaller particles (0.3 to $1.0 \mu\text{m}$), and $333 \pm 209/L$ vs $17 \pm 19/L$ ($P < .01$) for larger particles (1.0 to $5.0 \mu\text{m}$) at the end of the protocol in a comparison of mitigation vs portable HEPA filter. Use of a portable HEPA filter in a clinical exercise laboratory clearance experiment reduced aerosol clearance time 47% vs HVAC alone.

INTERPRETATION: The portable HEPA filter reduced the concentration of aerosols generated during exercise testing by $96\% \pm 2\%$ for all particle sizes and reduced aerosol room clearance time in clinical exercise testing laboratories. Portable HEPA filters therefore might be useful in clinical exercise testing laboratories to reduce the risk of COVID-19 transmission.

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KEY WORDS: aerosol; COVID-19; exercise testing; HEPA filter

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ABBREVIATIONS: CFM = cubic feet per min; HEPA = high-efficiency particulate air; HVAC = heating, ventilation, and air conditioning

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Take-home Points

Study Question: Can portable HEPA filtering effectively reduce the concentration of aerosols generated during exercise testing?

Results: Maximal graded exercise testing was performed in a small clean environment with controlled airflow and continuous measurement of aerosol concentration. Subjects exercised without mitigation then with portable HEPA filter running at 400 CFM. Portable HEPA filtration reduced the concentration of measured aerosols generated during exercise testing from $1,722 \pm 1,484/L$ to $96 \pm 124/L$.

Interpretation: Portable HEPA filter effectively mitigated aerosols that were generated during exercise testing by $96\% \pm 2\%$, potentially reducing the risk of SARS-CoV-2 transmission during this important medical procedure.

It has been suggested that vigorous exercise such as performed during clinical exercise testing, generates aerosols with potential for carrying COVID-19.¹ The Centers for Disease Control and Prevention recommends that aerosol-generating procedures be performed with appropriate personal protection equipment and, when possible, in negative pressure rooms to allow clearance of aerosols through room air exchanges by increasing room ventilation with or without the use of high-efficiency particulate air (HEPA) filters.²

Methods

Materials

An exercise experiment was performed in a $1.88 \times 2.29 \times 3.04$ m ($13.1 \text{ m}^3 = 13,100$ L) Colorado Altitude Training tent with a stationary cycle and internationally endorsed particle counter to document aerosol concentration.¹² We tested a portable HEPA filter with directional 700 cu ft per min (CFM) airflow (model SS-400-PFS; Sentry Air Systems, Cypress, TX) that was accomplished by means of an adjustable fume hood that could be placed near the mouth of the exercising subject (Fig 1A).

The tent was attached to intake and outlet HEPA-filtered fans H1000V (Abatement Technologies; Suwanee, GA) that generated a maximum flow of 950 CFM, which lowered particle concentrations to $<100/L$ within 5 to 10 min of filtering at maximum airflow prior to each test. True HEPA filters clean 99.97% of particles at $0.15 \mu\text{m}$, the most evasive particle size; both smaller and larger particles are filtered more effectively.⁷ For reference, SARS-CoV-2 has a diameter of 0.06 to $0.14 \mu\text{m}$ and has been detected in significant quantities in aerosols as small 0.25 to $0.5 \mu\text{m}$ and as large as 2.5 to $5 \mu\text{m}$.¹³

However, conducting exercise testing in the COVID-19 era presents unique challenges because it requires an effective means of mitigating aerosols without compromising test quality or diagnostic accuracy. Although time consuming, consecutive patient-to-patient prevention of transmission is crucial. It relies on appropriate surface cleaning and allowing the exercise laboratory to stay vacant for sufficient turnover time to clear the air of 99.9% of aerosols present at the end of the test.³ The prevention of patient-to-staff transmission is more difficult, because medical personnel are present in the exercise laboratory with the exercising patient.^{4,5} For this, there is a need for an aerosol effective mitigation strategy in real time.

The Centers for Disease Control and Prevention previously had suggested the use of portable HEPA filters as an adjunctive control strategy for SARS-CoV-1.⁶ Currently, HEPA air filters are being used as an adjunctive measure for decontamination of SARS-CoV-2 in different health care settings but have not been reported for exercise testing.⁷⁻¹²

The role of portable HEPA filters as a supplemental mitigation strategy for exercise testing is still unknown. The aim of this investigation was to determine the effect of the use of directed airflow and aggressive portable HEPA filtering on aerosol concentration during exercise testing and to evaluate its effect on room clearance time in a clinical exercise testing laboratory.

