Emerging Evidence on COVID-19

Evidence Brief on the Risk of COVID-19 Transmission in Flight, Update 1

Introduction

What is the evidence on transmission of COVID-19 during air travel and on assessing the risk and mitigation strategies around air travel?

Many changes have been implemented by airlines during the pandemic to reduce the risk of SARS-CoV-2 transmission during air travel. This evidence brief summarizes the literature on in-flight transmission of SARS-CoV-2, the characteristics of these events and the strategies used or studied to mitigate transmission in an airplane or during boarding and disembarkation.

Key Points

- Seventeen flight investigations (contact tracing or cohorts) were identified, of these five reported no secondary cases (two on repatriation and three commercial flights), twelve reported in-flight exposure. Whole genome sequencing results were available for three investigations and aided in linking cases to an on-flight single exposure.
    - No transmission to crew has been reported on repatriation flights.
    - Most in-flight transmission events occurred on flights without mandatory face masks. On flights with mandatory mask use, some transmission events occurred either due to incorrect mask use (e.g. not covering the nose) or perhaps due to removal of mask to eat or drink.
    - Symptom and temperature checks were conducted on some flights. Lack of adherence by passengers to self-reporting symptoms lead to a transmission event in at least one flight.
    - Proximity to an index case was a risk factor in investigations where seating charts were available.
    - One survey of passengers and crew after implementation of enhanced safety measures to curb transmission indicated that both the passengers and crew felt safer and with the exception of inflight physical distancing, most enhanced public health measures were implemented e.g. enhanced cleaning, universal face mask, hand hygiene, physical distancing on embarkation and disembarkation and designated crew only areas as well as quarantine areas for unwell passengers or crew.
- Mitigating the risk of SARS-CoV-2 transmission during air travel was discussed directly in five reviews and risk assessments (Table 2) and indirectly in thirteen reviews, risk assessments, simulation experiments and *in silico* studies (Table 3).

- The key findings of the SARS-CoV-2 literature on transmission during flights is that multiple interventions are needed to maximally reduce the risk of transmission (Table 2) as no single intervention was protective, this is summarized well in the Appendix figure from the Aviation Public Health Initiative report lead by Harvard (1).
    - Public health measures to maintain physical distancing during boarding, disembarkation and in-flight, enhanced cleaning, hand hygiene and universal mask use implemented in a layered approach significantly reduce the risk of transmission.
    - Airplane ventilation systems are designed to quickly refresh cabin air and this level of ventilation substantially reduces the time particles remain in the cabin compared to other indoor environments and thus opportunity for transmission, particularly when coupled with other public health measures (Table 2 & 3).
    - Adherence by passengers and crew are a critical factor to the success of the public health measures to reduce the risk of transmission. This includes adherence to symptom screening guidelines and on-board procedures.
- The indirect literature investigates the aerodynamics of droplets and aerosols to characterize high risk situations, or simulates boarding and inflight movements to suggest strategies for minimizing interaction of people and maximizing the distance between people in flight (Table 3).
    - Passengers who sneeze or cough while standing or moving about the cabin spread their respiratory droplets considerably further than those seated.
    - Wearing a face mask significantly decreased the spread of droplets (>90%) and was less disruptive to the ventilation flow.
    - Boarding an airplane by groups of related individuals, those seated in window seats first as well as other more complicated algorithms were shown to reduce the interaction with other people and decrease the time to board the plane.
    - Grouping families and strategically spacing passengers on flights that are not at capacity improves physical distance between passengers. Algorithms developed by researchers were presented to maximize this concept and demonstrated the potential performance of these algorithms compared to middle seat empty or aisle seat empty strategies. Across all of these strategies, their effectiveness decreased on fuller airplanes.

Overview of the Evidence

The in-flight transmission events recorded across studies were investigated through contact tracing investigations and cohorts. The contract-tracing investigations are at high risk of bias due to their

retrospective and descriptive nature. Cohorts were available for repatriation flights and are at lower risk of bias because the passengers and crew were follow-up in a uniform manner for a specific time period.

Other types of evidence include review literature ranging from good quality systematic reviews to commentaries. There was good agreement in the information and recommendations across the different review literature.

Quantitative risk assessments, simulation experiments and other *in silico* studies were highly variable in their objectives and approaches. No attempt to assess the validity of these studies was conducted. These studies aim to mimic a real world scenario usually to explore options for different interventions. Their results should be interpreted with caution as they may not reflect what would happen in a field setting.

There were only a small number of flights for which epidemiological investigations of possible transmission events had been undertaken. These events are likely under-reported and/or under-investigated due to the logistics and available resources for contact tracing.

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TRANSMISSION EVENTS ON AIRPLANES

There is likely a lot of under-reporting of COVID-19 exposure associated with airplanes. The table below lists 17 studies where in-flight SARS-CoV-2 transmission was investigated, 12 report transmission occurred and five report no transmission occurred during the flights. Several studies of repatriation flights where many precautions were taken report no transmission to the crew (2-4).

