

Community Outbreak Investigation of SARS-CoV-2 Transmission Among Bus Riders in Eastern China

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IMPORTANCE Evidence of whether severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the virus that causes coronavirus disease 2019 (COVID-19), can be transmitted as an aerosol (ie, airborne) has substantial public health implications.

OBJECTIVE To investigate potential transmission routes of SARS-CoV-2 infection with epidemiologic evidence from a COVID-19 outbreak.

DESIGN, SETTING, AND PARTICIPANTS This cohort study examined a community COVID-19 outbreak in Zhejiang province. On January 19, 2020, 128 individuals took 2 buses (60 [46.9%] from bus 1 and 68 [53.1%] from bus 2) on a 100-minute round trip to attend a 150-minute worship event. The source patient was a passenger on bus 2. We compared risks of SARS-CoV-2 infection among at-risk individuals taking bus 1 (n = 60) and bus 2 (n = 67 [source patient excluded]) and among all other individuals (n = 172) attending the worship event. We also divided seats on the exposed bus into high-risk and low-risk zones according to the distance from the source patient and compared COVID-19 risks in each zone. In both buses, central air conditioners were in indoor recirculation mode.

MAIN OUTCOMES AND MEASURES SARS-CoV-2 infection was confirmed by reverse transcription polymerase chain reaction or by viral genome sequencing results. Attack rates for SARS-CoV-2 infection were calculated for different groups, and the spatial distribution of individuals who developed infection on bus 2 was obtained.

RESULTS Of the 128 participants, 15 (11.7%) were men, 113 (88.3%) were women, and the mean age was 58.6 years. On bus 2, 24 of the 68 individuals (35.3% [including the index patient]) received a diagnosis of COVID-19 after the event. Meanwhile, none of the 60 individuals in bus 1 were infected. Among the other 172 individuals at the worship event, 7 (4.1%) subsequently received a COVID-19 diagnosis. Individuals in bus 2 had a 34.3% (95% CI, 24.1%-46.3%) higher risk of getting COVID-19 compared with those in bus 1 and were 11.4 (95% CI, 5.1-25.4) times more likely to have COVID-19 compared with all other individuals attending the worship event. Within bus 2, individuals in high-risk zones had moderately, but nonsignificantly, higher risk for COVID-19 compared with those in the low-risk zones. The absence of a significantly increased risk in the part of the bus closer to the index case suggested that airborne spread of the virus may at least partially explain the markedly high attack rate observed.

CONCLUSIONS AND RELEVANCE In this cohort study and case investigation of a community outbreak of COVID-19 in Zhejiang province, individuals who rode a bus to a worship event with a patient with COVID-19 had a higher risk of SARS-CoV-2 infection than individuals who rode another bus to the same event. Airborne spread of SARS-CoV-2 seems likely to have contributed to the high attack rate in the exposed bus. Future efforts at prevention and control must consider the potential for airborne spread of the virus.

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Human infection by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was first reported in late 2019 in Wuhan city of Hubei province in China.^{1,2} The World Health Organization declared the coronavirus disease 2019 (COVID-19) outbreak a public health emergency of international concern on January 30, 2020. The ongoing epidemic has since affected more than 150 countries and territories. As of August 5, 2020, more than 18 million cases have been confirmed and more than 650 000 people have died.³

Greater efforts are needed to contain and combat the virus; however, much remains unknown about SARS-CoV-2 transmission, limiting our ability to implement effective interventions. Several studies have demonstrated transmission through close contact and respiratory droplets produced when an infected person coughs or sneezes.⁴⁻⁶ Whether SARS-CoV-2 can be transmitted as an aerosol (ie, airborne) through inhalation of virus suspended in the air is unknown. Previous studies have suggested possible airborne transmission of other virulent coronaviruses, such as the severe acute respiratory syndrome coronavirus and the Middle East respiratory syndrome coronavirus.⁷⁻¹¹ Recent reports suggest that closed environments may facilitate secondary transmission of SARS-CoV-2.^{12,13} An experimental study demonstrated that SARS-CoV-2 can remain viable in aerosols for 3 hours or longer,¹⁴ and experimental evidence of transmission of SARS-CoV-2 between ferrets via the air was also established.^{15,16} Therefore, evidence supporting the potential for an airborne transmission route of SARS-CoV-2 is emerging. However, epidemiologic evidence from actual community transmission in human cohorts is lacking. To investigate the potential airborne transmission route, we present the investigation of an outbreak of COVID-19 among lay Buddhists worshipping in a temple in Zhejiang province.