Use of the clean tent allowed us to overcome experimental difficulties of measuring aerosol generation and mitigation without the high concentrations of aerosols of all sizes in background room air and a large airspace with complex air currents in the typical clinical exercise laboratory.

In a separate experiment, we tested the efficacy of the SS-400 PFS HEPA filter in clearing artificially generated aerosols in a clinical exercise testing laboratory (Fig 1B). No exercising subjects were involved in this experiment.

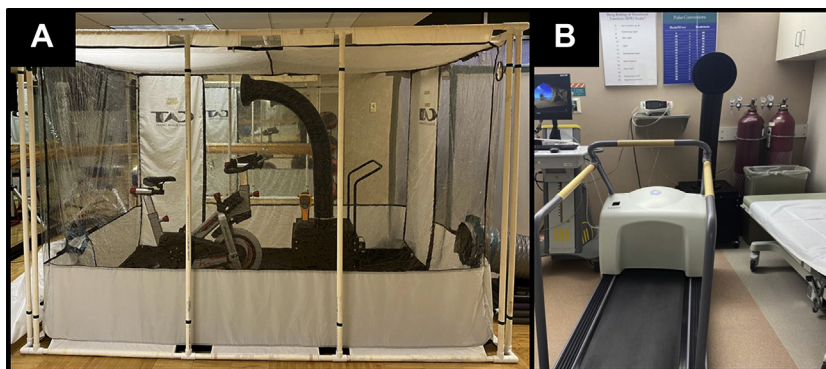
Subjects

Subjects were recruited without known cardiopulmonary disease, and none of them reported any upper respiratory tract symptoms and/or fever within 1 month of the test. Only verbal consent was obtained because no treatments were performed, and test procedures (cycle exercise) were no different than what subjects were doing on a regular basis.

Protocol 1: Exercise Studies

Tests were conducted with institutional review board permission (20-004751). After 10 min of cleaning by intake and outlet HEPA-filtered

Figure 1 – A, Colorado Altitude Training tent with a stationary cycle, a Fluke 985 particle counter (Fluke Corporation) and a portable HEPA filter with directional airflow (model #SS-400-PFS; Sentry Air Systems). B, Partial view of a clinical exercise testing laboratory with the portable HEPA filter in place. HEPA = high-efficiency particulate air.



fans and surface cleaning with the antiviral agent Oxivir Tb (Diversity), the subject entered the tent and sat on the exercise bike during 5 min of additional cleaning by the fans because some background room air was let inside the tent during entry. Then the airflow was turned off, and the protocol begun. The protocol consisted of 5 min quiet breathing, four stages of progressively harder exercise each lasting 3 min, and 3 min of active recovery with easy pedaling. Workloads were targeted at 25%, 50%, 75%, and 100% (maximal work) of heart rate reserve (HRR). Subjects were asked to maintain a constant, comfortable pedaling rate and to change workload by adjusting resistance. The workload was controlled by heart rate with the use of a Radical-7

forehead oximeter (Masimo) with display visible to the subject plus coaching from research staff outside the tent. Based on previous experience, we estimated that healthy subjects would produce a total of approximately 1000 L of expired ventilation during this 20-min protocol.

All subjects initially performed an exercise test without any mitigation. Then subjects repeated the exercise test with the SS-400-PFS portable HEPA filter with fume hood placed approximately 60 cm in front the mouth of the subject. It is important to note that the SS-400-PFS was vented into the clean tent, so that differential pressure outside and inside the tent was not altered.