Symptom and temperature screening at the airport were mentioned in a few investigations. The failure of individuals to self-report and adhere to the screening guidelines demonstrate that screening is not an effective control measure on its own; it needs to be used in conjunction with other precautions. This is demonstrated well in the business class outbreak reported by Khanh et al. (2020) where one index case caused 15 secondary cases on a flight where masks were not mandatory (5).

Many of the larger transmission events occurred before the mandatory use of facemasks on flights (5-8) or other risk reduction strategies had been implemented. There are also a few instances where transmission events occurred even though face masks were mandatory. Investigations that examined adherence and proper use of face masks in these cases reported both incorrect use of the mask (e.g. not covering the nose) and eating and drinking on the plane for a period of time when the mask was removed.

Outbreaks with seating charts, where available, were able to show the proximity of secondary cases to the index cases, which showed those seated within two rows of the index case were at higher risk of acquiring COVID-19 (5, 9). However there were several cases across the outbreaks that were seated much further away and the mode or circumstance of transmission was not obvious (could have been from movement in cabin, shared restrooms, or fomite transmission) and cannot be confirmed (5, 6, 10).

Across outbreak reports it was frequently mentioned that the window seat should be a safer seat as there are less contacts with other people compared to the aisle seats, however one investigation found that being in a window seat was a higher risk than the aisle seat (6). This was an unexpected finding that the authors could not explain. Table 3 describes studies that look at the potential differences in risk of sitting in different areas and seats on an airplane.

Whole genome sequencing (WGS) was undertaken in three investigations. In all cases it helped to identify cases linked to the same source and, particularly in the Australian investigation, WGS added a layer of information that the epidemiological investigation would have missed (6).

Several limitations are observed across these investigations mainly related to limitations in the data obtained. For example, pre/post flight contacts between index case and secondary contacts could not be excluded (5, 6, 9, 11, 12), or seating location was not known (5, 13).

Table 1: A list of transmission events that have occurred during flights (n=17)

STUDY	METHOD	KEY OUTCOMES
Flights with secondary cases identified		
Murphy (2020) (10) Outbreak Investigation Ireland Jun-Aug 2020	An outbreak investigation into COVID-19 cases linked to an international flight into Ireland in the summer, 2020. Masks were worn by 9 cases, not worn by 1 child case and was unknown for 3.	13 cases were linked to a single international flight (duration 7.5h). The cases had come from three different continents. Only 49 passengers and 12 crew were on the flight. No data on the crew or 11 passengers. Whole genome sequencing showed 5 strains from passengers matched suggesting a single point source of infection. The index case(s) was not identified through the epidemiological investigation, but plausible theories suggest a proportion of cases acquired COVID-19 in-flight. 4 of the flight cases were not seated near a positive case, had no contact in transit, wore face masks in-flight and would not have been considered a close contact.

		A social network is shown to demonstrate how the flight cases spread SARS-CoV-2 to 46 secondary contacts in the community.
Speake (2020) (6) Cluster Investigation Australia Mar 2020	The flight, an Airbus A330-200, on Mar 19, 2020 from New South Wales to Perth (duration 5h) had 28 business class and 213 economy passengers. An epidemiologic and whole-genome sequencing investigation were undertaken. Mask use was rare on this flight and inconsistent.	29 passengers on the flight had SARS-CoV-2, and an additional 35 had compatible symptoms but tested negative. 18 from cruise ships and 10 domestic/international travellers. Based on WGS 18 cases were considered primary: 13 Ruby Princess, 4 Ovation of the Seas and 1 traveller from the US. 11 secondary cases, 3 did not have WGS and were classified as possible, 8 are considered to have occurred in-flight. The 8 did not know each other, 4 from USA and 4 Australians. Among the 11 secondary cases, 8 were within 2 rows of an infected case and 3 were more distant. All secondary cases were from the mid section despite 5 infectious cases in the aft cabin. 64% in were in a window seat, risk ratio 5.2 (95%CI 1.6-15.4). WGS allowed proper attribution of cases to in-flight transmission.
Pavli (2020) (14) Cluster Investigations Greece Feb-Mar 2020	Contact tracing activities of international passengers arriving or departing from Greece Feb 26- Mar 9, 2020. No public health measures were noted.	18 flights with 21 index cases and 891 passengers and 90 crew were traced. Of the 21 index cases, 6 were symptomatic, 12 were pre-symptomatic and 2 developed symptoms 5-7 days after the flight. 5 secondary cases were identified that many have been in-flight transmission from one flight (Israel to Greece, duration 2h) with two COVID-19 cases. The secondary cases were seated within 2 seats of an index case.
Kankh (2020) (5) Cluster Investigation Vietnam Mar 2020	Flight from London, UK to Hanoi, Vietnam on March 2, 2020 (duration 10h). All successfully traced passengers and crew were interviewed, tested and quarantined.	There were 16 crew and 201 passengers. The index case started to experience symptoms the day before the flight, she was seated in business class. 14 passengers and 1 crew were identified as positive during the contact tracing investigation.

