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Air quality in an air ventilated fitness center reopening for pilot study during COVID-19 pandemic lockdown

Eva-Maria Huessler a,*, Anika Hüsing a, Markus Vancraeyenest b, Karl-Heinz Jöckel a,1, Bernadette Schröder a,1

a Institute of Medical Informatics, Biometry and Epidemiology (IMIBE), University Hospital Essen, Hufelandstraße 35, 45147 Essen, Germany
b FitX Verwaltung GmbH, Stoppenberger Straße 61, 45141 Essen, Germany

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A B S T R A C T

During COVID-19 lockdowns less people were able to fulfill the WHO recommendations on physical activity. Also, fitness centers were associated to SARS-CoV-2 superspreader events. However, the risk of infection can be strongly reduced by outdoor air ventilation. To investigate whether a reopening of fitness centers can be justified, CO₂ concentration was measured during four days in a fitness center.

Except for one room, the observed CO₂ concentrations were mainly under 800 ppm, which stands for high air quality. The strong decrease of CO₂ concentration during the 15 min evacuations following each hour of workout, speaks for the functionality of the ventilation system. In particular, the number of people present in the studio has a strong impact on the estimated CO₂ value. In a linear mixed model, an additional CO₂ concentration of 2.24 ppm (95% confidence interval [2.04, 2.43]) was estimated for this setting with a total volume of 4065 m³ in the fitness center and a possible air change rate per hour up to 10. This means, that for 45 visitors, 100 ppm can be added to the predicted concentration.

To summarize, a combination of ventilation, restriction of the number of visitors and surveying the CO₂ concentration allowing for further restrictions in case of need, seems to be an adequate means to reduce the risk of SARS-CoV-2 infection in fitness centers.

1. Introduction

Physical activity plays an important role in public health [1]. The World Health Organization (WHO) recommends for adults aged 18 to 84 an aerobic physical activity of moderate-intensity of 150 to 300 min per week or a physical activity of vigorous-intensity of 75 to 150 min per week [2]. Additionally, major muscle groups should be strengthened at least twice a week. During COVID-19 pandemic lockdowns, physical activity decreased tremendously worldwide [3,4]. In studies where subjects were interviewed about their physical activity before and during lockdown a decrease in time of vigorous to moderate intensity of 33% [3] and of 41% [4] was observed resulting in only 62.5% compliance to the WHO recommendations compared to 80.9% of compliance before lockdown [4]. However, when governments re-opened facilities, such as shops, restaurants, bars and theaters, sport facilities often did not have priority. Therefore, it is of special interest to study if and under which conditions a responsible operation of sport facilities such as fitness centers is feasible.

Physical activity can induce an increased inhalation of air to larger proportion inhaled through mouth, getting deeper into the respiratory tract [5]. Hence, outbreaks of COVID-19 in fitness centers have been analyzed in several studies [6–9]. Some studies suggest a higher risk of infection in fitness centers. Chang et al. [10] analyzed movements of 98 million people by analyzing mobile phone data. They conclude that a majority of SARS-CoV-2 infections can be associated to a minority of superspreader points of interest, including fitness centers. Kriegel [11] estimated that the risk of infection, assuming a SARS-CoV-2 infected person in the facility, is 2 to 3.4 times higher in a fitness center (30% or 50% occupied) than in a supermarket (80% occupied).

However, in these studies the ventilation was either not taken into account [9,10] or mentioned as improvable [6–8] or only considered as minimum standard [11]. The American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE) states that ventilation systems with a large amount of fresh air supply can reduce the risk of aerosol transmission [12]. The risk of direct transmission of larger droplets cannot be reduced by a ventilation system [12] but by a physical distance...
between people [13]. Contaminated surfaces seem to represent only a very small risk of SARS-CoV-2 infection [14]. Many studies support the fact that a large amount of fresh air ventilation plays one of the key roles in reducing the risk of SARS-CoV-2 infection [13,15,16]. Thus, the risk of infection can be reduced by a higher ventilation rate. To survey roles in reducing the risk of SARS-CoV-2 infection [13,15,16]. Thus, the fact that a large amount of fresh air ventilation plays one of the key very small risk of SARS-CoV-2 infection [14]. Many studies support the

E.-M. Huessler et al.