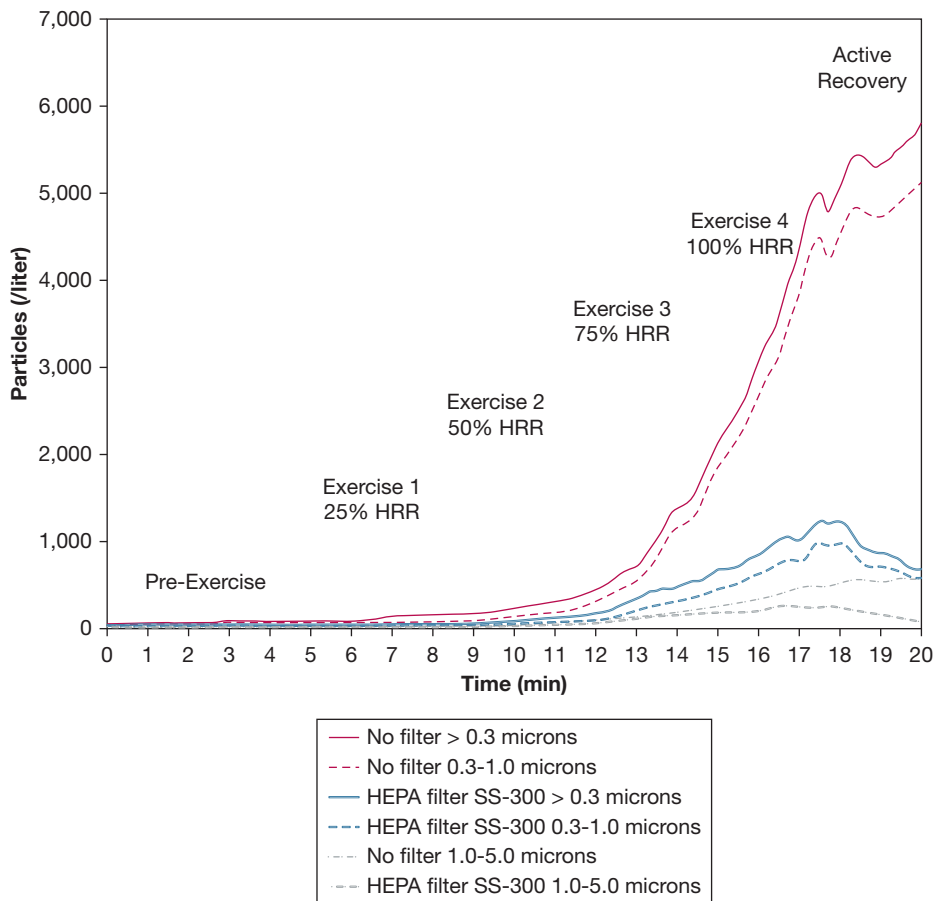


Figure 2 – Pilot data for six subjects that compares aerosol concentrations during the exercise protocol with no filter vs exercise with use of a portable HEPA filter with fume hood (SS-300-PFS; Sentry Air Systems). HEPA = high-efficiency particulate air; HRR = heart rate reserve.

Data Collection: For the exercise studies, particle concentrations were monitored continuously with updates every 10 seconds with the use of a Fluke 985 particle counter (Fluke Corporation) placed 1.0 m in front of the subject at approximately the seat height of the cycle. This device uses laser beam technology to count particles in different size categories that range from 0.3 to >10.0 μm .¹ Particles <5.0 μm are considered aerosols by the World Health Organization and might be implicated in airborne transmission of COVID-19.¹⁴ Thus, we chose to display three levels of particles: >0.3 μm (all particles measured), 0.3 to 1.0 μm (smaller aerosols), and 1.0 to 5.0 μm (larger aerosols) that also have the potential to carry virus beyond 1 to 2 m from the source.¹⁵

Data Analysis: We displayed the smoothed 30-s updated means of the three particle sizes every 10 seconds of the protocol during both conditions: no mitigation and mitigation with the portable HEPA filter. For statistical analysis, we performed repeated measures analysis of variance using SAS PROC GLM (SAS Institute Inc) to determine significance of differences in the means of aerosol concentrations at the end of each phase of the protocol between the two conditions (filter vs no filter). Multiple comparisons were addressed by Tukey method. Level of significance was set at a probability value of <.05. Data were analyzed with SAS Studio software (version 5.0; SAS Institute Inc.). Based on pilot data (Fig 2) that used a smaller portable HEPA filter with fume hood (SS-300-PFS [Sentry Air Systems] with 350 CPM airflow), we anticipated at least an 85% \pm 16% reduction in aerosol accumulation, meaning we could achieve statistical significance at a probability value of <.05 and 90% power with three or more subjects.

Results

Subjects

The subjects were six healthy volunteers (five men; one woman) age 20 to 56 years (mean, 36 \pm 14 y). Height was 175 \pm 8 cm; weight was 79 \pm 13 kg, and BMI was 26.0 \pm 3.2 kg/m². Subjects successfully maintained exercise heart rate within \pm 5% of the following average \pm SD targets: 25% HRR, 93 \pm 7 beats/min (range, 80 to 99 beats/min); 50% HRR, 120 \pm 9 beats/min (range, 108 to 120 beats/min); 75% HRR, 148 \pm 10 beats/min (range, 134 to 157 beats/min); 100% HRR, 175 \pm 12 beats/min (range, 158 to 186 beats/min).