	At arrival, there were temperature checks and symptom screening and some countries (not UK) had to undergo SARS-CoV-2 testing. Facemasks were not mandatory on airplanes.	12 were in business class and 92% were seated within 2 meters of the index case and 1 was more than 2 meters, risk ratio 7.3 (95%CI 1.2-46.2). Three other contacts (2 passengers and 1 flight attendant) did not have a close encounter with the index case as they were in economy class.
Choi (2020) (7) Cluster Investigation Hong Kong Mar 2020	A study examining confirmed COVID-19 cases in Hong Kong and travel history identified 4 people that shared a flight from Boston, USA to Hong Kong, China March 9, 2020. The airplane was a Boeing 700-300ER (duration >15h), with 294 passengers. Not all passengers were tested. No mandatory quarantine or airport screening was in place. Use of facemasks was not mentioned.	The cluster included 2 passengers (a married couple) in business class and 2 crew. The couple both had symptom onset on March 10, so they were already infected during travel. The flight attendants developed symptoms March 16 and 18. One of 2 flight attendants spent 5 days in Boston, the other could not be confirmed. Their viral sequences all matched 100% and were not sequences that had been seen in Hong Kong. However, close matches were identified from Toronto, New York and Boston. Based on this analysis the authors conclude it is likely that the couple transmitted SARS-CoV-2 to the flight attendants during the flight.
Hoehl (2020) (9) Outbreak Investigation Germany Mar 2020	102 passengers of a flight from Tel Aviv, Israel to Frankfurt, Germany March 9, 2020. 24 members were from a tourist group that unknowingly at the time had had contact with an infected hotel manager 7 days prior. No preventative measures were taken on the flight. Crew were not followed-up. Antibody tests were offered, however many passengers did not get tested, so additional transmission events may not have been detected.	The tourist group was tested for SARS-CoV-2 on arrival, 7 of 24 were positive. On the flight the 7 positive from the tourist group were symptomatic (n=4), presymptomatic (n=2) and asymptomatic (n=1). 1 of 71 other passengers with follow-up data reported having a positive RT-PCR test 4 days after the flight. 7 of 71 reported symptoms of COVID-19 within 14 days of the flight; one was confirmed with IgG serology and PRNT test. Both confirmed cases are considered likely on-board transmission events, they were sitting within 2 rows of an index case.

Bae (2020) (13) Cohort South Korea Mar 2020	299 passengers were on an evacuation flight from Milan, Italy to South Korea (duration 11 h) March 31, 2020. Medical checks were conducted before the flight, everyone wore N95 respirators except when eating and social distancing was observed on embarkation and disembarkation. All evacuees were under medical observation during a 14 day quarantine with RT-PCR testing on day 1 and day 14.	Based on RT-PCR testing and no development of symptoms, 6 evacuees had asymptomatic COVID-19. One evacuee, who self quarantined for 3 weeks before the flight and then 2 weeks after the flight, had an RT-PCR positive test on day 14 of quarantine in South Korea. The authors suggest her exposure must have been on the flight where she was 3 rows from an asymptomatic case and they shared the same washroom.
Kong (2020) (15) Retrospective cohort China Jan 2020	This paper details the travel and potential transmission of SARS-CoV-2 from an index case in tour group A to 3 other tour groups that were in Europe Jan 16-28. Shared flights and lodging were considered in the epidemiological investigation. Face mask use or other precautions were not mentioned.	Transmission within the tour group (group A) resulted in 13 confirmed or suspected infections and could have occurred on flights, bus or during tours. The first case was hospitalized Jan 22, and others in the group fell ill starting Jan 26. It seems unlikely that transmission from Group A to Group B tour group occurred on a January 16 flight as the 3 cases in Group B were not identified until January 29. It is plausible that transmission from Group A to two others and a tour guide from group C and an independent traveller, occurred on a Jan 28 flight. It is also plausible that transmission from Group A to 3 people in Group D occurred at lodging shared by both groups Jan 22.
Zhang (2020) (16) preprint Cohort China Mar 2020	During the month of March all passengers and crew suspected of being infected with SARS-CoV-2 on 830 international flights bound for Beijing were enrolled (n=4492/ 130000 total passengers). Suspects were quarantined, tested and epidemiological	Of the 4492 suspect cases, 161 became confirmed upon testing (mean age 28·6 years). 94/830 flights (>10%) had a case on it. On one flight Madrid to Beijing (duration 10h 18m), a cluster of eleven COVID-19 cases with a history of close contact were identified. No secondary cases from the passengers within two rows were identified. Two cases may have been exposed on their flight as they did not have a plausible non-flight exposure to COVID-19. Assuming these 2 cases were infected on

