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Transmission of SARS-CoV-2 by inhalation of respiratory aerosol in the Skagit Valley Chorale superspreading event

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Abstract

During the 2020 COVID-19 pandemic, an outbreak occurred following attendance of a symptomatic index case at a weekly rehearsal on 10 March of the Skagit Valley Chorale (SVC). After that rehearsal, 53 members of the SVC among 61 in attendance were confirmed or strongly suspected to have contracted COVID-19 and two died. Transmission by the aerosol route is likely; it appears unlikely that either fomite or ballistic droplet transmission could explain a substantial fraction of the cases. It is vital to identify features of cases such as this to better understand the factors that promote superspreading events. Based on a conditional assumption that transmission during this outbreak was dominated by inhalation of respiratory aerosol generated by one index case, we use the available evidence to infer the emission rate of aerosol infectious quanta. We explore how the risk of infection would vary with several influential factors: ventilation rate, duration of event, and deposition onto surfaces. The results indicate a best-estimate emission rate of 970 ± 390 quanta h^{-1}. Infection risk would be reduced by a factor of two by increasing the aerosol loss rate to 5 h^{-1} and shortening the event duration from 2.5 to 1 h.

Keywords: aerosol transmission, infectious disease, ventilation, virus, pandemic, risk

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Practical Implications

- During respiratory disease pandemics, group singing indoors should be carefully managed as singing can generate large amounts of aerosolized virus if any of the singers is infected.
- Ventilation requirements for spaces that are used for singing (e.g., buildings for religious services and rehearsal/performance) should be reconsidered in light of the potential for aerosol transmission of infectious diseases.
- Systems that combine the functions heating and ventilation (or cooling and ventilation) should be accompanied with a disclaimer saying “do not shut this system off when people are using the room; turning off the system will also shut down outdoor air supply, which can lead to the spread of airborne infections.”

Introduction

SARS-CoV-2 was first reported in China at the end of 2019 and rapidly spread to the rest of the world over the subsequent months. Evidence from laboratory studies has shown that the SARS-CoV-2 virus can remain infectious while airborne for extended periods.[1,2] The virus has been detected by PCR in the air in several healthcare environments.[3-9] Researchers have reported values for the SARS-CoV-2 viral load in the mouth that span an extraordinarily broad range: from 10^2 to 10^{11} copies per mL of respiratory fluid.[10-12] Viral loads vary over the course of the disease, tending to peak near the onset of symptoms.

Aerosol transmission is now strongly suspected to play a significant role in superspreading events (SSEs) under certain conditions. SSEs occur when a large number of secondary transmissions are produced early in an outbreak and transmission is sustained in later stages.[13] Some people release respiratory aerosol at an order of magnitude greater rate than their peers and might contribute to superspreading events.[14] The very broad range of viral loads in respiratory fluids may also be an important factor influencing SSE. An infectious respiratory aerosol is a collection of pathogen-laden particles in air emitted during respiring activities of an infected individual.[15]

Conditions that promote outbreaks of COVID-19 include large indoor gatherings and poor ventilation. An assessment of over 300 COVID-19 outbreaks involving three or more people confirmed that all transmission could be linked to indoor environments.[16] A Japanese study based on contact tracing concluded that the odds that a primary case transmitted COVID-19 in a closed environment was 18.7 times greater compared to an open-air environment.[17] Another study from Japan concluded that the typical settings for superspreading events included "singing at karaoke parties, cheering at clubs, having conversations in bars, and exercising in gymnasiums".[18] Poor ventilation has been a driving factor in other infectious disease outbreaks. Transmission of influenza from one index case to 72% of the onboard passengers occurred on an airplane that was grounded for three hours, during which the ventilation system was inoperative.[19]

In this paper, we first discuss the outbreak and establish the likelihood of an important contribution from aerosol transmission. We then estimate the infectious quanta emission rate during a choir rehearsal that has been identified as a superspreading event. Quanta are used to represent infectious respiratory aerosol when the actual viral dose in the aerosol and the human dose-response required to cause infection are unknown.[17,21] We then explore the sensitivity of the secondary attack rate of infection to the loss rate of aerosolized virus, whether by ventilation, deposition onto surface, or biological decay, as well as to duration of the event.

Case Study

A SSE occurred in Skagit Valley, Washington, USA.[22,23] When the Skagit Valley Chorale (SVC) met on the evening of March 10, 2020, one person attending the rehearsal had cold-like symptoms that had developed three days earlier; that individual subsequently tested positive for

COVID-19. This person is considered the "index case." Within a few days of the news report, we contacted the journalist that reported on the event, the county health department, and a member of the choir. An initial questionnaire and multiple follow up questions were sent to the choir contact, and most of the choir members provided information on their activities. The responses are included in the Supplementary Information in the same form as provided to us, except for items removed due to privacy concerns. At the time of the rehearsal the Skagit County Health Department was not recommending widespread closure of public venues or public events. They were recommending that those 60 y of age and older, or persons with underlying medical conditions, should avoid large public gatherings. Choral members were told to not attend on March 10 if they were sick with any kind of symptoms or if they had concerns.

The chorale met in the Fellowship Hall of a church in Mount Vernon, Skagit County. The day after the rehearsal on March 11, the governor of Washington recommended physical distancing and no large group meetings in three other nearby counties. At the time of the rehearsal, there were no known COVID-19 cases in Skagit Valley County, nor were any closures in effect. Before detecting the cluster on March 17, Skagit county had developed seven COVID-19 cases. The likelihood of a second index case at the rehearsal can be estimated as 0.32%, from the seven other cases that had been reported in the county at the time in which the choir outbreak became known, given the population of the county, and an assumption of 50% asymptomatic cases. Asymptomatic cases were less likely than for an average population given that the choir members are more elderly than the general population; e.g. 75.5% of those who became ill were 65 or more years old.[22]

The SVC has 122 members, but only 61 attended rehearsal on March 10, amid concerns about COVID-19 transmission. Precautions were taken during rehearsal, including the use of hand sanitizer, no hugging and no handshakes.[23] All 120 chairs were arranged by 3 people who arrived early, and members sat in their usual chairs, which increased their distance compared to other well-attended rehearsals. Lateral distance bewteen chair centers (and thus nose / mouth distances) was ~0.75 m, while forward distance between rows was ~1.4 m.

Some members began experiencing illness from March 11 to March 22. The timing of these potential secondary infections is consistent with what is known about the temporal dynamics of virus shedding and serial interval for COVID-19.[24] In particular three cases were identified the day after the rehearsal, according to the county report[22], although the choir members are not aware of cases before March 12 (see Supplemental Information (SI)). Several published analyses of the incubation time of COVID-19 include some probability of developing symptoms within one day of infection.[25,26, 27, 28] This would be more likely in the case of receiving a high viral dose, as would be expected in an event like this with such a high attack rate. It is also possible that there was more than one index case present at the rehearsal, and the impact of this possibility on our analyses is discussed below.

Among the 61 attendees at the rehearsal, 53 cases in total were subsequently identified including the index case, with 33 confirmed through positive COVID-19 tests and 20 unconfirmed but probable secondary cases based on symptoms and timing. Testing was unavailable to many of the choir members (see SI). Accounting for the one presumed index case, the secondary infection attack rate is thus in the range 32/60 to 52/60, or 53-87%.

The large number of infections arising from this event, compared to the low incidence in the county at the time, makes it unlikely that they were acquired at a different setting than the choir. This inference is consistent with the conclusion of the county health investigators, who interviewed all choir members and investigated other possible avenues for contact: transmission most likely occurred at the March 10th rehearsal.[22] It is also consistent with the opinion of the choir members (see SI). Infection of many choir members at the prior March 3rd rehearsal is also very unlikely, as discussed by Hamner et al.[22] Given a median incubation time of 4-5 days, if multiple members had been infected at the March 3rd practice, 70-80% of them should have presented symptoms by the time of the March 10th practice.[27]

A seating chart obtained through personal communication showed the layout of participants among 120 chairs plus the position of the choir director and piano accompanist. Although the chart cannot be reproduced because of privacy concerns,[22] a centrally important point for interpreting the cause of transmission is that the cases occurred throughout the room with no clear spatial pattern. Specifically, dividing the 120 seats into quadrants of 30 seats each, the occupancy levels (seats occupied/seats available) span a narrow range of 44-53%. The infection rate (reported infections/seats occupied) are substantial in each quadrant, with a low of 43% and being in the range 71-87% in the other three quadrants.

The rehearsal started at 6:30 pm. The SVC rehearsed in a single group in the Fellowship Hall for 45 minutes, with the members in fixed positions in their usual seats, then split into two approximately equal-sized groups for 45 minutes. One group, mostly male singers, went to practice around a piano in a different room of the church, while a second group stayed in the Fellowship Hall. Transitions between the 3 phases of rehearsal were rapid (see SI). After practicing separately, and following a 10-minute break, the members reconvened in the Fellowship Hall for another 50 minutes, until 9 pm. During the split session, those who remained in the Fellowship Hall occupied about half of the space, and thus had a similar person density as during the whole-group rehearsal (see SI).

Limited information is available about the heating and ventilating system; what was learned from personal communications is summarized here. The Fellowship Hall is heated and ventilated with a mechanical air heating system including an outdoor air intake and air recirculation. The air handling unit has a relatively new commercial forced-air furnace (see SI for the system capacity details). The furnace is installed with an outside make-up air function and it also has a separate combustion air intake, which is standard for gas appliances. But it is not known how much outside make-up air was supplied to the building that evening. The furnace is also outfitted with a MERV 11 filter, which has a rated single-pass efficiency of ≥ 30-65% for aerosol particles of diameter 1 μm or larger.[29,30] Three supply air registers are situated 2.4 m above the floor on one wall with a single return on an adjacent wall, just above the floor (~0.15 m). Someone in the front office reportedly turned on the heating system prior to the rehearsal to warm the space, and the thermostat was set to 20 °C (68 °F). It was about 7 °C (45 °F) outside, so the heating was on at the start of the rehearsal, but with so many people in the room, it did not need to stay on to maintain a comfortable temperature. During the entire rehearsal no exterior doors were open. It is not known whether the forced-air furnace fan operated (only) under thermostatic control or whether it ran continuously.