Methods

Data Collection

Data on demographics, travel history, and social and family activities were collected by a standard questionnaire and additional phone or in-person interviews through epidemiologic investigation carried out by local Centers for Disease Control and Prevention staff between January 27 and February 23, 2020. The standard case report form and details regarding the initiation of the outbreak investigation are provided in the eAppendix in the [Supplement](#). The research protocol was approved by the institutional review board at the Zhejiang Provincial Centers for Disease Control and Prevention and all human participants gave written informed consent.

Sample Collection and Diagnosis of COVID-19

Throat swabs (oropharynx and nasopharynx) were collected for all individuals involved in the outbreak and their close contacts identified through follow-up contact tracing. All samples were tested by reverse transcription polymerase chain reaction or by viral genome sequencing. Screened individuals were categorized into noncases, suspected cases, and confirmed

Key Points

Question Is airborne transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) a potential mean of spreading coronavirus disease 2019 (COVID-19)?

Findings In this cohort study of 128 individuals who rode 1 of 2 buses and attended a worship event in Eastern China, those who rode a bus with air recirculation and with a patient with COVID-19 had an increased risk of SARS-CoV-2 infection compared with those who rode a different bus. Airborne transmission may partially explain the increased risk of SARS-CoV-2 infection among these bus riders.

Meaning These results suggest that future efforts at prevention and control must consider the potential for airborne spread of SARS-CoV-2, which is a highly transmissible pathogen in closed environments with air recirculation.

cases of COVID-19. Criteria for COVID-19 case definitions and disease severity are provided in the eAppendix in the [Supplement](#).

Statistical Analyses

Attack rates were estimated as the number of diagnosed COVID-19 cases divided by the total number of people at risk, excluding the source patient of the outbreak. We compared the risk of COVID-19 between individuals taking the exposed bus (bus 2) and individuals taking the unexposed bus (bus 1) as well as the COVID-19 risk between individuals in bus 2 and all other individuals attending the worship event, excluding bus 2. In addition, we divided seats in bus 2 into high-risk and low-risk zones according to the definition of close contact with COVID-19 in travel-associated settings, an area within 2 meters¹⁷ (classification 1) or 2 rows¹⁸ (classification 2) of the source patient. On bus 2, the distance between 2 rows was measured at 0.75 m, which converts 2 meters to 3 rows. Therefore, the high-risk zone includes seats in the same row and within 2 or 3 rows (rows 6-10 or rows 5-11) of the index patient (seated in row 8); low-risk zones include seats in other rows ([Figure 17,18](#)). The COVID-19 risks in the 2 types of zones were compared. All comparisons used χ^2 or Fisher exact tests. Both risk ratios (RRs) and risk differences and corresponding 95% confidence intervals were calculated. For an exposure-disease category with no observations, we added a value of 0.5 to all cells.¹⁹ A Spearman rank correlation test was performed to test the correlation between the disease severity of those who developed infection and the distance to the index patient on bus 2 (eAppendix in the [Supplement](#)). Analyses were conducted using SAS, version 9.4 (SAS Institute), and statistical significance was set at $P < .05$.

Results

Evidence from an outbreak suggesting airborne transmission of SARS-CoV-2 is presented. Other materials associated with the transmission dynamics of the outbreak are included in the eAppendix in the [Supplement](#).