Aerosol Concentration During Exercise With and Without a Portable HEPA Filter

Figure 3 shows that aerosol concentration increased exponentially with increasing exercise intensity and continued into active recovery. There was a significant reduction in mean concentration of all particle classes with the use of the portable HEPA filter throughout the test. At the end of the 20-min exercise trial, with comparison of no mitigation vs portable HEPA filter, aerosol concentrations were 1,723 \pm 1,485 vs 93 \pm 124 (P < .04) for all particles \geq 0.3 μm , 1,340 \pm 1,281 vs 77 \pm 104 (P < .05) for smaller aerosols 0.3 to 1.0 μm , and 333 \pm 209 vs 17 \pm 20 (P < .01) for larger aerosols. This represented a 96% \pm 2% mitigation across all particle

Protocol 2: Mayo Clinical Exercise Laboratory Aerosol Clearance

As part of Mayo Clinic's infection prevention and control program in response to COVID-19, the clinical exercise laboratories were tested for room clearance time with heating, ventilation, and air conditioning (HVAC) set at the maximum possible 400 CFM generating nine to twelve air changes per hour in the 47 to 55 m³ exercise laboratories (17,620.4 floor area with 2.7 m of height ceilings) and again with HVAC plus the portable HEPA filter. One clearance trial with and one without the HEPA filter were performed in each exercise laboratory. The HEPA filter placement in a clinical exercise testing laboratory is shown in Figure 1B. For this study, we present results of room clearance studies in our largest exercise laboratory. Baseline particle concentration was measured, then the room was filled with artificially generated aerosols for 10 min with the use of an ultrasonic air humidifier. The Fluke 985 particle counter was used to measure all particles >0.3 μm . During aerosol loading, HVAC continued to run, but the portable HEPA filter was turned off. When room loading was complete, the aerosol generator was turned off, and particle concentration was measured with HVAC only or HVAC plus portable HEPA filter running. A 99.9% particle clearance target was calculated as (baseline + .001 \times [peak - baseline]). Monitoring continued with values recorded every minute until the target of 99.9% clearance was attained for each condition. No exercising subjects were involved in the room clearance experiment.

sizes. Differences between the filter and no-filter conditions became significant as early as 5 min of resting breathing and remained significant at each level of exercise. Table 1 gives data for all particle classes at each stage of the 20-min trial.

Figure 4 shows intersubject variability. Figure 4A describes the no-filter condition; Figure 4B presents aerosol concentration data in the three particle classes for the trial with the SS-400-PFS portable HEPA filter with the fume hood operating. Although there was significant intersubject variability in aerosol concentrations in the no-filter condition, use of the portable HEPA filter dramatically reduced aerosol concentrations for all subjects in a very uniform manner.

Figure 5 presents results of aerosol clearance data from the largest exercise laboratory with and without the SS-400-PFS portable HEPA filter operating. As shown, aerosol clearance with HVAC + HEPA filter was significantly faster. The 99.9% target clearance was reached at 18:40 min for the HVAC only trial vs 9:50 min for the HVAC + portable HEPA filter trial, resulting in 47% clearance time reduction.

Discussion

Our study demonstrates that exercise produced significant concentrations of aerosols and that the use of

