Environmental Surveillance and Transmission Risk Assessments for SARS-CoV-2 in a Fitness Center

Hongwan Li¹, SriPriya Nannu Shankar¹, Chiran T. Witanachchi¹, John A. Lednicky²,³, Julia C. Loeb²,³, Md. Mahbubul Alam²,³, Z. Hugh Fan⁴,⁵, Karim Mohamed⁵, Arantzazu Eiguren-Fernandez⁶, Chang-Yu Wu¹*

¹ Department of Environmental Engineering Sciences, University of Florida, USA
² Department of Environmental and Global Health, University of Florida, USA
³ Emerging Pathogens Institute, University of Florida, USA
⁴ Department of Mechanical & Aerospace Engineering, University of Florida, USA
⁵ J. Crayton Pruitt Family Department of Biomedical Engineering, University of Florida, USA
⁶ Aerosol Dynamics Inc., Berkeley, California, USA

ABSTRACT

Fitness centers are considered high risk for SARS-CoV-2 transmission due to their high human occupancy and the type of activity taking place in them, especially when individuals pre-symptomatic or asymptomatic for COVID-19 exercise in the facilities. In this study, air (N = 21) and surface (N = 8) samples were collected at a fitness center through five sampling events from August to November 2020 after the reopening restrictions were lifted in Florida. The total attendance was ~2500 patrons during our environmental sampling work. Air samples were collected using stationary and personal bioaerosol samplers. Moistened flocked nylon swabs were used to collect samples from high-touch surfaces. We did not detect SARS-CoV-2 by rRT-PCR analyses in any air or surface sample. A simplified infection risk model based on the Wells-Riley equation predicts that the probability of infection in this fitness center was 1.77% following its ventilation system upgrades based on CDC guidelines, and that risk was further reduced to 0.89% when patrons used face masks. Our model also predicts that a combination of high ventilation, minimal air recirculation, air filtration, and UV sterilization of recirculated air reduced the infection risk up to 94% compared to poorly ventilated facilities. Amongst these measures, high ventilation with outdoor air is most critical in reducing the airborne transmission of SARS-CoV-2. For buildings that cannot avoid air recirculation due to energy costs, the use of high filtration and/or air disinfection devices are alternatives to reducing the probability of acquiring SARS-CoV-2 through inhalation exposure. In contrast to the perceived ranking of high risk, the infection risk in fitness centers that follow CDC reopening guidance, including implementation of engineering and administrative controls, and use of personal protective equipment, can be low, and these facilities can offer a relatively safe venue for patrons to exercise.

Keywords: COVID-19, Airborne transmission, Inhalation exposure, Risk assessment, Biohazard risk

1 INTRODUCTION

The coronavirus disease 2019 (COVID-19) pandemic caused by severe acute respiratory syndrome coronavirus (SARS-CoV-2) officially started in December of 2019 (WHO, 2020). It has made significant marks in history, as the pandemic has: (a) resulted in more than 4.3 million deaths worldwide as of August 18, 2021; (b) caused lockdowns of cities/states/provinces; (c) transitioned reliance of business, school, and other day-to-day operations from human-to-human interactions to virtual online processes, etc. As awareness of how COVID-19 is spread increases among the public, users of fitness centers and gyms have expressed safety concerns regarding their use of such facilities...
(Kaur et al., 2020). In particular, whereas those with clinically apparent COVID-19 are likely to self-quarantine or be hospitalized, users of fitness facilities who are pre-symptomatic or asymptomatic are potential sources of virus transmission. Indeed, fitness centers have been implicated as high-risk environments for acquiring COVID-19 compared to other indoor environments due to their high human occupancy and the type of human activities that take place in them (Salonen et al., 2020). In fitness centers, it may be difficult for patrons to wear masks during heavy exercise, wash hands after touching equipment surfaces, and maintain physical distancing, and these places are often crowded. However, all of these preventive actions are recommended by the US Centers for Disease Control and Prevention (CDC) for reopening fitness facilities (CDC, 2020). Therefore, the reopening of fitness centers and gymnasiums (gyms) has been severely restricted by States and Counties. For example, Florida did not lift the 50% capacity restriction for fitness centers until June 5, 2020, when the state entered Phase 2 of the COVID-19 pandemic (Florida Phase 2, 2020). New York reopened gyms and fitness centers at up to 33% of capacity on March 31, 2021 (Reopening New York, 2021), and Los Angeles County in California permitted the operation of fitness centers at up to 10% capacity on March 15, 2021 (County of Los Angeles, 2021). Furthermore, at least one professional medical association that provides medical and public health education as well as legislative and regulatory advocacy and health policy research, the Texas Medical Assoc., ranked the risk of developing COVID-19 infection when working out at a gym as high (Texas Medical Assoc., 2020). An epidemiological study that analyzed mobile application data in Chicago from March–April 2020 inferred that reopening fitness centers can be particularly risky for SARS-CoV-2 transmission (Chang et al., 2020). Noteworthy, environmental sampling was not performed during the acquisition of that data.