The diagram illustrates the layout of a 15-row classroom and the progression of an infection. The central area represents the classroom, with rows labeled Row 1 to Row 15. The front of the classroom is labeled 'Front window' and the back is labeled 'Door'. The classroom is divided into three zones: Zone 1 (rows 5-10) and Zone 2 (rows 1-4 and 11-15). Air vents (warm air) are located at the front and back of the classroom. The infection starts with the index patient (a moderate case) in Row 8, Column 2. The infection spreads to other cases, which are color-coded: Noncase (white), Asymptomatic case (green), Mild case (yellow), Moderate case (red), and The index patient (a moderate case) (dark red). The number of tertiary cases infected is indicated by a purple circle with a number inside. The legend at the bottom defines the symbols and colors used in the diagram.

Row	Column 1	Column 2	Column 3
Row 1	NC		NC
Row 2		NC	NC
Row 3	NC	NC	NC
Row 4	NC	C23 3	C1 0
Row 5	NC	C31 1	NC
Row 6	NC	NC	NC
Row 7	NC	C26 4	C17 0
Row 8	C15 1	IP	NC
Row 9	NC	C22 0	NC
Row 10	NC	C19 0	C18 4
Row 11	NC	NC	NC
Row 12	NC	C16 1	C30 0
Row 13	NC	NC	NC
Row 14	NC	NC	C25 0
Row 15	NC	C10 0	NC

Legend:

- Noncase
- Asymptomatic case
- Mild case
- Moderate case
- The index patient (a moderate case)
- # No. of tertiary cases infected
- Air vents (warm air)

with ovals, and there are 4 green side windows and that could be opened for fresh air. C indicates case; NC, noncase.

gers on the 2 buses were from the same district of the city. The 2 buses were similar in design, with an air conditioning system on a heating and recirculating mode (vents were below the windows) and 4 openable windows (2 on each side); neither had an attached toilet. All other individuals traveled to the temple through other methods of transportation. The 2 buses came from 1 district in Ningbo city (Haishu District) to the temple, which is located in another district of Ningbo city (Yinzhou District). The travel duration to and from the temple on the bus was 50 minutes each way (100 minutes total). Passengers, including the index patient, remained seated in their own seats during the bus rides and did not change seats on the way back. The weather was sunny with a gentle breeze during the day (33.8 °F-50 °F). The worship event lasted 150 minutes, beginning at 10:00 AM and ending at 12:30 PM. The event

included a luncheon, with 10 attendees sitting at each round table in a spacious room with no recirculating central air conditioning systems on. The lunch lasted 15 to 30 minutes. Passengers from bus 2 did not sit together and were randomly mixed at lunch. All 293 lay Buddhists (including those who traveled on the 2 buses and the others) and the 5 monks presented at the worship place and they were mixed into large crowds. None of the event participants wore mask or any prevention during the rides and worshipping on January 19, 2020, as there was no public awareness of COVID-19 in the city at that time.

Among all patients who received a COVID-19 diagnosis during this outbreak, the presumed index patient, a lay Buddhist in their 60s, was the only person exposed to residents from Wuhan. On January 17, the individual had dinner at the same table with a group of 10 individuals, among whom 4 had travel histories to Hubei province. The index patient was also the first to develop clinical symptoms. As such, the index patient was presumed to be the source of transmission in this outbreak. The individual was initially asymptomatic during the bus trip but started to have cough, chills, and myalgias on the evening after returning from the temple. The next day, the patient felt better after bathing in a hot tub. However, the patient's spouse and child started to have fever and cough on January 22, 2020, and the entire family went to a hospital seeking treatment. During the hospital visit, the index patient had a normal body temperature. On January 25, 2020, the index patient's child received a diagnosis of suspected COVID-19, and consequently the entire family was admitted to a hospital for quarantine, where a computed tomography scan showed exudative inflammation in the lungs of the index patient. All 3 family members had confirmed COVID-19 positive results from reverse transcription polymerase chain reaction assays on January 28, 2020. The index patient's spouse and child did not participate in the worship event on January 19, 2020. Other secondary patients also started to develop symptoms within a relatively short period after the worship event. A detailed record for the length of time to first symptoms for all secondary cases and beyond (the secondary cases went on to transmit the disease to others) is included in eFigure 1 in the [Supplement](#), and the corresponding transmission dynamics are presented in eFigure 2 in the [Supplement](#). Many of these individuals were close contacts of the secondary cases, but they did not participate in the worship event.