Evidence Related to the Routes of Transmission

There are considered to be three primary routes of transmission for COVID-19: (1) direct contact (e.g. shaking hands) or indirect contact with contaminated objects ("fomites"), followed by touching one's eyes, nostrils, or mouth; (2) large ballistic droplets that travel directly from an infected person's nose or mouth to a susceptible person's eyes, nostrils, or mouth; (3) exhaled respiratory aerosols, which can linger in the air for minutes to hours, and may infect by inhalation.

There is no specific evidence that COVID-19 is transmitted via the fomite route,[31] and the US CDC has stated that while possible, this route is considered less likely,[32] possibly because of rapid inactivation demonstrated for lipid-enveloped viruses on human skin.[33,34,35,36] At the time of the chorale rehearsal on 10 March 2020, because of emerging concern about SARS-CoV-2, person-to-person contact and touching of surfaces was consciously limited, and hand sanitizer was used. No one reported direct physical contact between attendees to the County Public Health investigators.[22] Although some choir members helped arrange the chairs and ate snacks during the intermission, the index case did not participate in these activities, and many other members reported not eating the snacks.[22] Thus fomite transmission from the index case via chairs or snacks can be excluded. The index case used one of the bathrooms during the event and thus touched the door handle and other surfaces there, but only about six other choir members used that restroom (see SI), and many choir members who did not use any of the restrooms were also infected. Indeed, the clustering of infected cases on the seating chart does not support transmission from a point surface contact(s) unless the people who sat together all touched the same contaminated surface. Thus, it appears highly improbable that the direct and indirect contact routes could account for a significant fraction of the transmission during this event.

There is no direct evidence of transmission by ballistic droplets for any disease in the literature.[37] The risk of widespread transmission owing to large ballistic droplets during close proximity situations would seem to be low in this event, considering that it is likely to have been only one index case, who was seated in close proximity to only a small proportion of the other chorale members. One half of the chairs were unoccupied, increasing the distance between members. No one was located within 3 meters of the index case (where respiratory droplets from the index case would be expected to have landed (See SI) during either of the rehearsal periods. Two other members where located within 1 m to each side of the index case during parts of the rehearsal, while four other members were located within 2 m behind (and one 2 m to the side) of the index case during parts of the rehearsal. Ballistic droplets, propelled forward by exhaled breath, could not have traveled backwards in this low ventilation situation.

There was a single 10-min break (see SI), during which the participants talked with each other, mostly in groups of 3-4 people, while the index case conversed minimally with others throughout the rehearsal and the break (see SI). Many members arrived shortly before and left immediately after the practice (see Ref. 19 and SI). However, about 15 minutes of close proximity is thought to be needed for transmission.[32] Thus, it is physically not possible for the index case (or even several index cases) to have conversed with and impacted ballistic droplets onto 53 other members in such a short time.

Literature evidence suggests that singing could have been a contributing factor to the high secondary attack rate compared to other common indoor activities. The rate of aerosol emission during vocal activities increases with voice loudness.[15] A study of respiratory emissions also found higher emission rates of respiratory droplets to be associated with more extensive vocalization.[38] Outbreaks of tuberculosis, a disease known to be transmitted via inhalation, have been linked to singing.[39-41] At the time this article is being written, there have been additional media reports of COVID-19 outbreaks associated with choirs. Cases with high secondary attack rates have been reported in the Netherlands, Austria, Canada, Germany, England, South Korea, Spain, and France.[42,43,44]

Loudon and Roberts[45] characterized respiratory aerosol emitted during talking, singing and coughing. They reported that "fewer droplets were expelled during singing than during talking, but a higher proportion of them were in the smaller size range. The percentage of droplets still airborne as droplet nuclei after a 30-minute settling period were 35.7, 6.4, and 48.9 for singing, talking, and coughing, respectively."

If transmission by fomites and/or ballistic droplets were the dominant modes of transmission, then the secondary attack rate should have been much smaller than the observed range of 53-87%. We would also expect to see the secondary cases predominantly among those in closer proximity to the index case rather than distributed throughout the rehearsal room. Even in the case that a second index case had been present, the same considerations make such wide transmission by the fomite and ballistic drop routes very unlikely to explain the observed very high attack rate. Per Occam's razor, this explanation seems most probable: that inhalation of infectious respiratory aerosol from "shared air" was the leading mode of transmission.

Modeling Aerosol Infection Risk

This distinctive superspreading event, occurring in an enclosed community facility, with indoor space shared for a specified period of time, offers a good opportunity to examine a range of physical parameters that influence the eventual outcome. Our analysis was undertaken to explore whether this outbreak could have happened due to aerosol transmission and how future outbreaks could be avoided. In assuming only aerosol transmission what follows represents a worst-case scenario for aerosol transmission, i.e., highest possible quanta generation rate from the event. If a few cases arose from fomite or ballistic droplet routes, the quanta emission rate of the aerosol route would be proportionally lower.

There is no evidence to suggest that more than one person was infected and showing symptoms at the time of the rehearsal. Asymptomatic transmission, however, is important in the spread of COVID-19.[24] Available evidence suggests that 50% of transmission happens while asymptomatic; it is, however, estimated that only 20% of cases remain asymptomatic.[47,48,49] Thus, it is possible that individuals at the rehearsal were asymptomatic transmitters; however, as described earlier, we estimate this probability to be very small because of the low community prevalence of COVID-19 at the time of the rehearsal. Assuming that there is only one index case to account for all transmission and that all transmission was through aerosol is a conservative approach and provides a basis that can be used to develop precautionary mitigation approaches.

Hence, on the basis of the available information about this event, a modeling effort was undertaken with two goals. The first goal was to estimate an average quanta emission rate that is consistent with the evidence, while assuming that all transmission happens through exposure to aerosol from a single index case. This calculation proceeds in two steps: determining the average aerosol quanta concentration from the reported secondary infection attack rate, and then evaluating the emission rate that would have produced the inferred average concentration. The second modeling goal was to explore how a change in the loss rates, for example owing to improved ventilation and filtration, would have altered the infection risk. In pursuing both goals, the modeling effort uses an idealization of the more complex real situation, in part because some key data are lacking. A similar approach has been used in other studies to explore aerosol infection risk in indoor environments.[20,50]

The model of infection risk due to aerosol transmission is based on the Wells-Riley formulation,[46,51] as amended by Gammaitoni and Nucci.[52] In applying this approach, these assumptions are made: i) there is one infectious individual who emits SARS-CoV-2 quanta at a constant rate throughout the event, ii) there is no prior source of quanta in the space, iii) the latent period of the disease is longer than the time scale of the event, iv) the infectious respiratory aerosol quickly becomes evenly distributed throughout the room air, and v) infectious quanta are removed by first-order processes reflecting the sum of ventilation, filtration, deposition, and airborne inactivation. The assumption that the indoor environment can be modeled as well-mixed is substantiated in this case by the broad spatial distribution of secondary infections among the rehearsal participants. Additional information is provided in the SI describing supporting evidence of the well-mixed assumption. In epidemic modeling, where the aim is to assess the disease spread in the community, it is impossible to specify geometries, ventilation efficiency, and the locations of the infectious sources in each microenvironment. Therefore, adopting the well-mixed assumption is generally more reasonable than hypothesizing about specific patterns of emissions, airflow and removal processes.[53]

The modeled probability of infection (p) is related to the number of quanta inhaled (n) according to equation (1):[51]

$$p = 1 - e^{-n} \qquad (1)$$

Equation (1) is used to estimate the average quanta concentration during the practice, given estimates of the probability of infection based on the secondary attack rate. The aerosol quanta concentration increases with time from an initial value of zero following a "one minus exponential" form, which is the standard dynamic response of a well-mixed indoor volume to a constant input source. The time-average quanta concentration (C_{avg}, q m^{-3}) is the quanta inhaled divided by the volume of air breathed. The volume of air breathed (m^3) is equal to the duration of the event (D, h) multiplied by the volumetric breathing rate of rehearsal participants (Q_b, m^3 h^{-1}).

A well-mixed material balance model for the room (equation (2)) is applied next to relate the quanta concentration, C (quanta per m^3), to the emission rate, E (quanta per h):

$$\frac{dC}{dt} = \frac{E}{V} - \lambda C \qquad (2)$$

Here V = volume of the rehearsal hall (m^3) and λ = first-order loss rate coefficient for quanta (h^{-1}) due to the summed effects of ventilation (λ_v), deposition onto surfaces (λ_{dep}), and virus decay (k).[54] Assuming the quanta concentration is 0 at the beginning of the rehearsal, equation (2) is solved and the average concentration determined as follows:

$$C(t) = \frac{E}{\lambda V}\left(1 - e^{-\lambda t}\right) \qquad (3)$$

$$C_{avg} = \frac{1}{D}\int_0^D C(t)\,dt = \frac{E}{\lambda V}\left[1 - \frac{1}{\lambda D}\left(1 - e^{-\lambda D}\right)\right] \qquad (4)$$

Here, t = time (h). Equation (4) is rearranged to solve for the emission rate, E:

$$E = \lambda V C_{avg}\left[1 - \frac{1}{\lambda D}\left(1 - e^{-\lambda D}\right)\right]^{-1} \qquad (5)$$

A Monte Carlo simulation was run (N = 1000 iterations) to estimate E for the superspreading event given a range of input values. The unknown parameters (p, Q_b, λ_v, λ_{dep}, k) were specified as probabilistic using uniform distributions bounded by specified upper and lower limits. These parameters were assumed to be uncorrelated. A sensitivity analysis was undertaken to explore how using different parametric distributions influenced the predictions. See SI for details and results.