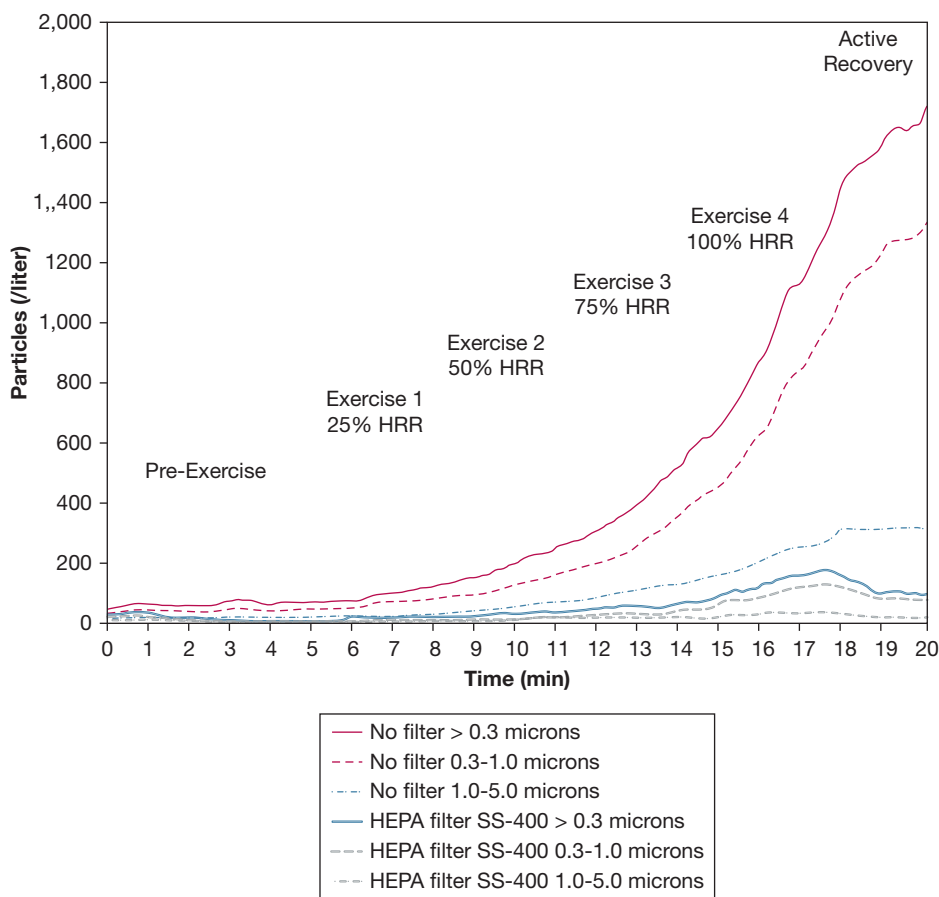


Figure 3 – Concentrations of particles (per liter) counted by the Fluke particle counter (Fluke Corporation) are displayed in subgroups of particles $>0.3 \mu\text{m}$ (total particles measured), $0.3\text{-}1.0 \mu\text{m}$ (small aerosols), and $1.0\text{-}5.0 \mu\text{m}$ (large aerosols) during the exercise protocol with and without the use of a portable HEPA filter with fume hood (model #SS-400-PFS; Sentry Air Systems). HEPA = high-efficiency particulate air; HRR = heart rate reserve.

a portable HEPA filter significantly reduced aerosol concentration during high levels of exercise in an indoor model setting. Thus, we show the potential role of these devices for aerosol mitigation in an exercise testing laboratory.

Application of a portable HEPA filter was recommended as a supplementary measure to mitigate aerosol exposure of medical personnel to SARS-CoV-1^{2, 7} and has been proposed as a strategy for aerosol mitigation of SARS-CoV-2 exposure.⁷⁻¹² Our study is the first to demonstrate its potential application in an exercise testing.

Because exercise laboratories are indoors with limited ventilation, there are concerns of exposing patients, medical personnel, and exercise participants to high concentration of aerosols with potential airborne infection in the current COVID 19 pandemic.¹⁶ We have shown that portable HEPA filtration can reduce aerosol

concentration during exercise and thus potentially reduce the risk of patient-to-staff transmission. Further advantages of portable HEPA filters for aerosol mitigation are ease of use, portability, relatively low cost, and high efficiency.⁶

The research letter by Helgeson et al¹ described exercise for 30 min at three levels for 10 min each at an average of 61%, 79%, and 91% of predicted peak heart rate by four subjects who exercised simultaneously (while wearing masks). At the end of the exercise period, a concentration of all Fluke-measured particles could be calculated as 2,058 particles/L at a location central to the four subjects. In our no-filter condition, the final particle concentration was $1,723 \pm 1,485/\text{L}$. Their environment was much larger (473.2 vs 13.1 m^3) and had ambient airflow of 6.3 vs 0 air changes per hour in our experimental set-up. However, they had four subjects exercising simultaneously, and their exercise protocol was 10 min longer. An exact mathematic comparison of

TABLE 1] Stage-By-Stage Summary Data (Mean±SD) for Each Particle Class and Experimental Condition: Air Recirculation With a High-Efficiency Particulate Air Filter vs No Air Recirculation With a High-Efficiency Particulate Air Filter