2. Methods

2.1. Study design

The here presented pilot study is an observational study. During four days in May 2021 (May 25, 8:00 a.m. to May 29, 07:55 a.m.) technical measurements such as CO2 concentration in parts per million (ppm), room temperature in Celsius and room humidity in percent were collected.

Starting at 08:00 a.m., the 24 h opening time per day was divided into time slots of one hour of workout for a group of athletes followed by an evacuation of 15 min, resulting in 19 time slots per day. In order to get access to the fitness center, visitors had to book in advance one of the available timeslots. Furthermore, a negative COVID-19 test, which must not be older than 48 h, had to be presented by the trainees, if the visitor cannot prove that he/she is fully vaccinated or recovered. Every visitor had to leave the fitness center during the break of 15 min. Wearing face masks (surgery or FFP2 mask) was mandatory except when working out.

Two different scenarios, each of which lasts two days, were consid-
ered. For test scenario A 15 m2 per person and for scenario B (first two days of study) 20 m2 are allowed. This results in a maximum number of 111 visitors in the fitness center at the same time for scenario A, and 83 visitors for scenario B. The fitness center consists of five rooms: Fitness 1, free weight area (both first floor), Fitness 2, a room for fitness classes and a ladygym (all three second floor). For a floor plan, see Figs. A.1 and A.2 in Appendix. The ladygym was only accessible for women and limited to a number of four women working out simultaneously. The fitness classroom was separated to the other rooms by closed doors. Every class lasted 30 min and was limited to a maximum number of ten visitors, who had to subscribe in advance. For a detailed class schedule, see Table A.1 in Appendix. Measurements of CO2 concentration, relative humidity and temperature, were taken every five minutes by two sensors per room at a height of 1.50 m.

2.2. Technical equipment

The measurements of CO2 concentration, relative humidity and temperature are taken by sensors, that measure all these variables with an automatic calibration. The measurement precision for the CO2 concentration is +/− 50 ppm plus 2% of the measurement.

A mechanical ventilation system is installed in the fitness center, where outdoor air is introduced in the fitness center. Incoming and outgoing air is filtered. For a detailed volumetric flow see Table 1. As a default, the ventilation system is set to 50% of its potential capacity. If in any of the rooms the threshold of 650 ppm is exceeded, the capacity will be gradually increased up to 100% where 100% is reached, when the CO2 concentration is around 800 ppm. This thresh-
old of 650 ppm will be called technical threshold in the following. In the fitness classroom, that is separated by doors to the other rooms, the volumetric flow rate lies between 575 m3/h per person (50% ventilation) and 1150 m3/h per person (100% ventilation) when the maximum number of ten visitors is reached. In the other rooms, the volumetric flow rate for scenario A (max. 111 visitors) lies between 187 m3/h per person (50% ventilation) and 374 m3/h per person (100% ventilation), and in scenario B (max. 83 visitors) between 250 m3/h (50% ventilation) per person and 500 m3/h (100% ventilation) per person. The German national organization for standardization (Deutsches Institut für Normung, DIN) recommends a minimum volumetric flow rate of 60 m3/h per person [21]. Thus, in scenario A with only 50% ventilation, volumetric flow rate is more than three times higher than recommended.

2.3. Data preprocessing

All analyses are conducted using SAS software, version 9.4 (Statisti-
cal Analysis System, SAS Institute Inc., North Carolina, USA). Graphics are generated by using R [22], version 4.1.1.

Missing values occurred the first day during the time from 04:30 a.m. to 05:35 a.m. During this time no technical measurements are available due to a technical breakdown so no data could be saved. These missing values are not replaced and therefore not considered in the analyses.

Access to the fitness center is recorded with a turnstile. 3,770 entrances were registered of which 551 entrances are counted for two time slots, as some visitors stayed for more than one slot. For the calculation of the number of visitors associated with a time slot, the visitors’ entrances were fully counted, independently of the length of stay.