The ranges of the uncertain model parameter values explored in the primary Monte Carlo simulation are summarized in Table 1. Constant values were used for the volume of the Fellowship Hall and the rehearsal duration.

Table 1. Parametric Values used in the Monte Carlo Simulation for Estimating E

Parameter	Value(s)	Distribution	Reference(s)
Probability of Infection, p (%)	53-87	Uniform	19
Volumetric Breathing Rate, Q_b (m^3 h^{-1})	0.65-1.38	Uniform	30, 31

Loss Rate due to Ventilation, λ_v (h^{-1})	0.3-1.0	Uniform	Appendix
Loss Rate due to Deposition onto Surfaces, λ_{dep} (h^{-1})	0.3-1.5	Uniform	32, 33
Loss Rate due to Virus Inactivation, k (h^{-1})	0-0.63	Uniform	1, 2
Volume of Rehearsal Hall, V (m^3)	810	Constant	Personal Communication
Duration of Rehearsal, D (h)	2.5	Constant	19

The lower breathing rate used in our simulations was from Binazzi et al.[56] who reported volumetric inhalation rates of singers to be in the range 0.22-1.0 m^3 h^{-1}. The upper breathing rate was from Adams et al.[55] for light activity (walking female and male middle age adults).[50] SARS-CoV-2 was found in air samples in two size ranges: 0.5-1 µm and > 2.5 µm.[7] The surface deposition loss rate range was based on data from Thatcher et al.[58] and Diapouli et al.[57] The range of values for virus decay is based on two sources: Fears et al.[1] showed no decay in virus-containing aerosol for 16 hours at 53% RH, whereas van Doremalen et al.[2] estimated the half-life of aerosol SARS-CoV-2 is 1.1 h, which equates to a decay rate of 0.63 h^{-1}. The loss rate due to ventilation is likely to have been in the range from 0.3 to 1 h^{-1} (see SI). We did not include filtration in our estimation of the loss rate.

Results

The mean (± standard deviation) inferred emission rate was E = 970 (± 390) quanta per h. Additional statistics for the distribution of E from the Monte Carlo simulation are as follows: geometric mean = 900 q h^{-1}; geometric standard deviation = 1.5; 10^{th}, 25^{th}, 50^{th}, 75^{th} and 90^{th} percentiles: 550, 680, 910, 1180, 1510 q h^{-1}.

We reiterate that the emission rate was derived based on a base case assumption of one index case and all transmission by aerosol inhalation. It is plausible that more than one person attending the rehearsal was infectious. If this was the case then the inferred emission rate would represent the sum of emission rates from each of the infectious individuals. The analysis assumes that viral transmission all occurred through aerosol inhalation. If additional transmission routes played some role in this outbreak, then our the actual quanta emission rates would have been correspondingly lower.

Quanta emission rates for influenza have been reported to be in the range 15-128 quanta h^{-1};[20,59] for measles: 5,580 q h^{-1};[60] and for tuberculosis: 1.25 to 30,840 q h^{-1} (the high value attributed to intubation).[61] The quanta for SARS transmission in a hospital and in an elementary school was estimated to be 28 q h^{-1}.[62] A forward model was used to estimate a large range of estimated quanta emission rates for SARS-COV-2, depending on activity level and respiratory activity: 10.5-1030 quanta h^{-1}.[50]

To explore the influence of changing the loss rate on the probability of infection, we performed sensitivity simulations in which we varied the loss rate. In these simulations, we used the mean emission rate of E = 970 q h^{-1} and a constant volumetric breathing rate of Q_b = 1.0 m^3

h^{-1}. If λ is systematically increased by some combination of increased ventilation, deposition, filtration, and inactivation loss rates, how would the probability of infection decrease? We also explored what would happen if the emission rate was set at the 10th and 90th percentile values from the Monte Carlo simulation. Using the model equations above with λ ranging from 0.6 to 12 h^{-1}, the percentage of the rehearsal participants infected is determined. The results are plotted in Figure 1.

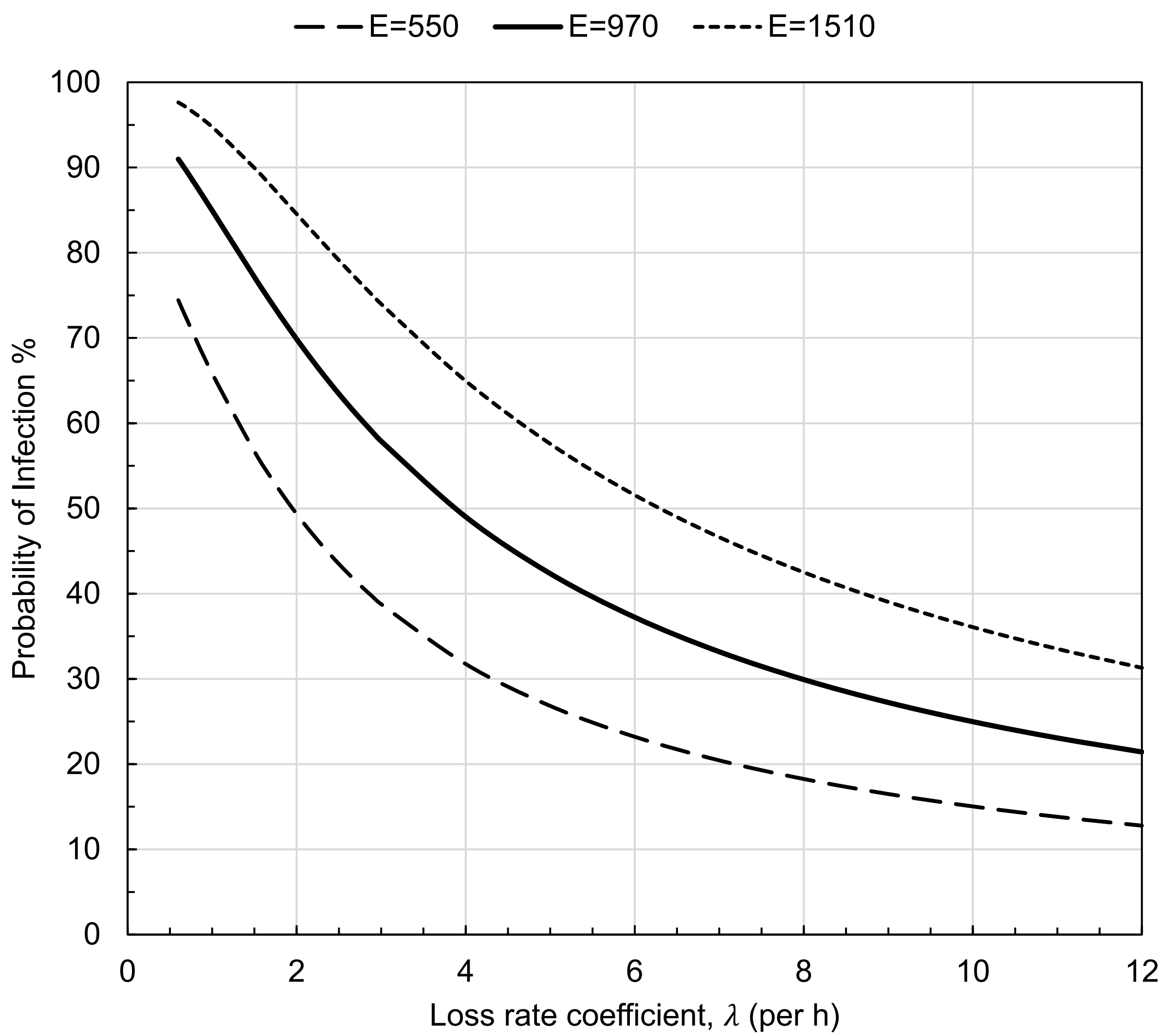

Figure 1. *Probability of infection for each rehearsal participant as a function of loss rates for varying aerosol quanta emission rates (E, q h^{-1}). Infection probability is plotted for the predicted mean emission rate (970 q h^{-1}) and the 10th and 90th percentile emission rates (550 and 1510 q h^{-1}, respectively.) Constant values were assumed for rehearsal duration (2.5 h), indoor volume (810 m^3) and volumetric breathing rate (1.0 m^3 h^{-1}).*

A key point displayed in Figure 1 is that, for the mean value E = 970 q h^{-1}, increasing the loss rate coefficient from a nominal baseline value of 0.6 h^{-1} to 5 h^{-1} would reduce the probability of infection by a factor greater than two, from 91% to 42%. For the full range of loss rates plotted in Figure 1, the infection risks spans a factor of eight: from 98% to 13%.

We also explored how changing the duration of the event would impact the probability of infection as a function of loss rate. Again, we use the mean emission rate of 970 q h^{-1} and a volumetric breathing rate of 1.0 m^3 h^{-1}. For durations ranging from 0.5 to 2.5 hours, and total loss rates ranging from 0.6 to 12 h^{-1}, the predicted percentage infected spanned a broad extent, from 4% to 91%. The results are plotted in Figure 2.