Particle Class	Time						
	0:00 Start Rest	5:00 End Rest	8:00 End 25% HRR	11:00 End 50% HRR	14:00 End 75% HRR	17:00 End 100% HRR	20:00 End Cool Down
≥0.3 μm							
No filter	46 ± 33	72 ± 63	125 ± 82	257 ± 131	526 ± 354	1,153 ± 881	1,723 ± 1,485
Filter	32 ± 21	6 ± 3	20 ± 16	37 ± 26	68 ± 49	160 ± 163	93 ± 124
Difference	14 ± 19	65 ± 61	74 ± 46	221 ± 118	457 ± 306	993 ± 729	1,626 ± 1,365
P value	NS	<.05	<.02	<.006	<.02	<.03	<.04
0.3-1.0 μm							
No filter	29 ± 23	48 ± 39	83 ± 48	165 ± 91	363 ± 276	853 ± 712	1,340 ± 1,281
Filter	21 ± 17	6 ± 3	9 ± 7	17 ± 13	42 ± 35	118 ± 137	77 ± 104
Difference	9 ± 14	43 ± 38	74 ± 46	148 ± 87	321 ± 244	734 ± 581	1,263 ± 1,179
P value	NS	<.04	<.02	<.009	<.03	<.03	<.05
1.0-5.0 μm							
No filter	13 ± 11	19 ± 18	32 ± 26	68 ± 36	127 ± 73	251 ± 162	333 ± 209
Filter	10 ± 6	1 ± 1	7 ± 8	14 ± 9	20 ± 16	34 ± 25	17 ± 20
Difference	4 ± 10	19 ± 18	25 ± 21	54 ± 29	107 ± 60	217 ± 141	316 ± 192
P value	NS	<.05	<.04	<.007	<.008	<.02	<.01

HRR = heart rate reserve; NS = not significant.

our findings with theirs is problematic, but it is reassuring that the peak aerosol concentrations that were achieved were of the same order of magnitude.

Our findings also demonstrate that portable HEPA filtration can reduce room clearance time significantly. We have demonstrated that aerosol removal in a clinical exercise laboratory is enhanced approximately 50% with the use of a SS-400-PFS plus HVAC vs HVAC alone. We show the results of a single comparison clearance trial for our largest exercise laboratory, although an approximate 50% reduction in clearance times with the portable HEPA filter has been demonstrated in multiple clearance trials across all exercise laboratories. The clearance times with the portable HEPA filter measured by this procedure may be conservative because, in actual practice, the portable HEPA filter would be running continuously, not shut off while aerosols are being produced. Moreover, the extreme aerosol concentration achieved during room clearance testing would never be approached in the clinical exercise testing setting where much lower particle concentrations would be expected with the portable HEPA filter running continuously. More rapid room clearance will allow a higher volume of testing in a clinical laboratory with reduced patient-to-patient transmission risk.

A portable HEPA filter with directional airflow likely would play a favorable role in various medical settings where an aerosol-generating procedure is being performed in a limited airspace with poor ventilation; therefore, these devices are being used in other areas within Mayo Clinic.

Increased air turnover with HEPA filtering might seem to play a beneficial role in the reduction of aerosol concentrations in other indoor exercise settings, such as cardiac rehabilitation centers, fitness facilities, and gymnasiums, although the fact that these are generally much larger spaces compared with an exercise testing laboratory with multiple people exercising simultaneously presents different challenges that must be addressed by different research designs.

Based on our data, we believe that we can recommend incorporation of portable HEPA filters with directional air flow into clinical exercise testing laboratories to reduce the risk of COVID-19 transmission. Other risk reduction strategies that include screening of patients for COVID-19 symptoms and recent contacts, plus polymerase chain reaction testing where appropriate, along with appropriate personal protection equipment for medical personnel who perform the test and surface cleaning, can also be used.