In addition to the entrances to the fitness center as such, the entrances to the fitness classroom were registered separately. The exact number of visitors, that were present in the fitness classroom during a specific time slot, is therefore known. For all other areas in the fitness center, it is only known, how many visitors were present overall during a specific time slot, but not for a specific area. Hence, for the analyses regarding the fitness classroom, only the number of visitors registered to the fitness classroom is considered. For the analyses regarding all other areas, the total number of visitors in the fitness center minus the number of visitors in the fitness classroom is calculated.

Descriptive analyses will be provided for the number of visitors in the fitness center as well as for the technical measurements, i.e. CO2, temperature and relative humidity. Measurements in the same and different rooms are compared through Pearson's correlation coefficients. Graphical representations will be provided, where appropriate.

2.4. Statistical analysis

The primary variable of interest is the concentration of CO2 (de-
pendent variable). To analyze the influence of potential covariates, e.g., the scenario and the number of visitors per slot on the dependent

| Area                  | Volumetric flow rate | Volume | ACH† |
|-----------------------|----------------------|--------|------|
| Fitness 1             | 13,300 m³/h          | 1,338 m³ | 9.94 |
| Fitness 2             | 13,000 m³/h          | 1,368 m³ | 9.50 |
| Free weight           | 12,900 m³/h          | 1,173 m³ | 11.00|
| Ladygym               | 1,800 m³/h           | 186 m³  | 9.70 |
| Total                 | 41,500 m³/h          | 4,065 m³ | 10.21|
| Classroom             | 11,500 m³/h          | 1,267 m³ | 9.07 |

†ACH, Air changes per hour.
variable, a regression model will be applied. There are two sensors in each room, that measure the concentration of CO₂ simultaneously. To avoid underestimation of the CO₂ concentration, only the maximum of two simultaneous measurements in a fitness area is considered for analysis. Since the measurements are recorded every five minutes, 13 measurements remain per time slot per room. To account for these repeated measures, a linear mixed effect model for repeated measurements will be applied to analyze the influence of the covariates on CO₂. For every time slot and fitness area, a random effect with an autoregressive correlation of first order will be modeled. As the exact number of visitors in the fitness classroom is known, this area will be analyzed separately. The other rooms will be analyzed jointly. In addition, a subgroup analysis per room will be provided.

In the joint analysis, the time within a time slot (time point \( t = 1, \ldots, 13 \), i.e. starting from 0 min to 60 min by 5 min), the square of the time point \( (t^2 = 1, 4, 9, \ldots, 169) \), the scenario (scenario A versus scenario B as reference), the fitness area (Fitness 1, Fitness 2 and free weight area versus ladygym as reference) and the number of visitors within a time slot will be considered in the model. For the subgroup analysis and the analysis of the fitness classroom, the number of visitors within a time slot will be analyzed by sex (female, male) and age (<30, ≥30). The number of visitors considered for the fitness classroom analysis is the actual number of visitors for this area. For all other rooms the number of visitors in the fitness center minus the number of visitors in the fitness classroom will be considered.

3. Results

3.1. Visitors

There were a total of 4,232 people in the entire fitness center (minus the people in the fitness classroom), and 89 people in the fitness class room (see Table 2). Almost two third of the visitors (without fitness classroom) are male and almost three quarter of the visitors are younger than 30 years. Hence, men under 30 represent the largest part of the number of visitors with 46%. In contrast, the fitness classroom is mainly attended by women (90%).

The maximum number of allowed visitors (111 in scenario A and 83 in scenario B) is not reached in any of the time slots (see Fig. 1). On average, the number of visitors is higher in scenario A, where more visitors were allowed in the fitness center.

3.2. Air quality measurements

In Table 3, the summary of the air quality measurements by room and scenario is represented. The CO₂ concentration varies from 378 ppm (fitness classroom) to 983 ppm (free weight). The mean values in all areas are larger in scenario A compared to scenario B with the highest mean values in the free weight area. The smallest mean values are observed in the fitness classroom.