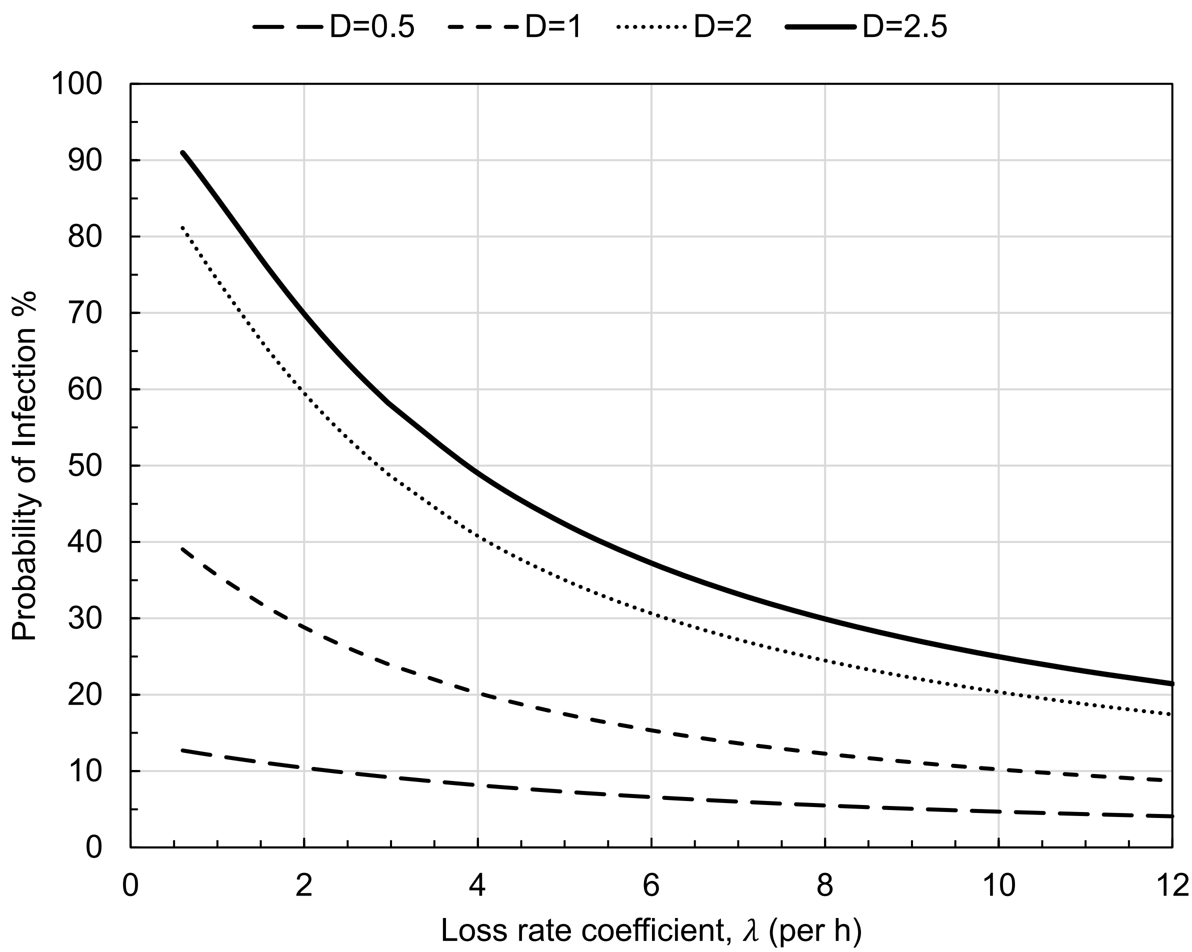

Figure 2. *Probability of infection as a function of loss rates for varying event duration (D, h). A mean emission rate (970 q h^{-1}) and constant volumetric breathing rates of 1.0 m^3 h^{-1} were assumed.*

Discussion

The inferred emission rate of 970 quanta h^{-1} is plausible given observations of SARS-CoV-2 in aerosol samples collected in hospitals and exhaled breath condensate collected from patients.

Concentrations of viral RNA in patient rooms averaged 3000 ± 2700 gene copies m^{-3} across 18 measurements in Nebraska[9] and 2600 ± 1000 gene copies m^{-3} across two measurements in Singapore.[3] If the dominant removal mechanism was ventilation at an average rate of 13 h^{-1} in Nebraska and 12 h^{-1} in Singapore, then these concentrations correspond to emission rates of the order 10^6 gene copies h^{-1} from a patient. This emission rate matches the range measured directly in the exhaled breath condensate of patients.[63] Evidence suggests that ratio of gene copies to infectious virus is roughly 10^3,[64,65] so the emission rate of 10^6 gene copies h^{-1} would correspond to 10^3 infectious virions emitted per hour. This compares favorably to the quanta emission rate if the infectious dose is close to 1 plaque forming unit (PFU). We do not yet know the dose-response relationship for SARS-CoV-2, but prior work indicates that the dose of SARS-CoV corresponding to illness in 10% and 50% of those exposed is 43 and 280 PFU.[21] (Watanabe et al. 2010) For influenza an inhaled dose as low as 0.7-3.5 PFU is sufficient to cause seroconversion in 50% of subjects.[66]

The emission rate can also be estimated by combining evidence on respiratory aerosol in exhaled breath with viral loads for SARS-CoV-2 in saliva. Concentrations of respiratory aerosol in exhaled breath that are smaller than 10 μm diameter are in the approximate range 1-10 nL m^{-3} for vocalization activities.[38] For this concentration range, a volumetric breathing rate of 1 m^3 h^{-1} would produce an emission rate of 1-10 nL h^{-1} of respiratory aerosol. In limited sampling of SARS-CoV-2 in saliva and other respiratory fluids, viral loads as high as 10^{11} gene copies mL^{-1} have been reported.[10,11,12,67] At 10 nL h^{-1}, a viral load in respiratory fluid of 10^{11} gene copies per mL (= 10^5 gene copies nL^{-1}) would lead to an emission rate of 10^6 gene copies h^{-1}, similar to the rate calculated above. Several factors contribute to substantial uncertainty in these comparisons including variability in viral shedding with type of respiratory activity,[68] viral load among infectious persons[69], the dose-response relationship, and other factors. However, the estimates do support the plausibility of the inferred quantum emission rate.

This modeling analysis has explored the very probable situation in which transmission by inhaling respiratory aerosol that was released during singing caused a large COVID-19 outbreak. Accumulating evidence points to these factors being important for increasing the risk of aerosol transmission indoors: dense occupancy, long duration, loud vocalization, and poor ventilation.

In the domain of indoor environmental quality control, the first and best measure is generally to minimize indoor emissions.[70] Because it is not yet possible throughout communities to identify individuals who are highly infectious and therefore are potential superspreaders, effective source control can not be so well practiced, short of suspending large gatherings of high-risk indoor events. Risks would be reduced if fewer people attended, if durations were shorter, and if attendees wore masks. The simulation results presented here show that the risk of secondary infections can be substantially reduced although not practically eliminated through a combination of increasing removal rates and by limiting the duration of indoor activities. The high ventilation rate in the hospital settings combined with other controls such as use of isolation rooms and effective personal protective equipment is likely to mitigate transmission from a high viral shedder in the healthcare environment.[3,9] In general community indoor spaces, which are not dedicated to infection prevention, controlling aerosol diseases transmission remains a great challenge during this pandemic. Ventilation rates corresponding to current standards would allow occupancy duration of only about 0.5 h for an infection risk level below 10% for a such high emission activity as investigated here. Indoor environmental quality control measures available to improve conditions include enhanced ventilation, mechanical filtration, and germicidal ultraviolet disinfection.[71,72] Widespread application of effective indoor environment controls could help limit the extent of superspreading events and therefore contribute to slowing the pandemic spread.

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Conflict of Interest

The authors of this paper certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Data Sharing Policy

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

1. Fears AC, Klimstra WB, Duprex P, et al. Comparative dynamic aerosol efficiencies of three emergent coronaviruses and the unusual persistence of SARS-CoV-2 in aerosol suspensions. *medRxiv* 2020 preprint doi: https://doi.org/10.1101/2020.04.13.20063784.
2. van Doremalen N, Bushmaker T, Morris DH, et al. Aerosol and surface stability of SARS-CoV-2 as compared with SARS-CoV-1. *New England Journal of Medicine*. 2020;382:1564–1567. DOI: 10.1056/NEJMc2004973
3. Chia PY, Coleman KK, Tan YK, et al. Detection of air and surface contamination by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2) in hospital rooms of infected patients. *Nature Communications,* 2020;11:2800 https://doi.org/10.1038/s41467-020-16670-2.
4. Ding Z, Qian H, Xu B, et al. Toilets dominate environmental detection of SARS-CoV-2 virus in a hospital. *medRxiv* 2020 preprint doi: https://doi.org/10.1101/2020.04.03.20052175.
5. Guo Z-D, Wang Z-Y, Zhang S-F, et al. Aerosol and surface distribution of Severe Acute Respiratory Syndrome Coronavirus 2 in hospital wards, Wuhan, China, 2020. *Emerging Infectious Diseases*. 2020;26:10-3201. https://ravikollimd.com/resources/COVID/Aerosol%20and%20surface%20Covid.pdf DOI: 10.3201/eid2607.200885
6. Jiang Y, Wang H, Chen L, et al. Clinical data on hospital environmental hygiene monitoring and medical staffs protection during the coronavirus disease 2019 outbreak. *medRxiv* 2020 preprint doi: https://doi.org/10.1101/2020.02.25.20028043.
7. Liu Y, Ning Z, Chen Y, et al. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. *Nature*. 2020:https://doi.org/10.1038/s41586-020-2271-3.
8. Lednicky JA, Lauzardo M, Fan ZH, et al. Viable SARS-CoV-2 in the Air of a Hospital Room with COVID-19 Patients. *Epidemiology*. 2020: https://doi.org/10.1101/2020.08.03.20167395
9. Santarpia JL, Rivera DN, Herrera V, et al. Transmission potential of SARS-CoV-2 in viral shedding observed at the University of Nebraska Medical Center. *medRxiv* 2020 preprint doi: https://doi.org/10.1101/2020.03.23.20039446.
10. Pan Y, Zhang D, Yang P, Poon LLM, Wang Q. Viral load of SARS-CoV-2 in clinical samples. *Lancet Infectious Diseases*. 2020;20:411-412. DOI: 10.1016/S1473-3099(20)30113-4
11. To, KK-W, Tsang, OT-Y, Leung W-S, et al. 2020. Temporal profiles of viral load in posterior oropharyngeal saliva samples and serum antibody responses during infection by SARS-CoV-2: an observational cohort study. *Lancet Infectious Diseases*. 2020;20:565–574. DOI: 10.1016/S1473-3099(20)30196-1
12. Wölfel R, Corman VM, Guggemos W, et al. Virological assessment of hospitalized cases of coronavirus disease 2019. *medRxiv* 2020 preprint doi: https://doi.org/10.1101/2020.03.05.20030502.