When fitness centers and gyms follow CDC fitness center reopening guidance (CDC, 2020), it is important to evaluate whether the risk of acquiring SARS-CoV-2 infections is still high in these facilities. Airborne transmission is an important route for the spread of SARS-CoV-2. During the early phase of COVID-19, about 40–45% of SARS-CoV-2-infected individuals were pre-symptomatic and asymptomatic (Oran and Topol, 2020). These asymptomatic and pre-symptomatic persons can release millions of virus-containing particles per hour during breathing, coughing, sneezing, and speaking (Ma et al., 2020; Prather et al., 2020). These virus-containing particles occur in two size categories: (a) small droplets whose diameters are \( \leq 5 \, \mu m \), and (b) large droplets with diameters \( > 5 \, \mu m \). As they are expelled, the small droplets can also evaporate quickly to form much smaller droplet nuclei, and both the small droplets and droplet nuclei can remain airborne in aerosols that drift long distances away from the emitter. SARS-CoV-2 can remain viable (infectious) for several hours in aerosols (van Doremalen et al., 2020), and aerosols with viable virus can travel more than 2 m (Lednicky et al., 2020b), the recommended distance for physical distancing. Airborne SARS-CoV-2 has been detected in hospital rooms for COVID-19 patients (Chia et al., 2020; Razzini et al., 2020; Wang et al., 2020). SARS-CoV-2 can also remain viable on surfaces, such as plastic and stainless steel, for several days (Pastorino et al., 2020; van Doremalen et al., 2020), and the virus has been found in swab samples of environmental surfaces in hospitals (Feng et al., 2020; Wei et al., 2020). Therefore, environmental surveillance comprised of air and surface samplings for SARS-CoV-2 can be used to assess the risk of acquiring infection in fitness centers and reveal whether adoption of CDC reopening guidance and implementation thereof with additional mitigation strategies lowers airborne transmission of SARS-CoV-2 in such facilities. To the authors’ knowledge, this study presents the results of the first environmental sampling for SARS-CoV-2 in a fitness center in the US.

2 METHODS

2.1 Fitness Center

This fitness center is located at an urban/suburban mix area of north-central Florida (FL), wherein air and environmental samplings were performed five times during peak hours (16:00–19:00) from August–November 2020 (Fig. 1). Although fitness centers in FL were permitted to operate at full capacity since June 5, 2020, the occupancy (~1600 daily) was approximately 65–70% of that pre-COVID-19 pandemic (before March 2020) through samplings. During the testing period reported in this study, it was operated at a temperature of 21 ± 1°C and a relative humidity...
of $51 \pm 2\%$. The site’s heating, ventilation, and air conditioning (HVAC) system consisted of 12 air handler units (AHUs) that produced a total of 10 air changes per hour (ACH) with 36% of the air recirculated. The filters in each AHU had a minimum efficiency reporting value (MERV) of 10 and were replaced monthly. During the lockdown in April 2020, new dual ultraviolet germicidal irradiation (UVGI) lamps (57–288 watts inside each AHU depending on the heating/cooling load and dimensions) were installed inside the AHUs (Table S3; Table and Figure numbers preceded by an “S” are in the Supplementary Materials) to disinfect air passing through the coils. Additionally, 15 fans using multi-vane stator and venturi nozzle technology built with UVGI lamps in the center (9 watts per lamp) were distributed in the upper room throughout the space. The flow rate of each fan was 930 m$^3$ h$^{-1}$.

The floor space dedicated to exercise covers an area of 7,000 m$^2$ partitioned between two floors in the facility. The fitness center consists of a large fitness space (Table S5), five studios for group/personal classes (e.g., aerobic, cycling, cardio muscular, yoga, and stretching activities), an indoor swimming pool, and an indoor basketball court. There is a children’s club that offers free babysitting; with a floor area of 120 m$^2$ and volume of 330 m$^3$, it uses the same HVAC system as the other parts of the fitness center. Children aged 6-weeks to 12-years can stay in the children’s club for up to two hours under staff supervision, with access to TVs, toys, and art supplies, etc. There were 10–13 children in the room during the sampling events of this report.