Analyses Suggesting That the Transmission Largely Occurred on Bus 2

Bus 2 carried 68 individuals (67 lay Buddhist passengers and a driver), of whom 24 passengers (35.3% [including the index patient]) developed infection and received a COVID-19 diagnosis after the event. None of the 60 individuals (59 lay Buddhist passengers and a driver) on bus 1 received a subsequent diagnosis of COVID-19. In addition, among the other 172 individuals (167 individuals [97.1%] who traveled to the worship event through other methods of transportation and 5 monks [2.9%]) at the worship event, 7 (4.1%) received a subsequent diagnosis of COVID-19, and all of them described being in close contact with the index patient during the event. Overall, 30

of the 299 individuals (10.0%) at risk during the event developed COVID-19 (excluding the index patient). Compared with individuals in the nonexposed bus (bus 1), those in the exposed bus (bus 2) were 42.2 (95% CI, 2.6-679.3) times more likely to develop COVID-19 ([Table](#)), and the risk difference was 34.3% (95% CI, 23.0%-45.7%). Compared with all other individuals attending the worship event, passengers in bus 2 had an 11.4 (95% CI, 5.1-25.4) times higher chance of developing COVID-19 ([Table](#)).

Analyses Suggesting Potential Airborne Transmission in Bus 2

We were able to identify seats for each passenger in the exposed bus ([Figure](#)). The bus had 15 rows of seats. Starting from the third row, each row had 3 seats on 1 side of the aisle and 2 seats on the other side of the aisle. The index patient sat in the middle seat on the 3-seat side of the eighth row. Other than the passengers sitting close to the index patient, the seats of other cases were scattered in the bus. Passengers in the high-risk zones had moderately but nonsignificantly higher risk of getting COVID-19 than those in the low-risk zones using either classification 1 (RR, 1.6; 95% CI, 0.8-3.2) or classification 2 (RR, 1.8; 95% CI, 0.9-3.3) ([Table](#)). On the 3-seat side of the bus, except for the passenger sitting next to the index patient, none of the passengers sitting in seats close to the bus window developed infection. In addition, the driver and passengers sitting close to the bus door also did not develop infection, and only 1 passenger sitting by an openable window developed infection. The index patient developed moderate symptoms ([Figure](#)). Among passengers who eventually developed COVID-19 on bus 2, 2 were asymptomatic, 3 had mild symptoms, and the remaining 17 had moderate symptoms. The disease severity of the secondary patients was not associated with their proximity to the index patient on the bus (Spearman correlation coefficient, 0; $P = .99$). In a further contact investigation of the 23 patients with COVID-19 on bus 2, the numbers of tertiary cases transmitted by each of them were reported ([Figure](#)).

Discussion

Previous investigations have reported respiratory droplets, either through close contact or the touching of inanimate objects (ie, fomites), as the major transmission route for COVID-19. As a result, washing hands using soap under running water for 20 seconds and masking mouths and noses when coughing or sneezing is widely suggested for disease prevention.¹⁷ Through detailed epidemiologic analysis, airborne transmission within a bus with recycled air seems likely to have contributed to a COVID-19 outbreak in eastern China. A natural occurrence involved in the outbreak helped to identify where most the transmission occurred. A review study on transmission of infectious diseases assessed the quality of evidence from various sources and considered "epidemiologic evidence of transmission through air over long distances" as very strong evidence of aerosol transmission.⁸ Our study provides such evidence and adds to other sources of existing evidence