13. Frieden TR, Lee CT. Identifying and interrupting superspreading events—Implications for control of Severe Acute Respiratory Syndrome Coronavirus 2. *Emerging Infectious Diseases*. 2020;26: https://doi.org/10.3201/eid2606.200495.
14. Asadi S, Wexler AS, Cappa CD, Barreda S, Bouvier NM, Ristenpart WD. Aerosol emission and superemission during human speech increase with voice loudness. *Scientific Reports*. 2019;9:2348. https://doi.org/10.1038/s41598-019-38808-z
15. Jones RM, Brosseau LM. Aerosol transmission of infectious disease. *Journal of Occupational and Environmental Medicine*. 2015;57:501–508. doi: 10.1097/JOM.0000000000000448
16. Qian, Hua, Te Miao, Li Liu, Xiaohong Zheng, Danting Luo, and Yuguo Li. "Indoor Transmission of SARS-CoV-2." Preprint. *Infectious Diseases (except HIV/AIDS)*, April 7, 2020. https://doi.org/10.1101/2020.04.04.20053058.
17. Nishiura H, Oshitani H, Kobayashi T, et al. Closed environments facilitate secondary transmission of coronavirus disease 2019 (COVID-19). *medRxiv* 2020 preprint doi: https://doi.org/10.1101/2020.02.28.20029272.
18. Furuse, Y, Sando, E, Tsuchiya, N, Miyahara, R, Yasuda, I, Ko YK, Saito, M, Morimoto, K, Imamura, T, Shobugawa, Y, Nagata, S, Jindai, K, Imamura, T, Sunagawa, T, Suzuki, M, Nishiura, H, and Oshitani, H. Clusters of Coronavirus Disease in Communities, Japan, January–April 2020. *Emerging Infectious Diseases*. 2020:26: https://wwwnc.cdc.gov/eid/article/26/9/20-2272_article
19. Moser MR, Bender TR, Margolis HS, Noble GR, Kendal AP, Ritter DG. An outbreak of influenza aboard a commercial airliner. *Am J Epidemiol*. 1979;110(1):1-6. doi:10.1093/oxfordjournals.aje.a112781
20. Rudnick SN, Milton DK. Risk of indoor airborne infection transmission estimated from carbon dioxide concentration. *Indoor Air*. 2003;13:237–245. https://doi.org/10.1034/j.1600-0668.2003.00189.x
21. Watanabe T, Bartrand TA, Weir MH, Omura T, Haas CN. Development of a dose-response model for SARS coronavirus. *Risk Analysis*. 2010;30:1129–1138.
22. Hamner L, Dubbel P, Capron I, et al. High SARS-CoV-2 attack rate following exposure at a choir practice — Skagit County, Washington, March 2020. *Morbidity and Mortality Weekly Report*. 2020;69: https://doi.org/10.15585/mmwr.mm6919e6
23. Read R. A choir decided to go ahead with rehearsal. Now dozens of members have COVID-19 and two are dead. *Los Angeles Times* 29 March 2020. https://www.latimes.com/world-nation/story/2020-03-29/coronavirus-choir-outbreak. Accessed May 7, 2020.
24. He X, Lau EHY, Wu P, et al. Temporal dynamics in viral shedding and transmissibility of COVID-19. *Nature Medicine*. 2020;26:672–675.
25. Lauer SA, Grantz KH, Bi Q, Jones FK, Zheng Q, Meredith HR, Azman AS, Reich NG, Lessler J. The Incubation Period of Coronavirus Disease 2019 (COVID-19) From Publicly Reported Confirmed Cases: Estimation and Application. *Annals of Internal Medicine*. 2020 172:9, 577-582

26. Zhao Q, Ju N, Bacallado S, Shah RD. BETS: The dangers of selection bias in early analyses of the coronavirus disease (COVID-19) pandemic. *arXiv*:2004.07743 2020
27. Backer JA , Klinkenberg D, Wallinga J. Incubation period of 2019 novel coronavirus (2019-nCoV) infections among travellers from Wuhan, China, 20–28 January 2020. *Euro Surveill*. 2020;25(5):pii=2000062. https://doi.org/10.2807/1560-7917.ES.2020.25.5.2000062
28. Li Q., Guan X., Wu P., Wang X., Zhou L., Tong Y., Ren R., Leung K. S. M., Lau E. H. Y., Wong J. Y., Xing X., Xiang N., Wu Y., Li C., Chen Q., Li D., Liu T., Zhao J., Liu M., Tu W., Chen C., Jin L., Yang R., Wang Q., Zhou S., Wang R., Liu H., Luo Y., Liu Y., Shao G., Li H., Tao Z., Yang Y., Deng Z., Liu B., Ma Z., Zhang Y., Shi G., Lam T. T. Y., Wu J. T., Gao G. F., Cowling B. J., Yang B., Leung G. M., Feng Z. Early Transmission Dynamics in Wuhan, China, of Novel Coronavirus-Infected Pneumonia. *N Engl J Med*, 2020;382:1199-1207
29. ASHRAE. ANSI/ASHRAE Standard 52.2-2017 Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size. American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. Atlanta, GA. 2017.
30. Fazli T, Zeng Y, Stephens B. Fine and ultrafine particle removal efficiency of new residential HVAC filters. *Indoor Air*. 2019;29:656–669.
31. WHO. Scientific Brief. Transmission of SARS-CoV-2: implications for infection prevention precautions. 9 Jul 2020. https://www.who.int/publications/i/item/modes-of-transmission-of-virus-causing-covid-19-implications-for-ipc-precaution-recommendations, accessed 28 August 2020.
32. Centers for Disease Control and Prevention. How COVID-19 Spreads. Updated June 16, 2020. https://www.cdc.gov/coronavirus/2019-ncov/prevent-getting-sick/how-covid-spreads.html Accessed 28 August 2020
33. Bean B, Moore BM, Sterner B, Peterson LR, Gerding DN, Balfour HH Jr. Survival of influenza viruses on environmental surfaces. J Infect Dis. 1982;146(1):47-51. doi:10.1093/infdis/146.1.47
34. Thomas, Y., Boquete-Suter, P., Koch, D., Pittet, D., Kaiser, L. Survival of influenza virus on human fingers. *Clinical Microbiology and Infection*, 2014, 20, O58-O64
35. Boone SA, Gerba CP. Significance of Fomites in the Spread of Respiratory and Enteric Viral Disease. *Applied and Environmental Microbiology* 2007;73:1687-1696; DOI: 10.1128/AEM.02051-06
36. Grayson ML, Melvani S, Druce J, Barr IG, Ballard SA, Johnson PDR, Mastorakos T, Birch C. Efficacy of Soap and Water and Alcohol-Based Hand-Rub Preparations against Live H1N1 Influenza Virus on the Hands of Human Volunteers, *Clinical Infectious Diseases*, 2009;48:285–291, https://doi.org/10.1086/595845
37. Chen W, Zhang N, Wei J, Yen H-L, Li Y. Short-range airborne route dominates exposure of respiratory infection during close contact. *Building and Environment*. 2020;176:106859. doi:10.1016/j.buildenv.2020.106859