2.2 Air Sampling

A total of 21 air samples were collected in the fitness center during five sampling visits (Table 1). Air was collected by four devices (Fig. S1): Viable Virus Aerosol Sampler (VIVAS) and BioSpot-VIVAS (Aerosol Devices Inc., Fort Collins, CO) as stationary samplers, and a 47 mm PTFE filter in an in-line holder (Millipore, Bedford, MA) and a NIOSH two-stage cyclone bioaerosol sampler (BC-251) as personal samplers. A 3-h air sampling at 8 L min$^{-1}$ was performed during each visit using either the VIVAS or BioSpot-VIVAS with their air intakes positioned --1.5 m above ground in the center of the large fitness space on the first floor. The sampling duration and sampled volume are well within those of other studies that detected SARS-CoV-2 virus using stationary samplers (Lednicky et al., 2020a, b; Santarpia et al., 2020). The BioSpot-VIVAS is a commercial version of the VIVAS, and both collect airborne particles on a 35 mm Petri dish containing 1.5 mL of liquid collection medium (LCM) as the collection vessel. Both VIVAS and BioSpot-VIVAS work by condensing water vapor onto particles in the air being sampled, thus enlarging the particle diameters in eight parallel growth tubes, making the larger particles easier to collect as they gently impact onto the LCM in the Petri dish (Ward et al., 2020). The four major sections of the
Table 1. SARS-CoV-2 rRT-PCR results of air and surface samples collected in the fitness center.

<table>
<thead>
<tr>
<th>Date</th>
<th>Type (Stationary) / Personal</th>
<th>Location</th>
<th>Number of Samples</th>
<th>rRT-PCR results</th>
</tr>
</thead>
<tbody>
<tr>
<td>8/31/2020</td>
<td>Air (Stationary)</td>
<td>Center of fitness center</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td>Air (Personal)</td>
<td>Throughout the fitness center</td>
<td>2</td>
<td>Negative</td>
</tr>
<tr>
<td>9/8/2020</td>
<td>Air (Stationary)</td>
<td>Center of fitness center</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td>9/14/2020</td>
<td>Air (Stationary)</td>
<td>Center of fitness center</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td>Air (Personal)</td>
<td>Throughout the fitness center</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td>10/5/2020</td>
<td>Air (Stationary)</td>
<td>Center of fitness center</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td>Air (Personal)</td>
<td>Throughout the fitness center</td>
<td>6</td>
<td>Negative</td>
</tr>
<tr>
<td>11/2/2020</td>
<td>Air (Stationary)</td>
<td>Center of fitness center</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td>Air (Personal)</td>
<td>Throughout the fitness center</td>
<td>3</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td>Air (Stationary)</td>
<td>Center of the children’s club</td>
<td>3</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td>Surface swab</td>
<td>Bean bag chair in Children’s club</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Toy in children’s club</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Baby mat in children’s club</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Check-out touchpad in fitness center</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Door handrail in fitness center</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Treadmill</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Deadlift bar</td>
<td>1</td>
<td>Negative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bench press</td>
<td>1</td>
<td>Negative</td>
</tr>
</tbody>
</table>

During each visit, the PTFE filter and NIOSH BC-251 sampler were operated at 3 L min⁻¹ for 1 h using SKC Airchek and Zefon ELF sampling pump (Table 1), respectively, as a personal sampler to investigate the spatial-weighted average of virus aerosol concentrations in the facility. The sampling duration and sampled volume are well within those by other studies that detected SARS-CoV-2 virus using personal samplers (Chia et al., 2020; Feng et al., 2020; Santarpia et al., 2020). The personal sampler was clipped onto masked sampling team member who walked through the workout area at the fitness center’s first and second floors. The air inlet of the personal sampler was held vertically at a height corresponding to the breathing zone of the sampling team member. A 5 µm pore size PTFE membrane filter (Millipore) was used to collect total airborne particles, whereas the NIOSH BC-251 collected airborne particles in three size groups: > 4.4 µm in a 15 mL centrifuge tube (Fisher Scientific, Waltham, MA), 1.1–4.4 µm in a 1.5 mL centrifuge tube (Fisher Scientific), and < 1.1 µm on a 2 µm pore size 37 mm diameter PTFE membrane filter (SKC Inc., Eighty Four, PA). After sampling, all personal samplers were sealed in a resealable polypropylene bag (26 cm × 27 cm), positioned vertically in a Styrofoam cooler (interior: 25 cm × 20 cm × 18 cm) with two ice packs (14 cm × 10 cm × 2 cm), then transported to a BSL2-enhanced laboratory for initial work-up. In the children’s club, air was collected using NIOSH BC-251 sampler, which was placed ~1.5 m above the ground, following the same sampling, transport, and storage process described above.

