

Perspective

In-flight transmission of SARS-CoV-2: a review of the attack rates and available data on the efficacy of face masks

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Highlight

The absence of large numbers of published in-flight transmissions of SARS-CoV-2 is not definitive evidence of safety. All peer-reviewed publications of flights with possible transmission are categorized by the quantity of transmission. Three mass transmission flights without masking are contrasted to 5 with strict masking and 58 cases with zero transmission.

In-flight transmission of SARS-CoV had previously been demonstrated during the symptomatic but not asymptomatic phase of illness. In 2003, up to 22 transmissions occurred on a single flight from a single index case;¹ conversely, several other carefully studied flights resulted in no transmission. SARS-CoV-2, the novel coronavirus that shares 86% homology with SARS-CoV, differs in having both significant transmission from pre-symptomatic and asymptomatic persons as well as secondary cases that may remain asymptomatic even with a 14-day follow-up period. At the same time, cases secondary to in-flight transmission may be detected in as few as 3 days post-flight. As timing is so critical, the burden of absolute proof for ascertaining in-flight transmission risk is high. A possible secondary case, who presents with COVID-19 symptoms, or is detected as an asymptomatic person with a positive COVID-19 PCR several days after arriving at their destination, could have been infected: (i) in the days before departure from the flight origination point; (ii) en-route to the airport; (iii) while at the airport; (iv) on the flight or even (v) on/after arrival at the destination airport.

This review presents a comprehensive table summarizing all peer-reviewed or public health publication of flights with likely, possible or unproven in-flight SARS-CoV-2 transmission from 24 January 2020 to 21 September 2020. The Table is ordered and categorized by the quantity and certainty of transmission. The order is not chronological due to variation in intensity and pandemic onset date in the various flight origin countries; a separate column describes SARS-CoV-2 incidence in the origin country at the time of the flight.

Generally, quantitation of risk is imprecise and must account for many variables, including 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. In the disruption of the pandemic, the opportunities for rigorous studies have been few, experienced that public health epidemiologists with experience with in-flight outbreak investigations have been otherwise occupied, and the sparse published literature is confounded by limited formal documentation of needed epidemiological facts around apparent secondary cases. Foremost, the human and financial resources to trace, interview and test hundreds of passengers from a flight have been lacking. Governments and the very large travel industry may face economic and political considerations in supporting overly detailed investigations.

Reported Mass Transmission Events (> 1 secondary case)

Four well-documented flights (Table 1) describe mass transmission events. Flights A and C present sophisticated proof from whole genome sequencing and provide essentially indisputable evidence of in-flight transmission to 11 and 2 secondary cases, respectively. Immediately pre-flight infection of the secondary cases is theoretically possible but highly unlikely given identical sequences with the index cases. Flight B with at least 15 secondary cases lacks genetic proof, but at the time (March 2) of the London–Hanoi flight, neither the UK nor Vietnam

had more than a handful of sporadic cases. Flight D arrived in Hong Kong, which since April has had mandatory arrival PCR testing on Day 0 and Day 14 with quarantine in between; 27 passengers were PCR+ on Day 0 <<https://wars.vote4.hk/en/cases>> (11 September 2020, date last accessed). Two likely secondary cases (one seated in Row 40 with 5 index cases) had negative Day 0 PCR testing and were PCR+ on Day 14; pre-flight transmission shortly before the relatively short flight cannot be ruled out. Of note, Emirates airlines had extremely strict pre-flight screening, in-transit screening and masking procedures on board (meals were served) in place at the time of this flight with an enormous number of COVID-19 cases during an 8-hour flight.