The room temperature varies from 19.4 °C to 30.5 °C (see Table 3). Noticeable is the maximum observed value of 30.5 °C in the ladygym, whereas in all other areas all temperature measurements are below 23 °C. The relative humidity varies from 37.5% (ladygym) to 62.5% (free weight).

Pearson’s correlation coefficient between measurements in the same room was usually high (≥0.77), with the exception of the ladygym, where one sensor was close to the open door to Fitness 2. This leads to a correlation of the CO₂ concentration between the sensors in the ladygym of only 0.33, whereas the correlation of CO₂ between the two close sensors in the ladygym and the Fitness 2 was 0.85. The variables CO₂ and temperature are (slightly) positively correlated with values from 0.08 to 0.50. CO₂ is also (slightly) positively correlated with relative humidity with values from 0.04 to 0.30 except for sensor 2 in the ladygym, where the correlation is −0.30. This negative correlation can probably be explained by the negative correlation of the variables temperature and relative humidity (values from −0.83 to −0.35).

As the values for the CO₂ concentration between the sensors are highly correlated in the areas Fitness 1, Fitness 2, free weight and fitness classroom, only the maximum of the two sensors is considered in the following. The CO₂ concentration in the ladygym will be represented separately for the two sensors, since they do not correlate very strongly.

In the areas Fitness 1, Fitness 2 and free weight, the CO₂ concentration is in general lower during night than during day (see Fig. 2). This can be explained by a lower number of visitors during nighttime. All graphs show a high variation, probably due to the 15 min break that follows of each time slot. The values for the CO₂ concentration seem to be higher in these three areas in scenario A, where more people are allowed in the fitness center. In the areas Fitness 1 and Fitness 2, it is only necessary for a few time slots to increase the power of the ventilation system (due to a CO₂ concentration greater than 650 ppm) regarding scenario B, but almost necessary for all time slots regarding scenario A. In the free weight area the threshold of 650 ppm is exceeded in nearly every time slot regardless of the scenario. In summary, the CO₂ concentration is much higher in the free weight area than in the other ones.

It is striking that the CO₂ concentrations measured by sensor 2 in the ladygym, are very low in comparison to the other rooms with values mainly between 400 and 500 ppm (see Fig. 3). This is probably due to the small number of four women that are allowed to work out simultaneously in this room. However, the values on May 25th in the afternoon until midnight are higher, with values up to 668 ppm.

The development of the CO₂ concentration in the fitness classroom is represented in Fig. 4. When no class is offered, i.e. no visitors are allowed in the room (black line), the CO₂ concentration varies slightly above 400 ppm, which is comparable to the CO₂ concentration of outdoor air [23]. During nighttime and just before 8:00 a.m. the CO₂ concentration decreases, which is probably due to the lower number of visitors in the fitness center. At the beginning of each class, the concentration increases, especially when a higher number of visitors attend a class. The technical threshold of 650 ppm was only reached once.

In the areas ladygym, Fitness 1 and Fitness 2 an exceeding of the threshold of 650 ppm can be observed if more than 45 visitors are present in the fitness center. In all of these areas there exist time slots with more than 60 visitors where the threshold was not reached. In contrast, in the free weight area the threshold is exceeded every time during time slots with more than 20 visitors.

To analyze the development of the CO₂ concentration within a time slot, the average values of the maxima of the two sensors for each time
Table 3
Summary of the measurements displayed by room and scenario.