Initial work-up of the samples was performed in a Class II, Type A2 biosafety cabinet (BSC) by trained analysts wearing personal protective equipment including masks, gloves and lab coats. Filters of the personal samplers were aseptically retrieved and immersed in sterile 1.5 mL of LCM for 30 minutes at room temperature to help rehydrate and dislodge virions stuck on the filter surface. The filters and fluids were subsequently transferred to sterile 100 × 15 mm plastic Petri dishes, and the filters scraped with flocked swabs pre-wetted with LCM and residual fluid in each swab extruded into the liquid corresponding to each filter. The recovery solutions were concentrated by centrifugation in Amicon Ultra-15 centrifugal filter units with Ultracel-100 membranes with a molecular mass cutoff of 100 kDa (Millipore) at 4,000 × g for 12 min to a volume of approximately
< 400 µL, and the concentrates adjusted to 400 µL by addition of recovery solution. They were then aseptically transferred to 2 mL sterile plastic cryotubes with O-ring seals (Sarstedt, Numbrecht, Germany), and the tubes stored in a locked –80°C freezer for subsequent analyses.

For the NOISH BC-251 sampler, 0.5 mL of LCM was added to the 1.5 mL tube, and 1.5 mL to the 15 mL tube, and after gentle mixing to resolubilize material collected on the surfaces, the resuspended particulates were concentrated and stored as for the VIVAS and BioSpot-VIVAS samples.

### 2.3 Surface Sampling

Moistened flocked nylon swabs were used to sample approximately 5 cm × 5 cm high-touch surfaces. As shown in Table 1, eight surface samples were collected in the fitness center and the children’s club. After sampling on the surfaces, swabs were inserted into 1.5 mL of LCM in sterile transport tubes. The transport and storage of the surface swabs followed the same general procedures used for air samples.

### 2.4 Detection of SARS-CoV-2 Genome

For molecular analyses, the frozen samples were thawed on ice, then analyzed by real-time reverse transcriptase-polymerase chain reaction (rRT-PCR) within 72 hours of collection at the University of Florida Emerging Pathogens Institute (EPI). The SARS-CoV-2 genomic RNA in air and surface samples were analyzed following the rRT-PCR procedures detailed in Lednicky et al. (2020a). The rRT-PCR method used in this work has been used to detect SARS-CoV-2 RNA in nasopharyngeal, throat, and saliva specimens from COVID-19 patients and environmental samples (Lednicky et al., 2020b). The limit of detection (LOD) is 1.5 SARS-CoV-2 genome equivalents per 25 µL rRT-PCR assay (Supplementary Materials Section S1).

### 3 RESULTS AND DISCUSSION

The rRT-PCR tests for SARS-CoV-2 vRNA were negative for all air (N = 21) and surface (N = 8) samples (Table 1). In each 3-h sampling period, there were 400-500 patrons in the fitness center, and the total attendance was ~2500, counting all five sampling events. Unfortunately, we were unable to test any patron for SARS-CoV-2, and how many infected patrons exercised during sampling was unknown. Considering the positive COVID-19 cases in Alachua County, FL, where the fitness center is located, the maximum daily cases were ~200 (Fig. 1). With the hypothesis that ~40% of infected individuals may be pre-symptomatic or asymptomatic (Oran and Topol, 2020), the maximum daily positive cases could be estimated to be 333, assuming the positive tests were merely from symptomatic individuals. Because symptomatic individuals were potentially isolated or quarantined, that means ~133 per 269000 people (county population), i.e., 1 per 2022, might work out in the fitness center and shed virus. In this situation, there were 1.2 contagious individuals in the fitness center throughout the five sampling events, or 0.24 contagious individual per sampling event; thus, the possibility that one patron spread the virus was low in the facility. That is in contrast with the previously perceived high-risk ranking (Texas Medical Assoc., 2020).

The sampled fitness center also followed CDC guidance to minimize the infection risk of SARS-CoV-2. The engineering control measures included: 1) improved ventilation with high-efficiency filter and additional UVGI systems in both AHU and upper room; 2) anti-bacterial wipes and hand sanitizers in multiple locations throughout the facility; 3) modified weight equipment for 2 m apart and opened only every other cardio equipment; 4) basketball court open for individual shooting only; 5) limited number of participants in each studio and 2.4 m × 2.4 m floor assignment for individuals to use; 6) touchless check-in at the front desk; 7) signs of wearing masks, hand washing, and physical distancing at the entrances, main fitness areas, and studios. Besides, the fitness center developed administrative policies for both employees and patrons, such as isolation of infected individuals, temperature screening, and offering virtual and outdoor classes. Mandatory face covering policy was implemented to further reduce the SARS-CoV-2 transmission in the fitness center.

The children’s club was operated with the same engineering and administrative control strategies as the main area, such as sanitizing toys multiple times per day, asking children to use hand
sanitizer, allowing only one parent in check-in area at a time. Children 2 years of age and older are encouraged to wear face coverings in the club.