Table. COVID-19 Risk Assessment of Different Sections of the Exposed Bus and Between the Exposed Bus and Unexposed Controls^a

Characteristic	Total	No. with COVID-19	% (95% CI)	Risk difference		Relative risk (95% CI)	P value	Relative risk (95% CI)	P value
Exposed bus and other attendees of the worship event, excluding the index patient									
Bus 1	60	0	0 (0 to 6.0)	0 [Reference]	NA	1 [Reference]	NA	NA	NA
All individuals except bus 2	232	7	3.0 (1.3 to 6.2)	NA	0 [Reference]	NA		1 [Reference]	
Bus 2	67	23	34.3 (24.1 to 46.3)	34.3 (23.0 to 45.7)	31.3 (19.7 to 42.9)	42.2 (2.6 to 679.3)	<.01	11.4 (5.1 to 25.4)	<.01
Overall	299	30	10.0 (7.1 to 14.0)	NA					
Different sections of the exposed bus, excluding the index patient									
Classification 1 ¹⁷									
Low-risk zones (rows 1-4, 12-15)	34	9	26.5 (14.4 to 43.3)	0 [Reference]	NA	1 [Reference]	NA	NA	NA
High-risk zone (rows 5-11)	33	14	42.4 (27.2 to 59.2)	16.0 (-6.5 to 38.4)		1.6 (0.8 to 3.2)	.17		
Classification 2 ¹⁸									
Low-risk zones (rows 1-5, 11-15)	44	12	27.3 (16.2 to 42.0)	0 [Reference]	NA	1 [Reference]	NA	NA	NA
High-risk zone (rows 6-10)	23	11	47.8 (29.2 to 67.0)	20.6 (-3.7 to 44.8)		1.8 (0.9 to 3.3)	.09		

Abbreviations: COVID-19, coronavirus disease 2019; NA, not applicable.

^a For exposure-disease categories with 0 counts, we added a value of 0.5 to all cells to calculate risk ratio.

showing experimental infection in animal models through the aerosol route, as well as viable pathogens detected in air at ambient conditions for hours in laboratory media.¹⁴⁻¹⁶

During the aforementioned outbreak, the index patient was the only person exposed to individuals from Wuhan and the first at the event to receive a diagnosis of COVID-19, suggesting a high probability that they were the source of the outbreak. The 2 buses mimicked a quasiexperiment and the second unexposed bus, which left and arrived at the temple at similar times with similar individuals, provided a credible control group. Both buses had an air conditioning system on a recirculating mode, which may have facilitated the spread of the virus in the exposed bus. Attack rates on the exposed and unexposed buses were distinct (34.3% vs 0%), suggesting that the exposure and the environment in which the exposure took place contributed to this outbreak. Additionally, passengers sitting closer to the index patient on the exposed bus did not have statistically higher risks of COVID-19 as those sitting further away. If COVID-19 transmission occurred solely through close contact or respiratory droplets during this outbreak, the risk of COVID-19 would likely be associated with distance from the index patient, and high-risk zones on the bus would have more infected cases. The index patient on bus 2, likely a super spreader of the outbreak, only developed symptoms on the evening after returning from the temple and was asymptomatic during the bus rides, suggesting that individuals with infection may be able to shed virus by breathing and cause secondary cases before they become symptomatic, echoing the findings from earlier presymptomatic reports.^{20,21}