| Area     | Scenario | CO$_2$ in ppm Mean (SD) [Min, Max] | Temperature in °C Mean (SD) [Min, Max] | Humidity in % Mean (SD) [Min, Max] |
|----------|----------|-----------------------------------|----------------------------------------|-----------------------------------|
| Fitness 1| A        | 592.7 (65.1) [444.1, 805.8]       | 21.3 (0.5) [20.6, 22.5]               | 50.9 (5.1) [39.4, 61.0]           |
|          | B        | 545.9 (47.3) [434.3, 699.6]       | 21.1 (0.2) [20.5, 22.1]               | 49.6 (3.6) [39.6, 57.9]           |
| Fitness 2| A        | 580.2 (66.3) [443.9, 760.0]       | 21.2 (0.7) [20.0, 22.8]               | 52.5 (4.6) [41.1, 60.7]           |
|          | B        | 536.4 (52.6) [429.1, 698.2]       | 21 (0.6) [19.9, 22.7]                 | 51.4 (2.9) [42.6, 58.7]           |
| Free weight | A    | 660.1 (96.5) [438.2, 982.6]       | 21.1 (0.3) [20.5, 22.1]               | 53.7 (4.1) [42.8, 62.5]           |
|          | B        | 633.5 (74.7) [416.6, 917.4]       | 21 (0.2) [20.3, 22.0]                 | 52.6 (3.2) [42.1, 59.1]           |
| Ladygym  | A        | 520.2 (76.8) [421.1, 719.8]       | 22.1 (2.0) [19.4, 30.5]               | 51.8 (6.8) [37.5, 62.2]           |
|          | B        | 502.5 (73.3) [391.5, 698.0]       | 21.6 (1.0) [19.4, 23.7]               | 50.8 (3.9) [39.5, 59.0]           |
| Classroom| A        | 442.8 (26.2) [393.5, 571.4]       | 21 (0.3) [20.6, 21.8]                 | 50.1 (4.3) [40.6, 56.4]           |
|          | B        | 424.4 (30.5) [378.3, 652.5]       | 21 (0.2) [20.5, 21.5]                 | 48.9 (2.7) [41.3, 55.7]           |

Fig. 1. Boxplots of the numbers of visitors per time slot displayed by scenario, where the mean is shown by a diamond.

Fig. 2. Development of the CO$_2$ concentration over time for the areas Fitness 1, Fitness 2 and free weight. The technical threshold of 650 ppm, the value from which the ventilation system starts to increase the ventilation flow, is marked by the red horizontal line. The black dashed vertical line represents the time when there was the change/switch from scenario B to scenario A.

3.3. Predictors of CO$_2$

In order to predict the CO$_2$ concentration and to analyze the effects of the covariates, i.e. number of visitors, scenario, time $t$ and $t^2$, a linear mixed model was applied, where for 76 time slots (19 per day) a random effect is estimated for each room. The results for the fixed effects are shown in Table 4. They reveal that the CO$_2$ concentration is estimated at the lowest in the ladygym. The room with the highest estimate is the free weight area with an estimate of a CO$_2$ concentration almost 100 ppm greater than for the reference of the ladygym. For scenario A the estimated effect is smaller, with 13 ppm more than for scenario B. More important is the number of visitors in the fitness center with an estimated effect of 2.24 ppm per person. Thus, 45 visitors would account for additional 100 ppm of CO$_2$. 

point within a slot are shown in Fig. 5, separated by room and scenario. Over all graphs, an increase of the CO$_2$ concentration can be detected at the beginning of a time slot and a decrease starting in the middle of a time slot. When no visitors are in the center due to the evacuation starting from time point 13, i.e. 60 min after start of the time slot, the CO$_2$ concentrations decreases rapidly. It is noticeable that the graph for the area Fitness 1 decreases slightly at the beginning of a time slot before increasing with a peak at a later time point in comparison to the other rooms. A possible explanation can be, that visitors, who want to strengthen their muscles in Fitness 1, conduct a warm-up first by using the cardiovascular equipment in the area Fitness 2.
Fig. 3. Development of the CO$_2$ concentration over time in the ladygym separated for sensor 1 and sensor 2. The technical threshold of 650 ppm, the value from which the ventilation system starts to increase the ventilation flow, is marked by the red horizontal line. The black dashed vertical line represents the time when there was the change/switch from scenario B to scenario A.

Fig. 4. Development of the CO$_2$ concentration over time in the fitness classroom. The different classes are displayed by different colors with the class names specified in the legend. The technical threshold of 650 ppm, the value from which the ventilation system starts to increase the ventilation flow, is marked by the red horizontal line. The black dashed vertical line represents the time when it was switched from scenario B to scenario A. The number of participants for each class is displayed by asterisks.