Since the reopening of the fitness center, the facility managers have not been made aware of claims by any patron that they acquired COVID-19 at the facility. Yet, it may not be the same in other fitness centers. During June–July 2020, community transmission of SARS-CoV-2 occurred at three fitness facilities in Hawaii, where two pre-symptomatic instructors potentially spread the virus through training interactions and possibly contributed to 21 positive COVID-19 cases (Groves et al., 2021). In September 2020, a training coach at a fitness center in Virginia tested positive for SARS-CoV-2 (CNN, 2020). He denied personal or environmental exposure to SARS-CoV-2 at the fitness facility and attributed its happenstance elsewhere. While he was pre-symptomatic for COVID-19, he potentially exposed ~50 patrons to SARS-CoV-2 through coaching, but none of them tested positive within a two-week period following revelation of his illness. A review of these cases reveals differences in how the space was ventilated: one of the three fitness facilities in Hawaii was poorly ventilated with only floor fans operational for air cooling, while the gym in Virginia had implemented the infrastructure of ventilation. The contrast in these cases echoes the CDC reopening guidance (CDC, 2020) that ventilation, i.e., provision of clean air by natural or mechanical means to a space or building (ISO, 2017), can play an important role in reducing airborne transmission of SARS-CoV-2.

While ventilation is expected to reduce the transmission, how much infection risk in such a fitness center can be lowered is not known. To evaluate the effectiveness of ventilation systems in minimizing the infection risk due to airborne transmission, an analysis was undertaken based on the Wells-Riley equation (Riley et al., 1978), which was developed for assessing the association of ventilation strategy to a measles outbreak in an elementary school. It has been used for assessing the impacts of ventilation on reducing airborne transmission of influenza A virus (Wagner et al., 2009), Mycobacterium tuberculosis (Knibbs et al., 2011), SARS-CoV-1 (Qian et al., 2009), and SARS-CoV-2 (Miller et al., 2020) in different indoor settings, including airplane, vehicle, choir rehearsal hall, and healthcare facilities. The Wells-Riley equation can be written as:

\[
P_i = 1 - e^{-\frac{T}{Q_b} \int_0^T C(t) dt}
\]

where \( P_i \) is the probability of infection risk defined as the probability of an individual patron getting infected due to inhalation exposures at the fitness center, \( Q_b \) is the breathing rate of an individual at heavy exercise, \( T \) is the duration of stay, and \( C(t) \) (quanta m\(^{-3}\)) is the quanta concentration at time \( t \). The term “quanta” in the infection risk model is a hypothetical infection dose unit, typically calculated from epidemiological studies. One quantum is the presence of pathogen in the air that can probably infect 63% of the people in the same indoor environment (Riley et al., 1978). The parametric values are listed in Table 2.

There are two key assumptions in the Wells-Riley equation: the room air is well-mixed, and the droplet nuclei of infectious aerosol quickly becomes evenly distributed in the confined space once released from the contagious individual. Additional assumptions are summarized in Supplementary Materials Section S2. In epidemiological modeling, which aims to assess the pathogen spread in the community, it is impossible to specify the geometries, ventilation, and the locations of the infectious pathogens in each microenvironment (Gammaitoni and Nucci, 1997). Therefore, the well-mixed assumption is commonly adopted rather than hypothesizing specific scenarios on the basis of statistical results (Dai and Zhao, 2020; Miller et al., 2020; Rudnick and Milton, 2003). Accordingly, a well-mixed room model (Fig. 2) was developed to assess the quanta concentration \( C \) in the fitness center:

\[
\frac{dC}{dt} = N \times E + C \times Q_{in} (1 - \eta_m) (1 - \eta_a) - C (Q_{out} + Q_{cut} + \beta V + nQ \eta_r)
\]

\[
= N \times E - C (Q_{in} (\eta_a + \eta_m - \eta_a \eta_m) + Q_{cut} + \beta V + nQ \eta_r)
\]