Our findings suggesting that airborne transmission of COVID-19 aligns with past reports of a severe acute respiratory syndrome outbreak on a plane and a recent COVID-19 out-

break in a restaurant.^{10,22} Severe acute respiratory syndrome and COVID-19 are caused by coronaviruses and all 3 outbreaks occurred in relatively enclosed spaces with airconditioned systems. The high attack rate in bus 2 is also consistent with an outbreak of influenza aboard a commercial airliner in which an inoperative ventilation system resulted in a high infection rate among passengers involved in a jet delay.²³ Meanwhile, transmission at the worship event between the bus rides only led to few infections, and all of those reported close contact with the index patient. The worship event occurred largely outdoors. The findings echo a recent study in which aerosolized traces of viral RNA were found in poorly ventilated spaces of 2 hospitals.²⁴ Specifically, their study found the highest aerosol particles concentration in a toilet that lacked ventilation, and we provide epidemiological evidence of a superspreading event resulted from the potential high aerosol particles concentration on a bus. These data suggest that forced, circulating air might play an important role in airborne spread of the virus, and gatherings in enclosed settings with minimal air ventilation should be limited.

Strengths and Limitations

Our study has several strengths. First, the outbreak in this report had a clear index and source patient and we were able to collect detailed information on the environment in which the outbreak occurred and exposure opportunities. Second, the bus outbreak mimicked a quasiexperiment in which 2 buses, 1 with an individual with disease and 1 without, carried similar passengers at similar times, providing a credible unexposed control group. The same outbreak also included an indoor (bus ride) and outdoor component (the worship event) of similar lengths, allowing a comparison between those settings. All

participants were mixed into large crowds at the worship event, but most of the infected cases were from bus 2. The result suggested that the transmission largely occurred in the exposed bus, where a much higher attack rate in a closed environment with recirculating air was observed. The potential role of mechanical air circulation for COVID-19 spread is also supported by a recent study that observed virus-contaminated air exhaust outlets.²⁵ Further, numerous nonairborne transmission options were considered through detailed epidemiologic investigations of the passengers in the exposed bus and their seating information, and the overall possibility was determined low. Therefore, it is hard to explain the lack of difference in the attack rate between individuals sitting close to the index patient and those clearly separated by distance without possible airborne transmission. For instance, cases C5 and C10 seated in the last row were more than 5 m from the index patient on the bus and neither reported direct contact nor sharing of spaces with the index patients during the event, yet they both developed infection. Lastly, the outbreak consisting of a social outdoor event with public transportation is a common daily event, providing potentially greater generalizability to our results.

Our study also has limitations. During the worship event outbreak, alternative sources of infection cannot be ruled out completely. However, there were no confirmed cases in Ningbo city before January 19, 2020 (when the worship event occurred). The first confirmed case of COVID-19 in Ningbo city was reported on January 20, 2020, and the city had a total of 69 confirmed cases by the end of January. Apparently, the outbreak occurred during the early stage of a modest level of disease spread in Ningbo city. Considering that Ningbo is a city with a total population of more than 8 million, the possibility of having more than 1 source patient at the worship event on

January 19 would be quite low. Meanwhile, most secondary cases started to show symptoms after January 21, 2020, more than 2 days after the worship event. The current literatures suggest that presymptomatic transmission often occurs within a 2-day or 3-day window before symptom onset (ie, viral shedding may begin 2 to 3 days before the appearance of the first symptoms).²¹ In addition, no one else on bus 2 had recent travel history to Wuhan or reported being in contact with someone from Wuhan. Considering these factors, the possibility of having another person on the bus who was able to spread the virus at the time of the bus ride was relatively low, if not completely impossible. Our sample size of infected cases within the exposed bus was somewhat limited, which could have contributed to the nonsignificant results regarding the association of distance from the index patient with infection risk. While the high attack rate and the distribution of cases on bus 2 is consistent with airborne transmission, there is no way to rule out a common surface, such as a pole, because of possible insufficient recall. However, given that there were participants with infection sitting in the last row, airborne transmission is likely to be a partial transmission route.

Conclusions

We investigated a COVID-19 outbreak in Zhejiang province and found that airborne transmission likely contributed to the high attack rate seen. The investigations suggest that, in closed environments with air recirculation, SARS-CoV-2 is a highly transmissible pathogen. Our finding of potential airborne transmission has important public health significance, and future efforts at prevention and control should consider the potential for airborne spread of COVID-19.

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