The positive effect of time $t$ within a time slot with an estimate of 32.0 and the negative effect of $t^2$ with an estimate of $-1.8$ result in a quadratic graph in dependence of the time $t$ (see Fig. 5) similar to Fig. 6. First, the estimated values increase continuously up to time point $t = 9$, i.e. after 40 min, where a maximum is reached with an estimate of an additional CO$_2$ concentration of 142 ppm before decreasing again.

### Table 4

| Variable         | Estimate | SE  | DF  | $t$-value | $p$-value | 95% CI       |
|------------------|----------|-----|-----|-----------|-----------|-------------|
| Intercept        | 330.48   | 6.69| 298 | 49.44     | $<$0.0001 | [317.32, 343.63] |
| $t$              | 31.96    | 0.88| 3598| 36.42     | $<$0.0001 | [30.24, 33.68]   |
| $t^2$            | -1.79    | 0.06| 3598| -30.25    | $<$0.0001 | [-1.91, -1.68]  |
| Fitness 1        | 26.74    | 4.80| 298 | 5.57      | $<$0.0001 | [17.30, 36.19]  |
| Fitness 2        | 9.86     | 4.80| 298 | 2.06      | 0.0407    | [0.42, 19.31]    |
| Free weight      | 98.19    | 4.80| 298 | 20.46     | $<$0.0001 | [88.74, 107.63]  |
| Ladygym (Reference) | -      | -   | -   | -         | -         | -            |
| Scenario A       | 13.04    | 3.57| 298 | 3.65      | 0.0003    | [6.02, 20.06]   |
| Scenario B       | 0 (Reference) | -   | -   | -         | -         | -            |
| No. of visitors  | 2.24     | 0.10| 298 | 22.88     | $<$0.0001 | [2.04, 2.43]    |

3.4. Subgroup analysis

The linear mixed model was applied to the data set split by room. Of main interest is the comparison of the different estimates for the number of visitors separated by age and sex (see Table 5). In the area Fitness 1, the effect of the numbers of visitors is estimated at the lowest for the number of women of at least 30 years with an estimate of...
1.73 ppm per person, and the highest for women under 30 years with an estimate of almost 3 ppm per person. In the area Fitness 2 the estimated effect is especially high for women and men over 30 years with 3.41 ppm and 2.66 ppm, respectively. In the free weight area the effect for the number of women over 30 years is estimated very close to zero with an estimate of 0.3 and a 95% confidence interval [-2.93, 3.52]. The largest effects are estimated for men over 30 years with 3.45 followed by men under 30 years with 2.88.

Even if men are not allowed in the ladygym, the highest effect is estimated for sensor 1 for men over 30 years with 3.13 ppm of CO₂ per person. This is probably due to the closeness to the Fitness 2 area. The smallest effect is estimated for men under 30 years similar to the fitness 2 area. For the sensor 2 in the ladygym, the estimated effects for the number of visitors are all very small with the largest effect for men under 30 years and with 1.26 ppm. That is the only of the four effects with a significant confidence interval not including zero. The small effects for sensor 2 can be due to the small number of women allowed in the ladygym. Interesting is that the effect for the number of men under 30 years is the largest and the only significant effect. A possible explanation can be, that women tend to prefer the ladygym especially, when the number of young men in the fitness center is large.

The fitness classroom is the only room for which the numbers of participants in the room itself are known. The effects for men in the fitness classroom are negative. However, these parameter estimates have a large standard error, so that the 95% confidence intervals for these effects are very large. This is probably due to the low number of men attending classes (only nine men in total), so that an estimation is not useful. The estimated effect for women over 30 years is very large with 8.83 in comparison to 2.79 for women under the age of 30 years, even if women over 30 years did not participate in the classes as much as women under 30 years.

4. Discussion

According to the German standard DIN EN 19779:2007–09, a CO₂ concentration ≤800 ppm stands for high air quality, >800 ppm but ≤1000 ppm for medium air quality, >1000 ppm but ≤1400 ppm for moderate air quality and >1400 ppm for low air quality [24]. A CO₂ concentration of approximate 400 ppm can be expected in outdoor air [23]. During the study period of four days outdoor air CO₂ concentrations between 391 ppm and 441 ppm were observed. This is larger than the minimum CO₂ values observed in the fitness center (minimum of 378 ppm in the classroom), which can be due to small measurement errors and different measurement methods.