where \( E = 896 \) quanta h\(^{-3}\) person\(^{-1}\) is the quanta emission rate from the contagious person, which is calculated from average estimated levels of SARS-CoV-2 quanta emission rates in previous
Table 2. Parametric values used in the infection risk assessment.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Value</th>
<th>Type</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_b$</td>
<td>Breathing rate of an individual at heavy exercise</td>
<td>3.3 m$^3$ h$^{-1}$</td>
<td>Constant</td>
<td>Morawska et al. (2009)</td>
</tr>
<tr>
<td>T</td>
<td>Duration of stay</td>
<td>3 h</td>
<td>Constant</td>
<td>Peak hours at the fitness center</td>
</tr>
<tr>
<td>V</td>
<td>Volume of the fitness center</td>
<td>$4.3 	imes 10^4$ m$^3$</td>
<td>Constant</td>
<td>Provided by facility owner</td>
</tr>
<tr>
<td>N</td>
<td>Number of contagious individuals</td>
<td>1</td>
<td>Constant</td>
<td>Assessment assumption; N can be increased to other values when evaluating its impacts</td>
</tr>
<tr>
<td>$Q_{re}$</td>
<td>Flow rate of recirculated air in the fitness center</td>
<td>$1.5 \times 10^5$ m$^3$ h$^{-1}$</td>
<td>Constant</td>
<td>Measured by facility HVAC personnel</td>
</tr>
<tr>
<td>$Q_{out}$</td>
<td>Flow rate of exhausted air to outdoors in the fitness center</td>
<td>$2.8 \times 10^5$ m$^3$ h$^{-1}$</td>
<td>Constant</td>
<td>Measured by facility HVAC personnel</td>
</tr>
<tr>
<td>$Q_f$</td>
<td>Flow rate of the fan with UVGI systems in the room</td>
<td>930 m$^3$ h$^{-1}$</td>
<td>Constant</td>
<td>Manufacturer</td>
</tr>
<tr>
<td>n</td>
<td>Number of fans with UVGI systems in the fitness center</td>
<td>15</td>
<td>Constant</td>
<td>Provided by facility owner</td>
</tr>
<tr>
<td>$\eta_m$</td>
<td>Filter removal efficiency of 1–3 μm particles</td>
<td>65, 90, and 99.97%</td>
<td>Varied</td>
<td>MERV 10, 13, and HEPA filters (U.S. EPA, 2020)</td>
</tr>
<tr>
<td>$\eta_r$</td>
<td>Virus inactivation efficiency of fans with UVGI systems</td>
<td>89.10%</td>
<td>Constant</td>
<td>Buonanno et al. (2020); Tseng et al. (2005) (Supplementary Materials Section S5)</td>
</tr>
<tr>
<td>$\eta_A$</td>
<td>Virus inactivation efficiency of UVGI in AHU</td>
<td>82–100%</td>
<td>Varied</td>
<td>Calculated based on the air flow rate passing through, residence time, and UVC lamp intensity (Supplementary Materials Section S6)</td>
</tr>
<tr>
<td>$\beta$</td>
<td>First-order loss-rate coefficient</td>
<td>0.93 h$^{-1}$</td>
<td>Constant</td>
<td>Sum of $\beta_{dep}$ and $\beta_{ina}$</td>
</tr>
<tr>
<td>$\beta_{dep}$</td>
<td>Deposition rate onto surfaces</td>
<td>0.3 h$^{-1}$</td>
<td>Constant</td>
<td>Thatcher et al. (2002)</td>
</tr>
<tr>
<td>$\beta_{ina}$</td>
<td>Decay rate due to virus inactivation</td>
<td>0.63 h$^{-1}$</td>
<td>Constant</td>
<td>van Doremalen et al. (2020)</td>
</tr>
<tr>
<td>ACH</td>
<td>Total air change per hour</td>
<td>1, 5, 10 ACH</td>
<td>Varied</td>
<td>Low to high ventilation; sum of outdoor air ($Q_{out}/V$) and recirculated air ($Q_{re}/V$) ventilations</td>
</tr>
<tr>
<td>$Q_{re}/(Q_{re} + Q_{out})$</td>
<td>Ratio of air recirculated</td>
<td>0, 50, 100%</td>
<td>Varied</td>
<td>High to low outdoor air intakes</td>
</tr>
</tbody>
</table>

Studies (Buonanno et al., 2020; Dai and Zhao, 2020; Harrichandra et al., 2020; Kriegel et al., 2020; Miller et al., 2020) considering the corresponding expiratory activities and breathing rates (Supplementary Materials Section S3). Other parameters in evaluating the infection risk are listed in Table 2. While an infection risk assessment can range widely for any real-world situation according to the stochastic variations in the parameters of the model used (Noakes and Sleigh, 2009), the determined values in the present study in Table 2 are justified and indicate the significance of ventilation strategies in reducing the risk level. It should be noted that with the assumption of well-mixed air in the room, the Wells-Riley model cannot determine the infection risk at an exact spot in the fitness center, due to the complexity of air flow in a large space (Noakes and Sleigh, 2009). To assess the effects of each ventilation measure, the impacts of ventilation and recirculation were examined when neither filtration nor disinfection devices were used (i.e., $\eta_m = \eta_r = \eta_A = 0$); the influences of filtration and air disinfection were evaluated when the air was 100% recirculated (i.e., $Q_{out} = 0$). MATLAB R2019a was used for modeling and calculations of $P_i$.