	investigations were conducted. Universal face mask use was implemented. It was noted that many passengers were also wearing other protective clothing, gloves and goggles.	the aircraft, the attack rate (AR) was 0.14% (0.0-0.34%) across 94 flights with 14505 passengers. Universal face mask use and airplane ventilation systems were considered protective against transmission.
Yang (2020) (8) Cluster Investigation China Jan-Feb 2020	A flight from Singapore to Hangzhou (duration 5h) carrying 325 people on January 23, 2020. Seat assignments were not obtained, so physical proximity of the index and other cases is not known. Masks were worn by flight attendants, but not by most passengers.	The index case developed a fever on the flight and did not wear a mask, he was identified during disembarkation and tested positive. All passengers were quarantined for 14 days. 11 other passengers developed symptoms and tested positive for an AR=3.4%.
Chen (2020) (11) Cluster Investigation China Jan-Feb 2020	A flight from Singapore to Hangzhou (duration 5h) carrying 335 people on January 24, 2020. The flight was strictly managed because 100 people on the flight were from Wuhan. All passengers were quarantined for 14 days. Face masks were worn on the flight except when eating and drinking.	16/335 COVID-19 cases were diagnosed among passengers, attack rate 4.8%. None of the crew were infected. Only one passenger did not have a plausible epidemiological history of exposure prior to the flight. On the flight, he was seated near 4 infected passengers from Wuhan for approximately 1 hour and did not wear his face mask properly (not tight and nose not covered).
Eldin (2020) (12) Case report France Feb 2020	A case investigation of a French national who developed COVID-19 shortly after returning to France. He had left France February 13 for Bangui, Central African Republic and returned to Marseille, France with his partner on	This investigation suggests that transmission occurred on the flight from Bangui to Yaoundé where French nationals were on the same plane as the first case of COVID-19 diagnosed in Cameroon after the February 24th flight. The case developed symptoms shortly after returning to Marseille France. The flight is the most plausible point of exposure.

	February 24th via Yaoundé, Cameroon.	
Flights with no secondary cases identified		
Cornelius (2020) (2) Descriptive Study USA Jan-Mar 2020	This article summarizes the repatriation of USA citizens by US Department of Health and Human Services air medical evacuation crews.	The study included 39 flights with > 2000 individuals. The article describes in depth the precautions taken to transport many potentially infected individuals. Best practices for IPC during air transport are described in the paper. No cases were identified of emergency workers acquiring COVID-19 during evacuation flights.
Nir-Paz (2020) (3) Cohort Israel Feb 2020	This article describes the repatriation of 11 citizens from the Diamond Princess cruise ship. Before boarding a 13.5 hour flight Feb 20, 2020 all 11 citizens had a negative SARS-CoV-2 RT-PCR test result. Precautions were taken, everyone wore surgical or FFP2 masks and crew had minimal interaction with passengers.	Two of the repatriated citizens (a couple), were SARS-CoV-2 positive upon arrival. Thus, it is assumed that they were infectious on the airplane. No secondary cases were identified among the other repatriated citizens or 4 crew members. Everyone on the flight were observed to wear their face mask except for eating and drinking.
Schwartz (2020) (17) Case reports Canada Jan 2020	Reports on the index case who arrived in Toronto on Jan 22, after taking a 15hr flight from China with 350 people onboard. No public health measures or mask wearing noted.	No secondary COVID-19 cases were identified despite public health follow-up.
Draper (2020) (18) Contact tracing investigation Australia Mar-Apr 2020	Two flights with an infected crew member were identified in Northern Territory, Australia. All 555 passengers were considered close contacts necessitating contact tracing and quarantining activities. There were 28 cases and 527 close contacts over the	Due to a delay in getting manifests, it was almost a week before the flight passengers were notified (n=195 people to quarantine). 326 air passengers from other flights were also monitored with 131 quarantined for being in the same row or within 2 rows of an infected case.

	two months. 94% follow-up rate was achieved. No public health measures or mask wearing noted.	No secondary cases (0%, 95%CI 0-1.1%) from flights were identified.
Qian (2020) (19) Contact-tracing investigation China Jan 2020	12 cases had taken a flight Ningbo to Zhejiang, China following a super spreading event at a temple in Ningbo. No public health measures or mask wearing noted.	Eleven of these cases were linked to the temple; the exposure of one case was unknown, but not considered to have occurred on the flight. No secondary cases are known to have occurred from the flight. The results of contact-tracing investigations identified 88 cases of COVID-19 admitted to five hospitals in Zhejiang province, China.

AR = attack rate

TRANSMISSION POTENTIAL OF SARS-COV-2 ON AIRPLANES

Five citations are included in Table 2, these are a mixed group of review literature, commentaries, reports, a passenger survey and a quantitative risk assessment that examine the risk of SARS-Cov-2 transmission while flying. The report released by the Aviation Public Health Initiative (APHI) October 27, 2020 is the most comprehensive assessment of the risk of SARS-CoV-2 transmission from gate-to-gate (1). This report evaluates the available evidence and considers expert opinion and simulation results in its evaluation of reducing risk transmission of SARS-CoV-2 on flights. They outline why a layered risk mitigation strategy is necessary and the importance of compliance from passengers and the airlines. Similar conclusions and recommendations are described in the other reviews and commentaries in Table 2.