To reduce the risk of a SARS-CoV-2 infection, the German Environment Agency (Umweltbundesamt) recommends a high ventilation rate and states that a CO₂ concentration of less than 1000 ppm can be applied as an indicator if the air change is sufficient [25]. They argue that a CO₂ concentration of more than 1000 ppm is potentially linked to an increased SARS-CoV-2 infection risk. The German “expert group for aerosols” recommends during COVID-19 pandemic to start ventilation when CO₂ concentration is larger than 800 ppm. They argue that a CO₂ concentration smaller than 800 ppm, obtained by ventilation, is a useful approach to reduce aerosol concentration and that up to now there is no evidence, that a threshold of 1000 ppm is not sufficient [18].

In our study of indoor air quality in a fitness center, the CO₂ concentration of 400 ppm for fresh air was exceeded most of the time. However, the threshold of 1000 ppm was never reached in any of
If there are 45 additional visitors in the fitness center, the predicted center. In contrast to the scenario effect, the effect for the number is not surprising, since the difference between the scenarios can be (equal number of visitors, equal time, equal area). This small effect fitness center. The estimate of the CO2 concentration was mostly in scenario A, when more people were allowed in the time slot in which the number of visitors in the fitness center was observed mainly in scenario A, when more people were allowed in the time slot in which the number of visitors in the fitness center was time slot in which the number of visitors in the fitness center was.

The highest effect is estimated for the free weight area with nearly 100 ppm more in comparison to the ladygym. The high effects for men in the subgroup analysis for the free weight area suggest that mainly men, but also young women work out in this area. This group of men, who are under 30 years and/or men, represents more than 90% of all visitors. In order to improve the air quality in the free weight area a more stringent restriction of the number of visitors should be allowed in this area.

On average, the concentration of CO2 increases first within a slot and then decreases several time points before the 15 min break. This can be explained by an increased breathing during exercisers in the middle of a time slot and a higher number of visitors, as visitors could leave the room as well as the building early. From the time, from which no visitors should remain in the fitness center, the CO2 concentration is decreasing rapidly. This reduction speaks for the functionality of the ventilation system.

When a room is evacuated at a given time point, i.e. all visitors leave the room at the same time, decay methods can be used to estimate the air changes per hour by the observed CO2 concentrations (see, e.g., Batterman [27]). As in this setting, there is an evacuation of 15 min after each time slot, decay air changes can be obtained, and are here estimated by using two CO2 measurements in comparison to the replacement CO2 concentration [27] (estimation results not shown in the previous sections). For estimation, the concentration change over the period should be large with at least 100 ppm or more [27], so that in this setting only starting CO2 concentrations of at least 500 ppm are considered, allowing at least 100 ppm of change. The mean of the estimated air change rates per hour is equal to 2.4 with maximal estimated values for the single rooms between 5.6 and 9.7. Comparing these estimated air changes to the theoretical air changes in Table 1 with an average air change per hour of 10.2, indicates that these theoretical air changes per hour are reachable. This holds especially, when taking into account that the ventilation system was mainly working only at 50% of its capacity during the evacuation periods because of small CO2 concentrations, whereas the theoretical air changes in Table 1 were calculated for 100% capacity. However,
these estimations should be interpreted cautiously, as the estimation method leads to varying results, that are dependent on the starting values and that do not take into account the capacity of the ventilation system.