38. Morawska L, Johnson GR, Ristovski ZD, et al. Size distribution and sites of origin of droplets expelled from the human respiratory tract during expiratory activities. *Journal of Aerosol Science*. 2009;40:256–269.
39. Bates JH, Potts WE, Lewis M. Epidemiology of primary tuberculosis in an industrial school. *New England Journal of Medicine*. 1965;272:714–717.
40. Mangura BT, Napolitano EC, Passannante MR, McDonald RJ, Reichman LB. *Mycobacterium tuberculosis* miniepidemic in a church gospel choir. *Chest*. 1998;113:234–237.
41. Washko R, Robinson E, Fehrs LJ, Frieden TR. Tuberculosis transmission in a high school choir. *Journal of School Health*. 1998;6:256–259.
42. Read R. Scientists to choirs: Group singing can spread the coronavirus, despite what CDC may say. *Los Angeles Times* 01 June 2020. https://www.latimes.com/world-nation/story/2020-06-01/coronavirus-choir-singing-cdc-warning. Accessed 08 June 2020.
43. Peinado F, Ferrero B. El virus se ceba con las voces del coro de la Zarzuela. *El Pais* 01 June 2020. https://elpais.com/espana/madrid/2020-06-02/el-virus-se-ceba-con-las-voces-del-coro-de-la-zarzuela.html. Accessed 06 June 2020.
44. Charlotte N. High Rate of SARS-CoV-2 Transmission due to Choir Practice in France at the Beginning of the COVID-19 Pandemic, *medRxiv* 2020 preprint doi: https://doi.org/10.1101/2020.07.19.20145326
45. Loudon RG, Roberts MR. Singing and the dissemination of tuberculosis. *American Review of Respiratory Disease*. 1968;98:297–300.
46. Noakes CJ, Sleigh PA. Mathematical models for assessing the role of airflow on the risk of airborne infection in hospital wards. *Journal of the Royal Society Interface*. 2009;6:S791–S800.
47. Lee S, Kim T, Lee E, et al. Clinical Course and Molecular Viral Shedding Among Asymptomatic and Symptomatic Patients With SARS-CoV-2 Infection in a Community Treatment Center in the Republic of Korea. *JAMA Intern Med*. 2020. doi:10.1001/jamainternmed.2020.3862
48. Buitrago-Garcia, D. C., Egli-Gany, D., Counotte, M. J., Hossmann, S., Imeri, H., Ipekci, A. M., Salanti, G., Low, N. Asymptomatic SARS-CoV-2 infections: a living systematic review and meta-analysis. *medRxiv* preprint, 2020, 2020.04.25.20079103
49. Arons M. M., Hatfield K. M., Reddy S. C., Kimball A., James A., Jacobs J. R., Taylor J., Spicer K., Bardossy A. C., Oakley L. P., Tanwar S., Dyal J. W., Harney J., Chisty Z., Bell J. M., Methner M., Paul P., Carlson C. M., McLaughlin H. P., Thornburg N., Tong S., Tamin A., Tao Y., Uehara A., Harcourt J., Clark S., Brostrom-Smith C., Page L. C., Kay M., Lewis J., Montgomery P., Stone N. D., Clark T. A., Honein M. A., Duchin J. S., Jernigan J. A. Presymptomatic SARS-CoV-2 Infections and Transmission in a Skilled Nursing Facility. *N Engl J Med*, 2020;382:2081-2090

50. Buonanno G, Stabile L, Morawska L. Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment. *Environment International*. 2020;141:105794.
51. Nicas M, Nazaroff WW, Hubbard A. Toward understanding the risk of secondary airborne infection: Emission of respirable pathogens. *Journal of Occupational and Environmental Hygiene*. 2005;2:143–154.
52. Gammaitoni L, Nucci MC. Using a mathematical model to evaluate the efficacy of TB control measures. *Emerging Infectious Diseases*. 1997;3:335–342.
53. Sze To GN, Chao CYH. Review and comparison between the Wells–Riley and dose-response approaches to risk assessment of infectious respiratory diseases. *Indoor Air*. 2010;20:2–16.
54. Yang W, Marr LC. Dynamics of airborne influenza A viruses indoors and dependence on humidity. *PLoS ONE*. 2011;6:e21481.
55. Adams WC. Measurement of breathing rate and volume in routinely performed daily activities. Final Report, Contract No. A033-205. California Air Resources Board, Sacramento, CA. 1993.
56. Binazzi B, Lanini B, Bianchi R, et al. Breathing pattern and kinematics in normal subjects during speech, singing and loud whispering. *Acta Physiologica*. 2006;186:233–246.
57. Diapouli E, Chaloulakou A, Koutrakis P. Estimating the concentration of indoor particles of outdoor origin: A review. *Journal of the Air & Waste Management Association*. 2013;63:1113–1129.
58. Thatcher TL, Lai ACK, Moreno-Jackson R, Sextro RG, Nazaroff WW. Effects of room furnishings and air speed on particle deposition rates indoors. *Atmospheric Environment*. 2002;36:1811–1819.
59. Knibbs LD, Morawska L, Bell SC. The risk of airborne influenza transmission in passenger cars. *Epidemiology and Infection*. 2012;140:474–478.
60. Riley EC, Murphy G, Riley RL. Airborne spread of measles in a suburban elementary school. *American Journal of Epidemiology*. 1978;107:421–432.
61. Beggs CB, Noakes, C. J., Sleigh, P.A., Fletcher, L.A., Siddiqi, K. The transmission of tuberculosis in confined spaces: an analytical review of alternative epidemiological models. *Int J Tuberc Lung Dis*. 2003;7(11):1015-1026.
62. Liao C-M, Chang C-F, Liang H-M. A probabilistic transmission dynamic model to assess indoor airborne infection risks. *Risk Analysis*. 2005;25:1097–1107.
63. Ma J., Qi X., Chen H., Li X., Zhan Z., Wang H., Sun L., Zhang L., Guo J., Morawska L., Grinshpun S. A., Biswas P., Flagan R. C. & Yao M. Exhaled breath is a significant source of SARS-CoV-2 emission. *medRxiv* preprint 2020, doi: 10.1101/2020.05.31.20115154

64. Bordi L, Piralla A, Lalle E, et al. Rapid and sensitive detection of SARS-CoV-2 RNA using the Simplexa™ COVID-19 direct assay. *J Clin Virol*. 2020;128:104416. doi:10.1016/j.jcv.2020.104416
65. Corman VM, Eckerle I, Bleicker T, Zaki A, Landt O, Eschbach-Bludau M, van Boheemen S, Gopal R, Ballhause M, Bestebroer TM, Muth D, Müller MA, Drexler JF, Zambon M , Osterhaus AD, Fouchier RM, Drosten C. Detection of a novel human coronavirus by real-time reverse-transcription polymerase chain reaction. *Euro Surveill*. 2012;17(39):pii=20285. https://doi.org/10.2807/ese.17.39.20285-en
66. Alford, R. H., Kasel, J. A., Gerone, P. J., & Knight, V. Human Influenza Resulting from Aerosol Inhalation. *Proceedings of the Society for Experimental Biology and Medicine*, 1966;122:800–804. https://doi.org/10.3181/00379727-122-31255
67. Jones TC, Mühlemann B, Veith T, et al. An analysis of SARS-CoV-2 viral load by patient age. *medRxiv* 2020 preprint doi:10.1101/2020.06.08.20125484.
68. Yan J, Grantham M, Pantelic J, et al. Infectious virus in exhaled breath of symptomatic seasonal influenza cases from a college community. *Proceedings of the National Academy of Sciences of the USA*. 2018;115:1081–1086.
69. Pan Y, Zhang D, Yang P, Poon LLM, Wang Q. Viral load of SARS-CoV-2 in clinical samples. *Lancet Infect Dis*. 2020;20(4):411-412. doi:10.1016/S1473-3099(20)30113-4
70. Nazaroff WW. Four principles for achieving good indoor air quality. *Indoor Air*. 2013;23:353–356.
71. Nardell EA, Nathavitharana RR. Airborne spread of SARS-CoV-2 and a potential role for air disinfection. *JAMA*. 2020:doi:10.1001/jama.2020.7603.
72. Morawska L, Tang JW, Bahnfleth W, et al. How can airborne transmission of COVID-19 indoors be minimised? *Environment International*. 2020;142:105832.
73. Lindsley WG, Blachere FM, Beezhold DH, et al., Viable influenza A virus in airborne particles expelled during coughs versus exhalations. *Influenza and Other Respiratory Viruses*. 2016;10:404–413.

Supplemental Information

Ventilation Rate Estimates

The ventilation rate for the baseline case was estimated assuming that the HVAC fan was not operating during the rehearsal and there was no recirculated air. We assume that once the rehearsal space was heated prior to the practice, heating did not turn on again because the metabolic energy generated by the SVC rehearsal attendees was sufficient to maintain a comfortable temperature without supplemental heating. For conditions of metabolic activity at 1.2 met, clothing insulation of 1.0 clo, at 22 °C (71 °F), the metabolic heat generation per occupant is 78 W. [1] Assuming that half of the metabolic energy goes to continuously heat the room air (with the other half lost through the building envelope by conduction and to heat storage), then each occupant would contribute 39 W to the ventilation air. Given the reported difference between indoor and outdoor temperature (23 °F = 13 K) and the heat capacity of air (1 J g^{-1} K^{-1}), one can derive the ventilation rate to be 39 W $person^{-1}$ ÷ 13 J g^{-1} = 3 g s^{-1} $person^{-1}$. At a density of 1.2 g L^{-1}, the resulting ventilation flow rate would be 2.5 L s^{-1} $person^{-1}$. For a room volume of 810 m^3 with 61 occupants, the corresponding air-change rate would be 0.7 per h^{-1}. We bracket this estimate by applying an uncertainty of ± 50% so that the modeled range in the Monte Carlo simulation is 0.3-1.0 h^{-1}.

By way of comparison, we have estimated the outdoor air ventilation rate based on the relevant ASHRAE standard combined with information from the mechanical drawings for the rehearsal hall under the assumption that the HVAC fan was on for the event duration. The outdoor make-up air flow specified by ASHRAE Standard 62.1 for places of worship (Table 6.2.2.1) is 2.5 L s^{-1} $person^{-1}$ + 0.3 L s^{-1} per m^2 of floor area.[2] The default occupant density is 120 persons per 100 m^2 of floor area. The corresponding outdoor air rate per m^2 of floor area would then be (120/100) × 2.5 + 0.3 = 3.3 L s^{-1} m^{-2}. The reported averaging ceiling height for the Fellowship Hall is 4.5 m and the estimated floor area is 180 m^2. The total ventilation flow rate would therefore be 180 × 3.3 = 594 L s^{-1} = 2100 m^3 h^{-1}, corresponding to an air-change rate of 2.6 h^{-1}. Additionally, mechanical drawings of the rehearsal hall show specifications of 3 × 1560 cfm supply registers (indicated to be 8 ft above the floor along one wall). This information indicates that the ventilation system is designed to supply 4700 cfm = 8000 m^3 h^{-1}, which would be a mixture of outdoor air and recirculated indoor air (filtered through a MERV 11 filter). That supply flow rate corresponds to 10 room volumes per hour. Applying the outdoor air flow rate from ASHRAE 62.1, at this overall flow rate, the mix would be about 25% outside air and 75% recirculated air. These 2.5-10 effective air changes per hour are unlikely to have been provided during the rehearsal, based on personal communication received during our investigation.