A single passenger and crew survey examined the impact and perception enhanced safety measures to reduce the risk of SARS-CoV-2 transmission gate-to-gate (4). There was positive feedback about implemented changes such as crew only restrooms, frequent cleaning of restrooms, designated quarantine areas on the plane, masking everyone, use of face shields, frequent hand hygiene (alcohol gel provided to all passengers), symptom and temp checks. Passengers reported physical distancing of 1.5-2m could be maintained at checking, pre-boarding and boarding, but not in-flight. Crew reported handing passengers surgical masks, face shields and alcohol gel prior to the flight was impractical due to carry-on luggage.

One risk assessment estimated that a flight in the USA on June 30 had a risk of contracting SAR-CoV-2 of 1/4300 on a full flight and 1/7700 if the middle seat empty policy was in place (These numbers depend on the disease activity in the population) (20). A similar risk assessment was identified for influenza, the influenza model took into account length of flight as well (Table 3) (21).

Table 2: Reviews, reports, passengers survey and risk assessments related to SARS-CoV-2 transmission on airplanes (N=5)

STUDY	METHOD	KEY OUTCOMES
Marcus (2020) (1) Aviation Public Health Initiative Report from the Harvard TH Chan School of Public Health USA[1] Sep 2020[1]	This APHI Report includes data up to September 28, 2020 This research-led guidance report reflects a mixture of literature review, *in silico* models and expert engagement to assess the following question: *In the midst of this complex, novel coronavirus crisis, how can aviation leaders advance an independent evidence-based program to reduce the risks of SARS-CoV-2 disease transmission and with that, enhance the safety and confidence of its workforce and passengers?*	Layered non-pharmaceutical interventions (NPIs) significantly reduce the risk of disease transmission and includes: optimal ventilation, disinfection of surfaces, wearing face masks, procedures to encourage social distancing particularly during embarkation and disembarkation, but also during flight (e.g. no queuing for the restrooms or walking about the plane and minimizing interaction with crew.) Airplane ventilation is highly sophisticated and delivers high amounts of clean air to the cabin which rapidly disperses exhaled air. Crew and Passenger Behavior: Public safety on board and airplane depends a lot on individual behaviours: first health attestations and screening pre-boarding, mandatory face masks, social distancing and orderly conduct to avoid congestion combined with hand washing and cleaning. This is encouraged via the penalty of being on a "no-fly" list for non-compliance. Overall, there is limited data on in-flight transmission, however it appears that a very low number of infections could be attributed to in-flight transmission and there is evidence that NPIs, particularly mask use, resulted in no transmission despite infectious passengers onboard. They describe 13 manuscripts (also included in Table 1) of studying in-flight transmission. Of note, no crew from repatriation flights acquired SARS-Cov-2, a demonstration that adherence to NPIs is effective. Layered risk mitigation strategies can significantly reduce the risk of transmission, but require compliance from passengers and the airlines.
Freedman (2020) (22)	Narrative review of all publications of possible in-	Describes 4 well documented flights, three included in Table 1 (5-7) and the forth is an online inventory of flights to Hong Kong that reported transmission to 2

Literature Review NA[1] Sep 2020[1]	flight SARS-CoV-2 up to Sept 21, 2020. This review summarized transmission events by attributes such as mask wearing on the flight in an attempt to describe and quantify the risk under different scenarios and considerations such as differing incidence rates of SARS-CoV-2 at origin and destination, intensity of viral load in index cases, flight duration, masking practices onboard, pre-flight screening and passenger spacing. There were not enough data points to quantify the risk.	passengers, 1 seated with 5 index cases, masks were used on-board (duration 8 h). 3 single transmission events have been reported, 2 were published (9, 11). 6 high risk flights with no transmission are listed, 1 is published (17). The inventory of flights from Hong Kong lists many flights with positive passengers and no secondary transmission attributable to the flight. 5 evacuation flights of which 3 are published (3, 13) are listed with one possible transmission event. The review states >1.7 million passengers were repatriated by their government or a cruse ship company during the pandemic, few have been documented in the literature. Flight lists with known COVID-19 cases were identified from Canada and Australia. These lists are for other passengers to self identify and isolate. US CDC is also collecting data, but has not published any findings. What risk factors have been identified? Clear clustering of cases where seat plans were available, but some transmission occurred to people > 2 rows from the index case. The flights with large transmission clusters occurred before face masks were mandated on flights and several high-risk flights with no transmission had mandatory masks.
Harris (2020) (23) Commentary NA[1] Aug 2020[1]	How safe is it to fly? This commentary looks at the publications available up to August 2020. Historical outbreaks have been reported for tuberculosis, influenza like illness, SARS-CoV-1.	Ventilation in an aircraft is very good. However it can be disrupted by passengers moving around, coughing etc. Aisle seats tend to have more contact with others compared to a window seat. They suggest following available guidance: wear a well-fitting mask and a face shield or glasses, use alcohol wipes to wipe surfaces, do not congregate or que for the washroom, change seats if near a symptomatic person, avoid drinking and eating if possible.