In a study by Blocken et al. [28] the aerosol and CO$_2$ concentration was measured in different scenarios in a fitness center. With ventilation alone, the aerosol as well as the CO$_2$ concentration could be reduced. This indicates, that the CO$_2$ concentration can indeed be an indicator for the risk of SARS-CoV-2 infection. If the air is cleaned (e.g., by filtration), but not ventilated, only the aerosol concentration could be reduced, but not the CO$_2$ concentration. Therefore, if air is filtered, the CO$_2$ concentration does not indicate how high the aerosol concentration is. However, this only means, that, if using the CO$_2$ concentration as indicator, one would be more cautious than necessary, e.g., by increasing the air ventilation [29]. Thus, a combination of ventilation and filtering seems to be an effective measure to control the risk of infection. Hence, if the ventilation system supplies sufficiently fresh air, if the CO$_2$ concentration is surveyed consequently with the possibility of intervention, if the incoming air is additionally filtered and if it is controlled for the number of visitors not only in the fitness center itself, but also in the different areas, an operation of fitness facilities with a reasonable risk of infection seems feasible.

5. Conclusion

As a threshold of 1000 ppm was never reached, a volumetric flow rate between 250 m$^3$/h (50% ventilation) and 500 m$^3$/h per person seems to be sufficient. However, as the infection risk increases with a higher amount of physical activity [26], it could be advisable for this setting, to implement additional restrictions at least for the free weight area, since the free weight area is the only area with CO$_2$ concentrations regularly above 800 ppm and an area where high physical activity is expected. Such additional restrictions can be, e.g., a smaller amount of visitors for this area or additional filtration.

Because of a strong decrease of CO$_2$ concentration during every 15 min break, one can conclude that the ventilation system serves its purpose. The number of visitors present in the fitness center has a strong impact with 2.24 ppm per person (95% confidence interval [2.04, 2.43]) on the estimated CO$_2$ value. Consequently, limiting the number of people seems to be an adequate means to keep the CO$_2$ concentration low.

The results of this study are in line with recommendations of limiting the number of visitors and to focus on ventilation to keep air quality high [21]. Here, not the aerosol concentration itself was measured to evaluate the risk of infection, but the CO$_2$ concentration. As discussed, the CO$_2$ concentration is a good indicator for the aerosol concentration if air is not cleaned. It would, nevertheless, be of interest to analyze the aerosol emission during physical exercise more in detail, as done by Blocken et al. [28] and few others, e.g., Almstrand et al. [30] and Johnson and Morawska [31].

The conducted study was a pilot study under several restrictions. For instance, the visitors had to book time slots to exercise in advance, so that visitors arrived and left more or less at the same time with the other visitors who booked the same slot. These slots with the ensuing evacuation do not represent real life conditions where visitors are allowed to arrive and to leave at any time. Thus, it would be of interest to compare real life data of the fitness center to the data of this restricted pilot study. Such an analysis could help to answer the question, if predefined breaks are important to reduce the CO$_2$ concentration or if a more even occupancy without predefined slots and breaks would be preferable to avoid peaks of visitors. Furthermore, it could be interesting to analyze by how much the high CO$_2$ concentrations of
more than 800 ppm could have been reduced if the ventilation system would have worked as intended at 100%. More information can be accessed, if the number of visitors were not only available for the whole fitness center but also for every single room.

The results suggest that an opening (or not closing) of fitness centers can be conducted in a reasonable way with only a small risk of superspreader events if air flow is controlled as well as changed consequently, and if the number of visitors is restricted. An additional air filtering can further decrease the risk of SARS-CoV-2 infection.

**CRediT authorship contribution statement**

Eva-Maria Huessler: Writing – original draft, Visualization, Software, Methodology, Formal analysis. Anika Hüsing: Writing – review & editing, Supervision, Methodology. Markus Vancraeyenest: Resources, Investigation, Conceptualization. Karl-Heinz Jöckel: Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. Bernadette Schröder: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

**Declaration of competing interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Appendix. Details of fitness center**

See Figs. A.1 and A.2, Table A.1.
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### Table A.1

| Time          | May 25 | May 26 | May 27 | May 28 |
|---------------|--------|--------|--------|--------|
| 08:15–08:45   | body x | fatburn x | body x | fatburn x |
| 09:30–10:00   | booti x | booti x | sixpack | backworx |
| 17:00–17:30   | backworx | fatburn x | backworx | fatburn x |
| 18:15–18:45   | yogilatix | booti x | fatburn x | body x |
| 19:30–20:00   | fatburn x | sixpack | yogilatix | booti x |