Fig. 3 shows that at the sampled fitness center that was ventilated with 10 ACH, 36% recirculated air, MERV 10 filter, and UVGI in both upper-room and AHU, the calculated probability of infection was 1.77%, much lower than previous infection risk of outbreaks in a call center, a restaurant, and a choir rehearsal hall, which were 8.5%, 11.7%, and 87%, respectively (Li et al., 2020; Miller et al., 2020; Park et al., 2020). If there were 500 patrons in the facility, the probable number of infected people was 9, a value derived from the product of the probability of infection and the total number of occupants. With a conservative assumption that the cloth mask has a
filtration efficiency of 50% (Konda et al., 2020), the infection risk at the fitness center was 0.89% (Supplementary Materials Section S7) when patrons use face masks. Alternatively, if the number of contagious individuals in the fitness center was reduced from 1 to 0.24, i.e., the ratio considering attendance through 3-h sampling period and the county pre-symptomatic and asymptomatic cases, the probability of infection risk decreased from 1.77% to 0.43%. The estimated infection risks of SARS-CoV-2 in the fitness center in aforementioned scenarios (i.e., 0.43–1.77%) were even lower than that predicted for a customer with 10-min exposure to a contagious case in a poorly
ventilated pharmacy store (i.e., 2.8%) (Buonanno et al., 2020). The result suggests that the high ranking of infection risk in fitness centers should be reevaluated for those that follow CDC guidance.

When the fitness center is operated at 100% recirculated air (i.e., no outdoor air intake) without any filtration or air disinfection devices, the resultant probability of infection is 13.7%. Considering up to 500 patrons in the facility, the probable number of infected people is 69. That means, using the ventilation control strategies adopted by the fitness center, the probable number of infected people may be reduced by 87%, from 69 to 9. The infection risk can be further reduced by 94% considering the filtration effects of face masks. The modeling results illustrate that the ventilation strategies adopted by the fitness center may effectively lower the transmission risk of SARS-CoV-2. This reduction is consistent with the findings that the aerosol concentrations in a gym were decreased by 80–90% when ventilation and air disinfection was implemented, according to measurements of the aerosol particle concentrations with individuals performing physical exercise in the facility (Blocken et al., 2021). Dai and Zhao (2020) also reported that increasing the ventilation rate from 100–350 m³ h⁻¹ to 1200–1400 m³ h⁻¹ allows exposure time to be increased from 0.25 h to 3 h while maintaining infection probability below 1% in a confined space. For a multi-room building using central air handling system, Pease et al. (2021) echoed that increasing the air change rate could remove virus from the source room faster but cautioned that it may contribute to increased infection probability in connected rooms, if there is no filtration. It should be noted that when the air is 100% recirculated, the ventilation rate does not affect the \( P_i \) and the infection risk remains at 13.7% from 1 to 10 ACH, since the airborne SARS-CoV-2 is simply distributed from one room to other indoor spaces using the same HVAC system. If the air is 50% recirculated, the infection risk can be reduced from 10.5% to 3.23% by increasing the ventilation from 1 to 10 ACH, and the probable number of infected people with ~500 patrons in the fitness center can be decreased from 53 to 16. Further reducing the air recirculation and introducing more outdoor air can minimize the infection risk from 13.7% to 1.81% when the facility is operated at 10 ACH with 0% air recirculation (i.e., 100% outdoor air intake). In other words, by introducing outdoor air to indoor environments, the ventilation systems can dilute quanta concentrations and reduce airborne transmission. This agrees with the real-world cases that a well-maintained ventilation system contributed to the negative results of air samples in the COVID-19 patient rooms in a hospital (Young et al., 2020), while poor ventilation in a restaurant drove the community spread of COVID-19 in Guangzhou, China (Li et al., 2020). Similarly, a modeling study for airborne transmission of influenza A virus in passenger cars shows that infection risk can be reduced if no air is recirculated (Knibbs et al., 2012).

For fitness centers where it is challenging to introduce sufficient outdoor air in the central air systems, filtration and air disinfection are essential to reduce the infection risk. As shown in Fig. 3, using MERV 10 and MERV 13 filters at 10 ACH, the estimated probability of infection from the infection risk model can be reduced from 13.7% to 2.62% and 1.99%, respectively. The infection risk can be further reduced to 1.81% using HEPA filters, i.e., 99.97% removal efficiency for 0.3 µm particles (U.S. EPA, 2019), which is as effective as the outdoor air ventilation strategy. The high-efficiency filtration may contribute to the lack of airborne transmissions from an infected passenger on a long-distance flight (Schwartz et al., 2020). An infection risk assessment study found high-efficiency filters can reduce the risk by up to 93% in rooms that are connected to a COVID-19 patient’s room through ventilation with the same AHU (Pease et al., 2021). Fig. 3 also shows that using UVGI in the upper room and in AHU at 10 ACH, the probability of infection can be reduced from 13.7 to 11.7 and 2.15%, respectively. Using UVGI in the AHU may be more effective under this situation since a large volume of air was recirculated and disinfected by the UVGI. The efficiency of UVGI in the upper room can be increased based on the intensity, flow rate, and residence time of each unit and the total number of installed units.