		Use same precautions in the airport and exercise physical distancing when possible.
Pongpirul (2020) (4) Passenger and crew survey Thailand Apr 2020	This study targeted passengers and crew of two repatriation flights operated by Thai Airways (TG476 from Sydney 9.25h and TG492 from Auckland to Bangkok 11.5h), total 335 passengers and 35 crew. An online questionnaire was administered to get individual feedback about social distancing, mask wearing, and other procedures put in place to reduce the risk of SARS-CoV-2 transmission. In depth interviews were conducted with crew.	Response rate for the online questionnaire was low: 22.5% Several risk reduction measures were implemented and well received. These included crew only restrooms, frequent cleaning of restrooms, designated quarantine areas on the plane, masking everyone, use of face shields, frequent hand hygiene (alcohol gel provided to all passengers), symptom and temp checks. Findings included physical distancing of 1.5-2m could be maintained at checking, pre-boarding and boarding, but not in-flight. Due to carry-on luggage, crew found that handing passengers surgical masks, face shields and alcohol gel prior to the flight was impractical.
Arnold (2020) (20) preprint Quantitative Risk Assessment USA Jun 2020	This risk assessment calculates the risk of SARS-CoV-2 infection resulting from exposure on an airplane. It did not account for loading/unloading, going to the bathroom, length of the flight, and made some assumptions about the "protection" afforded by the seat backs as a barrier between rows. It is based on economy class in airplanes with 6 seats in a row.	Based on the assumptions, the risk of contracting COVID-19 from a nearby passenger on a flight in the USA on June 30, 2020 was about 1 in 4,300 on a full flight. Under the "middle seat empty" policy, that risk falls to in 7,700. These numbers are based on the estimate that 1 in 120 Americans have COVID-19 on a given day, 40,000 confirmed cases per day x 10 x 7 days is about 1/120 of the US population of 330,000,000. They suggest wearing a mask could reduce the risk by 82% (not part of the RA and no reference.)

AIRPLANE VENTILATION AND RESPIRATORY INFECTIONS

Several simulation and *in silico* models have been developed to explore ways to minimize the risk of transmitting and infectious disease on an airplane or during embarkation and disembarkation. There were three studies on boarding an airplane, four on optimal seating patterns to minimize in-flight transmission and four on the aerodynamics of respiratory droplets in an airplane when coughing and sneezing that have been published during the pandemic (Table 3). A single review of these studies up to June 2020 is also listed in Table 3. These studies look at strategies for boarding to minimize passenger interactions and seating plans to maximize distance and interaction with other people. All simulations report on the increased risk as the capacity of the airplane increases. The studies that look at ventilation on the airplane and how coughing or sneezing impacts airflow describe the distance and range of droplets and aerosol from various seats (e.g. window, middle, aisle) and when standing or walking about the cabin, the latter two activities lead to much further spread of respiratory droplets and aerosols (Table 3).

An ECDC systematic review on evidence for influenza transmission (24) reports on transmission during flights reported in the literature with similar findings, low number of secondary cases and seating of a secondary case was usually within two rows of an infected person. Interestingly the length of the flight was not associated with risk of transmission in the studies captured in this review.

Table 3: Studies and reviews that examined the aerodynamics of respiratory droplets on airplanes and infection prevention and control for respiratory infections (n=13)

STUDY	METHOD	KEY OUTCOMES
Simulation and *in silico* models		
Boarding		
Milne (2020) (25) Predictive Model NA[1] Aug 2020[1]	In these stochastic simulation experiments, the authors assess nine adaptations of boarding methods according to four performance metrics. Three of the metrics are related to the risk of the virus spreading to passengers during boarding. The fourth metric is the time to complete boarding of the two-door airplane when apron buses transport passengers to the airplane.	Average boarding time is the comparable measurement between several scenarios. Increased social distance (1m to 2m) = increased boarding time. Increased proportion of people with luggage = increased boarding time. Seating the window seat passengers before aisle seat passengers decreases the risk of seat interference (where the aisle seat has to get up to let the window seat in). Aisle seat risk is higher when social distance is lower (1m), luggage is carried, when boarding is random.

		The author indicates that window seat risk is less than aisle seat risk during boarding, but does not estimate what the difference may be.
Cotfas (2020) (26) Predictive Model NA[1] May 2020[1]	An agent-based model is used to simulate the passenger boarding process, mainly interactions with agents and other people (used NetLogo platform). They model the length of time to board the plane under a number of scenarios and considering hand luggage storage times. The outcome is about length of time already seated passengers come into contact with other people either as they pass by down the aisle or due to having to get up to let a person into the window or middle seat.	Back to Front boarding of the plane took the longest time, but had the lowest health risk in the simulation. The risk is similarly low if a 2-meter social distance is maintained when boarding. Boarding is more efficient and less risky when passengers do not have luggage to store.
Schultz (2020) (27) preprint UK[1] Jul, 2020[1]	A cellular automata model that models the movement of passengers during the boarding process. They do not consider face masks. They model distance to index case and contact time to estimate transmission risk.	The model shows that compared to random boarding of people, boarding groups (e.g. families) together individually will result in the shortest boarding time 41% of the random scenario and least transmission risk 0.09 compared to 0.57-0.62 for any of the random scenarios when the plane is half-full. These boarding times were relatively stable at 75% and 100% capacity; however, transmission risk increased to 0.31 and 0.66 for the boarding in groups, individually scenario.
In flight transmission and seating		
Ghorbani (2020) (28) preprint *In silico* study	The model, Monte Carlo Simulations, optimizes the number of passengers and their arrangements under a social	The figures in the paper depict optimal arrangement of passengers in an airplane. Key to safely increasing the number of