Assumption of Complete Mixing

A major assumption of complete mixing was used in this analysis. Many indoor spaces are indeed appropriately modeled as well mixed and for this specific event, it is a reasonable assumption due to the following considerations.

- There is an absence of any strong pattern in the spatial distribution of secondary cases, which supports the well-mixed assumption.
- The thermal conditions during the rehearsal would tend to promote relatively rapid mixing. In particular, we observe that the outdoor air temperature was quite cool (7 °C), which would have led to a tendency for the wall and ceiling surfaces to be cool. The metabolic heat release from occupants during the rehearsal is estimated to be about 60 persons x 80 W/person ~ 5 kW. The heat generated by distributed occupancy near floor level would combine with cooling at the walls and ceiling to promote effective mixing so as to generate relatively short mixing time scales.[3]

- Although there is no perfect analog in the literature, the mixing study of Baughman et al. (1995) is informative.[4] In that study, use of a 500 W electrical heater in an unoccupied 31-m^3 room generated a mixing time for a point-source pollutant release of 13-15 min. Even faster mixing was attained in the case when heat was generated by incoming solar radiation through a window onto the floor. These experimental findings document that fairly fast mixing times can be realized purely through buoyancy-driven flow.

Taken in combination, these indications seem to us sufficient to substantiate our decision to model this event using a well-mixed representation of the indoor space.

Sensitivity Analysis on Parametric Distributions for the Monte Carlo Simulation

To understand how the assumption that the model parameters were uniformly distributed, we repeated the work reported in the main paper but using alternative distributions. We amended our original Monte Carlo simulation in four separate variations. In each, one of the input parameters is changed from what we reported in Table 1 to triangular or fixed-value distributions. These four, respectively, address breathing rate, air-change rate, decay rate, and deposition rate.

- For breathing rate, the average for men and women age 60-70 was used from the U.S. EPA's Exposure Factors Handbook,[5] selecting the "sedentary/passive activity" case for the lower bound of the triangular distribution, and "moderate activity" case for the upper bound. The range, then, is 0.34-1.4 m^3 h^{-1} with an average, 0.87 m3 h^{-1}, that is moderately higher than would be the case for "light" activity. We applied both a symmetric and asymmetric triangular distribution in separate simulations.
- For air-change rate, we used the earlier values of 0.3 and 1.0 per h as the bounds of a symmetricaltriangular distribution.
- For decay, we used the two reported values from Table 1 as single, fixed options (0 and 0.63 per h).
- For deposition, the same conceptual approach as for air-change rate was used, with 0.3 and 1.5 per h selected as the bounding values in a symmetrical triangular distribution.

The results are summarized in Table S1.

Table S1. Monte Carlo Simulation Results using Different Parametric Distributions for Breathing (Q_b), Air-Exchange (λ_v), Decay (k), and Deposition (λ_{dep}) Rates.

				Quanta Emission Rate (*E*, quanta/h)	
Parameter*	Change	Min	Max	Mean ± St. Dev.	GM (GSD)
Q_b (m^3/h)	Triangular	0.34	1.4	1200 ± 530	1100 (1.51)
λ_v (h^{-1})	Triangular	0.3	1	1020 ± 410	940 (1.48)
k	Fixed	0	0	870 ± 350	810 (1.48)
k	Fixed	0.63	0.63	1100 ± 430	1030 (1.47)

These simulation results are indicative of the degree of uncertainty associated with unknown input parameter distributions. Note that the mean estimated values of *E* for the five cases in Table S1 range from about 10% less to about 20% more than the primary estimate of *E* = 970 (± 390) quanta per h reported in the main paper.

* Each input parameter is changed separately from the original base-case simulation.

Information Provided by Choir Spokesperson

The choir spokesperson responded to multiple requests for information, always in writing. All of the responses have been reproduced in this section, except where the information would reveal the identity or gender of the index case. The seating chart and some response text have been removed for this reason. Text edited for privacy is enclosed in square brackets [like this]. The responses have been reordered by topic for ease of reading.

General Questions

Question: How many people contributed to the questionnaire responses you provided? Is it accurate to say "a majority of the members present at the March 10 rehearsal"?

Choir Spokesperson: Yes, we had most of the choir answer.

Question: What was the age of those that did not fell ill? Where they younger than those who fell ill? Or similar ages?

Choir Spokesperson: This outbreak was no respecter of age. The age range of infected people was 31 to 84. Our group's median age is probably 65.

Question: Where those who did not fell ill tested? (either immediately after the event, or later on through antibody testing). Otherwise, some of them could have been infected, but be asymptomatic, correct?

Choir Spokesperson: There was no testing available for most of us. Some doctors in the group managed to get tests, but others were told not to come get a test unless they were much sicker. One woman was told she looked "too healthy" to get a test. My husband and I were told we were presumed positive. We knew we had it because we carpool with a doctor and his wife, and they got tested. Remember, this was March 10 and we live in a rural area.

Question: There were 3 people who started having symptoms 1 day after the rehearsal, according to the report from the public health agency. If you know who those are, where those [from the group of singers that would have spent the most more time with the index case]. And were they seated closer to the index case?

Choir Spokesperson: I don't know of anyone who started having symptoms 1 day after rehearsal. The earliest I heard about through our survey is the 12th, or two days afterward. That would be a person right next to our index case in [location X] and [another person about 12 feet away from the index case]. [Both were from same group of people where the index case was during the separate 50 min. rehearsal]. The majority got sick on the 13th. I am not sure the county health dept. is correct here.

Question: You provided some corrections for our description of the event after you read the original manuscript, which were incorporated in the version submitted to the journal. Would you be ok reviewing a draft of the revised paper before resubmission, or specifically the sections where we describe the event? So that we avoid making mistakes?

Choir Spokesperson: I would be happy to do that. I taught composition to high-schoolers, so it will be fun! I can dust off my red pencil…

Questions about the rehearsal space and layout

Question: The LA times mentions that the space is "about the size of a volleyball court" (which is about 60 ft x 30 ft). And that "cushioned metal chairs extended in six rows of 20, with about a foot between chairs and one aisle down the center. There were twice as many seats as people." I've made the schematic below trying to match that description. Is this approximately accurate? If not, can you point out the differences?

Choir Spokesperson: This is accurate. See attached pdf for rehearsal locations and infections. [Not shown for privacy]

Question: What is the approximate height of the room?

Choir Spokesperson: Ceiling is vaulted, running the width of your diagram. High point approx. between rows E and F, and is at about 20'. Ceiling height at room perimeter is about 10'

Question: Did the conductor face everyone as drawn? Did the conductor sign along?

Choir Spokesperson: The conductor faced everyone as shown. He does not sing along, but sometimes sings a section to demonstrate correct notes/timing.

Question: Was the piano next to the conductor?

Choir Spokesperson: The piano is always located on his right. The accompanist sitting on the bench is about 12' from the conductor.

Question: I am pretty sure the answer is no, but one of the reviewers asked if there was video surveillance in the hall, so I just wanted to confirm that there was not.

Choir Spokesperson: No

Question: Do you know where different people were seating that got sick and not? This information would be extremely useful, even if not totally accurate. I added letters for the rows and numbers for the columns of the chairs for ease of communication. Ideally you could print the chart, and mark with an X the chairs where the occupant got sick, and a circle on the chairs that had an occupant who did not get sick.

Choir Spokesperson: See attached pdf with locations of people who got sick and not, including the dates when known, and of the index case.

Question: If you know that people sitting on one part of the room got sick earlier or later, this would be very useful.

Choir Spokesperson: Start dates indicated on diagram where known. Seems to be mostly on 3/13. Some people had such mild symptoms they did not know they were sick or had no symptoms and tested positive.

Questions about the activities during the rehearsal

Question: In terms of the non-singing times, would the list below be approximately correct? (And if not, please update)

- 6:20-6:30: Arrival of members in the ~10 min before the rehearsal, people chit-chatting etc
- 6:30-7:10: First part of rehearsal, everyone together in one room
- 7:10: Breaking into bass/baritone and soprano/alto group, some talking along the way, but not a break
- 7:10-8:00: Separate rehearsals for 50 min
- 8:00-8:15: 15 min break, people talking, having snacks
- 8:15-9:00: rehearsal with everyone together in one room
- 9:00: "Most attendees left the practice immediately after it concluded" per county report

Choir Spokesperson: This is accurate, but probably not exact. The break is usually only about 10 minutes. I have seen reports that say one group "stood around a piano" during the and that is NOT correct. They sat in the church pews to sing and the piano was separated from the singers by at least 10 feet.

Question: the LA times article mentions that "At one point the members broke into two groups, each standing around separate pianos to sing." Was that on the same room? Were you any closer to each other during that time? How long did that last?