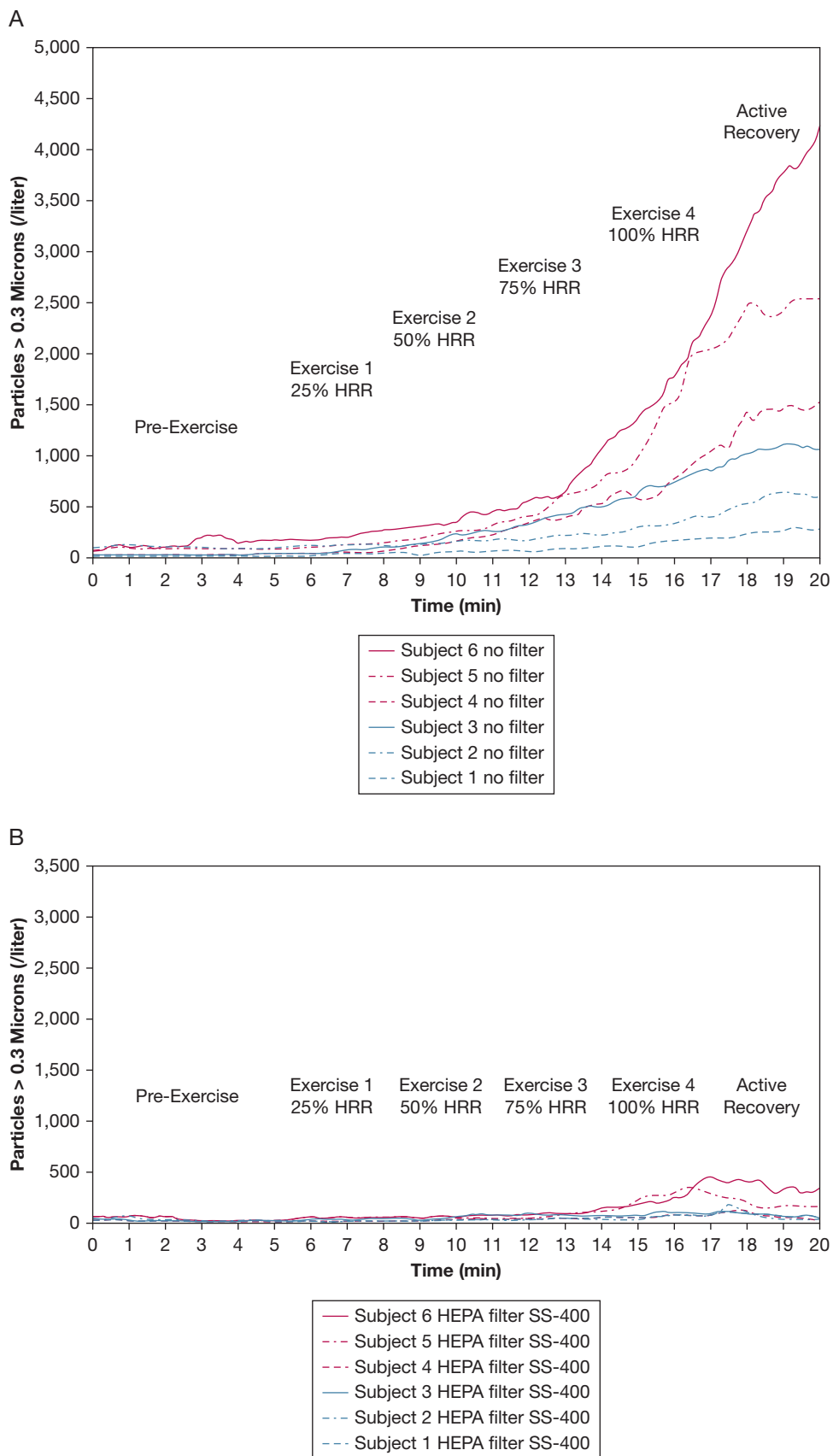


Figure 4 – Individual subject data shows A, aerosol concentration vs protocol time for the no-filter condition vs B, the trial with the use of a portable HEPA filter (model #SS-400-PFS; Sentry Air Systems) with fume hood. HEPA = high-efficiency particulate air; HRR = heart rate reserve.