NA[1] Oct 2020[7]	distancing measure for the airline industry for single aisle and double aisle scenarios.	passengers is to group families closely together.
Salari (2020) (29) *In silico* study NA[1] Jun 2020[1]	A mixed integer programming (MIP) model to properly assign passengers to seats on an airplane while effectively preserving two types of social distancing: keeping the passengers seated far enough away from each other and providing a safe distance between seat assignments and the aisle. They use an airbus A320 with 20 row, single aisle and three seats on each side. The MIP model ran a number of scenarios: - Middle seat empty - Social distance of 3.3 ft when seated - Aisle seat empty - Hybrid	If social distance is completely adhered to, no aisle seat use and no one within 3.3ft, the max load is 20 passengers in a 120-seat plane. If passengers can sit in the aisle seat, this increases to 30 passengers socially distanced 3.3ft+. Sitting in the aisle should include strategies to limit movement / possible exposure of people moving around the plane. Middle seat blocking policy lead to less multiple people within 3.3.ft compared to the leave the aisle seat open policy. The more people on the plane, the more people were seated close to each other and thus considered to be in increasingly higher risk situations with 1, 2 or 3+ people within 3.3.ft. See figures for illustration.
Wagner (2009) (21) Quantitative Risk assessment USA[1] Dec 2009[1]	This quantitative risk assessment estimates the possibility of within-flight transmission of H1N1. The simulation uses a Boeing 747.	Even during long flights, a low to moderate within-flight transmission risk if the source case travels First Class. Index sits in first class, • 0-1 infections could occur during a 5-hour flight, • 1-3 during an 11-hour flight, • 2-5 during a 17-hour flight. However, within-flight transmission could be significant, particularly during long flights, if the source case travels in Economy Class.

		Index sits in economy class, • 2-5 infections could occur during a 5-hour flight, • 5-10 during an 11-hour flight, • 7-17 during a 17-hour flight.
Hertzberg (2018) (30) Environmental monitoring study and an *in silico* study USA[1] Mar 2018[1]	During flu season on 10 transcontinental US flights, they chronicled behaviors and movements of individuals in the economy cabin on single-aisle aircraft and did some environmental sampling. They simulated transmission during flight based on these data. This data-driven, dynamic network transmission model of droplet-mediated respiratory disease is unique.	None of the 229 environmental samples were positive. The results indicate there is low probability of direct transmission to passengers not seated in close proximity to an infectious passenger.
Aerosol Simulations on an Airplane		
Silcott (2020) (31) *Unpublished* Simulation experiments USA Aug 2020	The simulations used 767-300 and 777-200 aircrafts/models to study aerosol penetrations by an infected COVID-19 passenger into the area around them. 300 replications were conducted including terminal loading and unloading. Inflight simulations conducted in the hanger and at 35 000ft. This study does not take into account human behaviour e.g. talking, eating, drinking, adherence to mask wearing or other modes of transmission e.g. fomite.	High air exchange rates 1.8 x 10^8 on aircraft. Cumulative particle exposure was 10x less on the airplane compared to a residential house. Particles were in the cabin less than 6 minutes (vs. 1.5h in a house). Air particulate removal was 15x faster than in a house and 5x faster than in a modern hospital isolation room. Surgical masks were used in simulations, there was a >90% reduction in droplets released during the cough simulation compared to no mask. Sharing a row with a COVID-19 case is the highest risk, the row behind and in front are the next highest risk. There was little

		practical difference in risk between seats. See figures in paper. The individual air nozzle did not make a difference to the risk. During embarking and disembarking, keeping the air circulating, loading in small groups may reduce risk. There was low risk of jet wave exposure from an infected person already sitting on the plane.
Kotb (2020) (32) *In silico* study Egypt[1] Sep 2020[1]	In this computational fluid dynamic (CFD) modeling simulation to examine what happens to respiratory droplets when expelled by a sneeze or cough by a person moving around an airplane cabin.	The airflow of coughing and sneezing droplets produced from the moving passengers could reach seated passengers several rows from the source compared to when standing still. Cough distance 1.1m, sneeze went further when standing still. Comparing the droplets spread range resulting from the moving passenger and stand-still one, the quicker the passenger moves, the further the droplets spread. Figures illustrate coughing/sneezing during standing and in motion in an economy class airplane cabin.
Yan, 2020 (33) Simulation experiment Australia[1] Aug 2020[1]	This study developed a computational model to mimic a Boeing 737 economy section with three rows and 9 manikins.	The cough flow was found to have a long and effective impact on contaminants transport, up to 4 s (or 8x longer than the cough). A wide range of sizes of droplets was dispersed in the direction of the cough due to the strong jet-effects of coughing compared to what occurs with ventilated flow (see figures in paper).
Yang (2018) (34) *In silico* study Australia[1] Dec 2017[1]	Using computational fluid dynamics, this study investigated the effect of cough-jet on local airflow and containment transport in a typical airplane cabin. The	The travel distance of cough particles was heavily influenced by the direction and type of cough. The aisle seat person coughing resulted in longer particle travel distance than the middle and window seat.