4 LIMITATIONS

Due to relatively low positive COVID-19 cases in Alachua county during the study period of this report, it was not surprising that the air and surface samples tested negative for SARS-CoV-2. In fitness centers located at areas with a much higher incidence of COVID-19, the effectiveness of reopening measures warrants further sampling studies. We did not get access to other fitness
centers, and the presence of virus in air and surfaces may be different in those facilities that are poorly ventilated and crowded with patrons. The infection risk model is related with SARS-CoV-2 quanta emission rates that were estimated from attack rates in outbreaks, and little is known for the quanta emission rates of new variants of SARS-CoV-2. The air is assumed evenly distributed, while SARS-CoV-2 exposure can be higher near the contagious individual; a more comprehensive computational fluid dynamic (CFD) modeling can provide details about the spatiotemporal distribution of the virus, though it is far beyond the scope of the present study. Borro et al. (2021) developed CFD models to investigate the impacts of ventilation rates on the flow of airborne particles; they found that high ventilation rates may promote turbulent transport of the particles emitted by an infected individual, resulting in droplet disruption and enhance dispersion within the room. Although the inlet and outlet vents were fixed in that study, they recommended further evaluation of how to redesign vents in reducing the dispersion effects. The removal and inactivation efficiencies for SARS-CoV-2 using filter and UVGI were obtained from the manufacturers or estimated by empirical equations; laboratory testing of their true performance in the given setting can improve the accuracy of risk assessment. Other measures such as reducing duration of stay and avoiding crowded fitness centers can also decrease the probability of infection (Morawska et al., 2020). The vaccination effects and reopening measures, such as physical distancing and hygiene efforts, were not considered in the infection risk assessments resulting from inhalation exposure, though they are expected to further reduce the transmission risk.

5 CONCLUSIONS

Complementing many epidemiological studies based on statistics of human mobility data to evaluate SARS-CoV-2 exposure in public spaces (Cheng et al., 2020; Ghinai et al., 2020; McMichael et al., 2020), we conducted the first environmental sampling study during peak hours in a fitness center in the US. All air (N = 21) and surface (N = 8) samples tested negative for SARS-CoV-2 RNA by rRT-PCR. The fitness center was operated at 10 ACH ventilation, 36% recirculated air, MERV 10 filter, and UVGI in both upper room and AHU, which resulted in the probability of infection due to airborne SARS-CoV-2 transmission of 1.77%. Compared to the ventilation system of all air recirculated without any filtration or air disinfection, the infection risk was reduced by 87% in the adopted situation. Considering the filtration of virus-laden aerosols by face masks, the infection risk was further reduced to 0.89%, and the probable number of infected people in a fitness center with ~500 patrons can be decreased by 94%, from 69 to 4. To minimize airborne transmission, it is recommended for fitness centers to ventilate with high ACH, minimize air recirculation, use high efficiency filter, and install air disinfection devices. Amongst these measures, operating at high ventilation with minimal air recirculation is critical, which can effectively reduce the probability of infection from 13.7 to 1.81%, even without any further treatment. For buildings that cannot avoid air recirculation due to energy consideration, using filtration and air disinfection devices are essential to reducing the probable infection risk. In fitness centers following CDC guidance, including engineering controls (especially improved ventilation), administrative controls, and face coverings, the risk of developing COVID-19 infection can be low in the facility, which is in contrast to the ranking of high risk by the professional medical association. The restrictions of reopening fitness centers warrant re-evaluation by policy makers, in terms of the infection risk at facilities adopting CDC guidance.

ACKNOWLEDGEMENTS

This work was supported by National Science Foundation (Grant No. 2030844) and National Institutes of Health (Grants No. R44ES030649 and R01AI158868). The authors are grateful to Joe Cirulli, the owner and founder, and the staff in the visited fitness center for access and assistance in sampling and providing operating information. The authors thank Dr. William Lindsley (NIOSH) for free loan of the NIOSH bioaerosol samplers to us and Dr. David Kaplan for loaning us the state-licensed truck for transporting the sampling system. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation and National Institutes of Health.
DISCLAIMER

No conflict of interest declared.

SUPPLEMENTARY MATERIAL

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.210106

REFERENCES


County of Los Angeles (2021). County of Los Angeles department of public health order of the health officier Appendix L: Reopening protocol for gyms and fitness establishments.