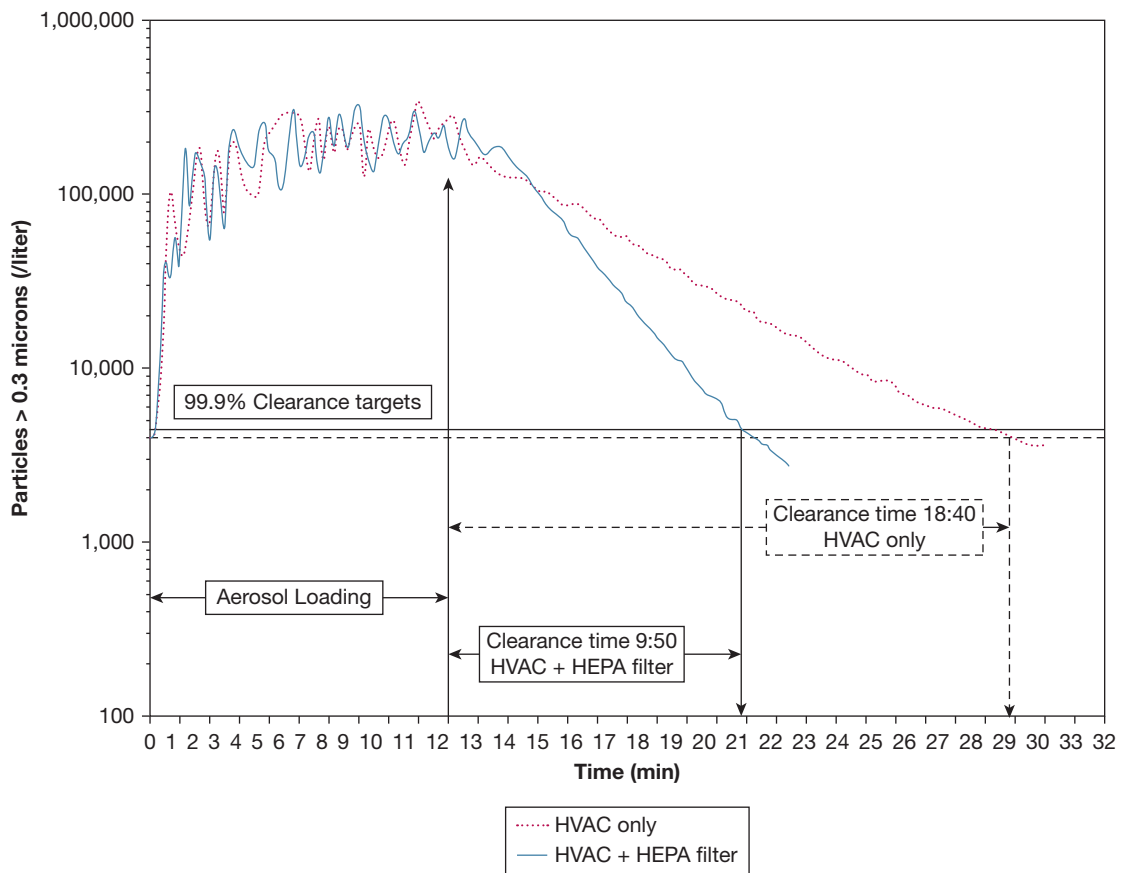


Figure 5 – Results of clinical exercise room clearance testing. Room clearance trials with HVAC only and with HVAC plus portable HEPA filter with fume hood (model #SS-400-PFS; Sentry Air Systems) running are shown. Target 99.9% aerosol clearance lines are marked for the HVAC only trial (blue lines) and HVAC plus portable HEPA filter trial (red lines). The target clearance was reached at 18:40 for the HVAC only trial vs of 9:50 for the HVAC plus portable HEPA filter trial, resulting in a 47% clearance time reduction. HEPA = high-efficiency particulate air; HVAC = heating, ventilation, and air conditioning.

Interpretation

Limitations

We acknowledge some limitations to our study. First, we did not work with viable virus or infected patients but measured only the mitigation of exercise-generated aerosols with potential to carry viruses. Actual transmission of virus and subsequent infection will depend on other variables, such as host susceptibility, viral load, and background air flow characteristics. Second, we have a small number of subjects with no baseline cardiopulmonary disease. However, the results were conclusive across all subjects and had statistical power to compare the amounts aerosol in between different models. We consider that the results of aerosol mitigation by portable HEPA filtering with the SS-400-PFS were so robust and consistent ($96\% \pm 2\%$ aerosol

mitigation) that six subjects were sufficient to demonstrate its considerable benefit.

Conclusions

First, we confirm that exercise is an aerosol-generating procedure that produces measurable quantities of aerosols in the size range with potential to carry COVID-19. Second, to our knowledge, this is the first demonstration of the usefulness of portable HEPA filters with directional air flow to reduce the concentration of aerosols that are generated during exercise testing. Third, we have identified a supplementary role of portable HEPA filters in reducing the time for aerosol clearance in a clinical exercise testing laboratory between tests, with the potential benefit of allowing more tests to be performed in a safer manner over a daily clinical schedule.

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