	particle dispersion from a cough in a three-seat airplane row was simulated.	The middle seat was considered the most at risk of exposure seat.
Reviews		
Jayaweera (2020) (35) Review Sri Lanka[1] Jun 2020[1]	Literature Review on aerodynamics of SARS-CoV-2 in droplets and aerosols – in an Airplane Cabin (see appendix). The section of the review that focuses on airplane cabins.	They describe the flow of air in the cabin and reports a complete air exchange within 2-3 minutes, which should be good for quickly dissipating virus-laden droplets. They also indicate the air is passed through a HEPA filter, which can remove particles >0.3 µm. Cough-jet trajectories with no mask, surgical mask and N95 mask are described in the paper.
Leitmeyer (2016) (24) Systematic Review ECDC[1] Aug 2016[1]	A systematic review was conducted on air travel association with the spread of influenza through infected passengers and potential for in-flight transmission. 14 publication, 11 from H1N1 pandemic were included. The systematic review is high quality and includes studies up to October 2015.	Across studies, 2165/4252 traceable passengers were followed-up and of these 163 secondary cases were identified (7.5% secondary attack rate). 42% were seated within two rows of the index case. The length of the flight was not associated with risk of transmission in this review.

[1] Country of study based on author affiliations and date of study based on publication date.

Methods:

A daily scan of the literature (published and pre-published) is conducted by the Emerging Sciences Group, PHAC. The scan has compiled COVID-19 literature since the beginning of the outbreak and is updated daily. Searches to retrieve relevant COVID-19 literature are conducted in Pubmed, Scopus, BioRxiv, MedRxiv, ArXiv, SSRN, Research Square and cross-referenced with the COVID-19 information centers run by Lancet, BMJ, Elsevier, Nature and Wiley. The daily summary and full scan results are maintained in a refworks database and an excel list that can be searched. Targeted keyword searching is conducted within these databases to identify relevant citations on COVID-19 and SARS-COV-2. Search terms used included: flight or airplane or aircraft or plane. The search netted 507 citations, which were screened for relevance to the review. Additional references to relevant synthesis research not related to SARS-CoV-2 or the current pandemic were identified through citations in articles on the current pandemic and an additional google search was executed October 28, 2020 to identify any new non-indexed reports using (COVID-19 or SARS-CoV-2) AND (flight OR

plane). Potentially relevant citations were examined to confirm it had relevant data and relevant data is extracted into the review.

This review contains research published up to October 28, 2020.

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APPENDIX

NPI table from Marcus (2020) (1) highlights the interventions that can be used together to help minimize the risk of SARS-CoV-2 transmission when flying.

Table 1.1 Non-pharmaceutical Interventions that can be used to Control Transmission of the Novel Coronavirus SARS-CoV-2, where Layering NPIs can create Additive and/or Synergistic Benefits in Reducing the Risk of Exposure to COVID-19 for Passengers and Crewmembers during Air Travel

Phase of Gate-to-Gate Passenger Journey	Non-Pharmaceutical Interventions that can be Layered to Mitigate Risk of SARS-CoV-2 Transmission during Air Travel													
	Section 6.0 Testing & Screening			Section 7.0 Face Coverings			Section 8.0 Process Management		Section 9.0 Cleaning & Disinfection				Section 10.0 Physical Engineering	
NPI Layering Intervention	*Health Symptom Self-screening*	*Temperature Screening*	*Viral Testing*	*Mask*	*Respirator*	*Face Shield*	*Limiting Cabin Service*	*Boarding and Deplaning*	*Cleaning*	*Electrostatic Spray*	*UV Disinfection*	*Anti-microbial Coatings*	*Ventilation*	*Enhanced Ventilation for Boarding/Deplaning*
Preparation of Airplane	–	–	–	++	–	–	–	–	++	++	*	*	–	–
Pre-Boarding	++	++	*	++	–	–	++	++	++	–	–	–	++	*
On Board at Cruise	–	▲	–	++	▲	▲	++	–	++	–	–	*	++	–
Deplaning	–	*	–	++	–	–	–	++	++	–	–	–	++	*

NPIs Non-pharmaceutical Interventions

– Not applicable
++ Recommended
* Desirable/optional
▲ May be appropriate under certain circumstances

Route of Transmission:

- Direct contact with infectious droplets
- Inhalation of infectious aerosols
- Indirect contact with infectious agents contaminating inanimate surfaces (fomites)