Choir Spokesperson: This is incorrect. When we split into two groups, the tenors and basses (mostly men) went with the conductor and our accompanist to the large church sanctuary, where the conductor stood in the front facing the singers, who were seated in the pews. People did not need to sit close together, since the room easily seats 150 and there were only around 20 singers. The piano in that room is off to the side, with the accompanist seated about 20' from where the conductor was standing. The sopranos and altos all shifted to the right side of your diagram, so were in rows A-F, seats 11-20. Again, there were only around 35 singers and 60 seats, so not all seats were occupied. One of our singers led the sectional rehearsal from the piano. This lasted about 45 minutes, and we took a brief break (10 min.) when we got back together. So we *rehearsed in the same room for 45 minutes, split for 45 minutes, took a break for 10 minutes. Then we were all in the same room rehearsing for 50 more minutes, until 9pm.*

Question: one possible alternative to air transmission would be transmission through touching objects. Even though you clearly tried to not touch objects of each other, it is still important to learn a little more about this. The article mentions "Some members helped set up or remove folding chairs. A few helped themselves to mandarins that had been put out on a table in back." How many people help with the chairs?

Choir Spokesperson: Three people set up chairs. All 3 got sick on the 13th or 14th. Everyone is responsible for putting their own chair away afterward. People fold their chair and carry it to a rolling rack, where the chairs are hung on pegs. Sometimes, people will stand by the racks and assist with placing the chairs on them. I am sure that happened that night. Then the racks are wheeled into a storage area. Some people have others who take care of their chairs, so not everyone who got sick touched a chair. (I have a bad shoulder, so my husband takes care of my chair every week, along with others. I was sick on the 13th and he was sick on the 15th.)

The index case did not help with setting up or removing the chairs.

Question: How of the people touched the mandarins? Did they get sick or not?

Choir Spokesperson: About ½ of those in attendance had an orange. Both those who ate one and those who did not got sick.

Question: Where there any other objects that many people could have touched? E.g. a door handle for entering or exiting the room or building?

Choir Spokesperson: When we arrive, there is a singer who "greets" us and directs us to any handouts or music we need to pick up. (There was a piece of music for the women that night.) The exterior door is usually propped open during this time, since most of us arrive within about 10 minutes of each other. That means very few people needed to touch the door handle. When we arrived on that evening, we were all directed to a large bottle of hand sanitizer, which most everyone used.

Some people touched the interior door handles when going to and from the rehearsal room to the sanctuary and to the restrooms, but since we moved in groups, a few held the door and most did not have to touch it. Some people used the restrooms, so those doors were touched. Those who did or did not use the restrooms all got sick.

Question: In terms of the periods with talking, how much mingling was there? Did people talk to just a few friends, or did they talk to a lot of people?

Choir Spokesperson: Since our break is so short, there is not a lot of time for mingling. If people need to use the restrooms, that takes most of the time, so they might talk to the people in line for the bathroom, but that's it. Those who get a snack go to the table in the back, and then leave the table to make room for others to access the goodies. I would say that, on average, people speak to 2 or 3 people during the break. As I said above, the group is seriously about the music, not overly social. Our director keeps strict control over the time we have to maximize the learning.

Questions about activities of known index case

Question: We would like to include some additional info about the index case that should not reveal the person's identity: in particular, that the person did not have anyone sitting in the 3-6 ft area immediately forward, where large droplets would have landed; that the person did not handle the chairs or had snacks; and that the person did go to the bathroom (but that many who did not go, also got ill). These help firm the case against the other routes of transmission.

Choir Spokesperson: The index case sat [at location X], so no one was in front of [them, within the likely 9 feet landing radius of expired droplets] The person to [their] right was about 5 feet away, and the person to [their] left was about 4 feet away. [They] turned slightly to [one side] to see the director and so [their] exhalations would have been more toward the person on [one side], who [did contract COVID-19]. Our index case went to the bathroom. [They] used the restroom off the hall, not the main restroom. [They did not help with the chairs that evening].

The restrooms off the hall [that the index case used], which are closer, are single men's and women's rooms. The vast majority of singers go to the restrooms located a little further away because they have multiple stalls. I am one of the people who uses the closer single restrooms. I usually meet the same people coming and going during the break, and I would say there are only about 6 people who use these regularly.

The index case did not have any snacks. [That evening that person had very limited interactions with others]

Question: In particular, do we know how many people the index case may have talked to in the periods with talking?

Choir Spokesperson: I talked with the person [they] told about [the index case's] sore throat. [The index case] arrived just in time to start. [They] sat [in a specific location], so I noticed [them] coming in every week. [Their] talking to people was minimal [during the entire rehearsal].

Question: I assume that the identity of the index case continues to be confidential, which is of course appropriate. But I just wanted to ask in case it had somehow become public, which would perhaps relax the restrictions on what we can say.

Choir Spokesperson: all the other choir members already know who it was, but there are probably legal/privacy concerns we should heed!

Questions about the rehearsal space

Question: It would be very useful to learn more about the heating / ventilation system in the room. Does the room have forced air ventilation? Or radiators or other system? Was the system in use during that rehearsal? Where doors or windows open during the rehearsal?

Choir Spokesperson: The room is heated by a relatively new commercial forced air furnace. There is no other source of heat. The people who get there early to set up turned the heat up to 68 degrees. It was about 45 degrees outside, so the heat was on initially, but with so many people in the room, it did not need to stay on to maintain the 68 degrees. During the rehearsal, from 6:30 to 9:00pm, no exterior doors were open.

Question: It would be very useful to talk to whoever maintains the heating and ventilation system for the building, could you help us locate that contact information?

Choir Spokesperson: here is the contact info. [Removed for privacy]

Question: Was there anyone else in the building during the rehearsal, even if in different rooms?

Choir Spokesperson: Those who set up for the rehearsal say the building was dark and locked when they arrived at 6pm. We do not know of anyone else who was there during our rehearsal, but someone could have been in a back office or room and we did not see them.

Questions related to the possibility of transmission outside the choir rehearsal

Question: Was there anyone who may have had some very mild symptoms at the time of the rehearsal? Or someone who got sick earlier than the rest? This would give us a candidate location for the initial contagion. Understood that this is a very delicate subject. We don't want to know anything about the person, but just the location within the room, the first / second piano group, and whether they handled chairs mandarins / other objects or not would be useful.

Choir Spokesperson: Of all who responded, only one person said someone was coughing behind [them], and that was during the women's sectional. The one reporting this was seated in X (removed for privacy) for that portion. Someone's husband, who came to pick up his wife, said there was someone coughing as they exited the building at 9pm. Almost everyone else said they heard no coughing, sneezing, etc. during the entire time. If someone HAD coughed or sneezed, *most of us would have turned to look. We specifically told the singers not to attend if they had any symptoms whatsoever, even if they believed it to be just seasonal allergies. So we were sensitive to that.*

The index case was seated in X [removed for privacy] and told another singer that [they] wasn't feeling well and had a sore throat. During the sectional, [they] would have moved to Y [removed for privacy]. The index case did not have an orange or move a chair, but [they] did use the restroom located down the hall on the left side of your diagram.

Question: Did choir members see each other elsewhere during the week before the rehearsal? Or did they carpool to the rehearsal? If so, how many may have done so? (The County Report says that they investigated other possibilities, and concluded that the rehearsal was where contagion happened, but they don't give any detail on this)

Choir Spokesperson: I think the county is correct in their assessment.

It is possible that people saw each other during the week, but our choir is comprised of people from a large area who attend to sing. It is not a highly social group in that it is not comprised of groups of friends who see each other all the time. It is pretty seriously about the music. We don't have social gatherings except for our summer picnic just before rehearsals start in September. We have been in the group since 2005, and the only people we see socially are the ones in our carpool! I know of several groups of us who drive from Anacortes, which is 14 miles away from the rehearsal site. One carpool has 5, one has 4, one has 2. Other people live closer to the church, so don't need to pool. There may be a couple more groups, but I am not sure of that.

The county report mentions one person who attended the March 3rd but not the March 10th rehearsal, and that fell ill with COVID-19. Did that person have some contact with the index patient where transmission could have happened? Or any comments on that situation?

Choir Spokesperson: I am pretty sure no one had contact with the index case during that week. I don't know of anyone who got Covid before March 10 except our index case, but it is apparent that the disease was in our area in early March.

Questions about the timing of the secondary cases

There were 3 people who started having symptoms 1 day after the rehearsal, according to the report from the public health agency. Can you confirm this?

Choir spokesperson:I don't know of anyone who started having symptoms 1 day after rehearsal. The earliest I heard about through our survey is the 12th, or two days afterward. That would be the woman right next to our index case in F6 and the woman in C1. The majority got sick on the 13th. I am not sure the county health dept. is correct here.

[To make sure] I called several people, and no one remembers hearing of someone who was ill before Thursday, the 12th. Two people reported feeling ill on that day. Most felt symptoms on Friday or Saturday. This is an excerpt from our director's email to the group on March 17; he is the person people were communicating with regarding the outbreak.

"Well, this is a little sooner than I'd expected to be in touch. We have some news of concern to relate. At least 6 of us from the Chorale came down with a fever Friday night or Saturday, including me. Two have been tested and the tests are being sent on to test for Coronavirus. We are told we won't hear those results until Thursday; we will keep you apprised as to the results."

References

- Ahmed K, Akhondzada A, Kurnitski J, Olesen B. Occupancy schedules for energy simulation in new prEN16798-1 and ISO/FDIS 17772-1 standards. *Sustainable Cities and Society*. 2017;35:134–144.
- ASHRAE. *ANSI/ASHRAE Standard 62.1-2016 Ventilation for Acceptable Indoor Air Quality.* American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc. Atlanta, GA. 2016.
- Baughman AV, Gadgil AJ, Nazaroff WW. Mixing of a point source pollutant by natural convection flow within a room. *Indoor Air.* 1994;4:114-122.
- AK Melikov, Human body micro-environment: The benefits of controlling airflow interaction, *Building and Environment*. 2015;91:70-77.
- EPA. Exposure Factors Handbook, Table 6-2, Chapter 6. 2011. https://www.epa.gov/expobox/exposure-factors-handbook-chapter-6