Evacuation/repatriation flights

Once international border controls began, thousands of chartered evacuation flights with >1.7 million passengers were organized mostly by the repatriating government or a cruise line. Since 29th January, the US Government alone has helped to coordinate the repatriation of at least 85 000 Americans on 881 flights <https://en.wikipedia.org/wiki/Evacuations_related_to_the_COVID-19_pandemic>. A number of these flights have carried COVID-19 cases,⁵ but no national databases or unified international registries documenting evacuation flights or their passenger loads are publicly available, and few data have been published to date. The Korean CDC (Flights E and F) managed such flights meticulously and has published well-documented data on these. The one secondary case from a clearly documented total of 6 index cases on Flight E had quarantined alone for 3 weeks prior to the flight, and her socially distanced path to the aircraft from home was managed by the Korean CDC. On-board, she and all other passengers were masked (except for meals) but she did use a specific lavatory that had been used by an index case. No transmission was found from 2 PCR+ index cases on a small jet (Flight G) repatriating 9 other masked PCR negative Israeli evacuees from the Diamond Princess. No follow-up data are yet available for any possible secondary cases during the repatriation of 300 masked US evacuees from the Diamond Princess (Flight H) <https://omaha.com/news/local/people-some-of-whom-have-tested-positive-for-coronavirus-quarantined/article_0c9c09f9-a6ff-5b83-8a59-6cf3a0b2041e.html> where 14 PCR+ evacuees were seated in a separate section of the aircraft or from the Costa Luminosa (Flight I).

Possible Single Transmissions with Weak Evidence

Incomplete epidemiologic evidence to determine likelihood for 3 proposed in-flight transmissions (Flights J, K and L) <<https://www.taiwannews.com.tw/en/news/3916558>> is available.

High-Risk Flights with no Evidence of Transmission

Very early in the pandemic, a flight from Wuhan to Toronto (Flight M) with 2 passengers of 350 PCR+ on arrival had no secondary transmission; however, only active follow-up of flight passengers for symptom development and not systematic PCR was undertaken. The strongest evidence that in-flight transmission is not inevitable even with large numbers of infected persons

aboard comes from a unique public database maintained by the government of Hong Kong <wars.vote4.hk/en/cases>. All PCR+ patients are displayed with arrival date, flight number and date of the positive PCR test. Between 16th June and 4th July, 5 separate Emirates airlines flights with 7 or more passengers with positive PCR tests on Day 0 arrived in Hong Kong (Flights N–R). No secondary cases were identified on Day 14 screening despite 58 passengers who were PCR+ on the 5 flights each of 8-hour duration with a total of ~1500–2000 passengers. At the time of these flights, Emirates had strict in-flight masking protocols (meals were served). The Hong Kong database consists of single passenger case reports for hundreds of flights with passengers who tested positive at Day 0 or Day 14 and should be the subject of further analysis.

Lack of Published or Public Data on Flights with Proven COVID-19 Cases

As two examples, Canada <<https://www.canada.ca/en/public-health/services/diseases/2019-novel-coronavirus-infection/latest-travel-health-advice/exposure-flights-cruise-ships-mass-gatherings.html>> and Australia <<https://www.health.nsw.gov.au/Infectious/covid-19/Pages/flights.aspx>> have long public lists each containing >1000 flights with a documentation of having retrospectively known COVID-19 cases on board. In each of these countries, the flight information and seat row numbers of known cases are kept live for 2 weeks in order to encourage other passengers who self-identify to self-isolate or get tested; however, no available information on any secondary cases in other passengers is posted. Public health authorities in other countries have similar lists, but analyses of these databases have yet to be published. The USA presents a more difficult landscape for such analysis, as high background infection rates obscures the determination of place of acquisition. US CDC has stated awareness of 1600 cases on US flights and 11 000 contacts within 2 rows but has not yet published in-flight transmission estimates.

Data on known cases in flight crew are mostly available only to the airline medical departments and infection may have been acquired anywhere off or on-duty, but such data are regarded as protected private health information by most airlines. No aggregate data with de-identified statistics for flight crew have been published.

Case Clustering-Proximity to Index Cases

The 3 major, and best documented in-flight transmission events, Flights A–C had clear case clustering (see Table 1 for details). Cases in flight A were restricted to a small area of the mid-cabin on an A330 widebody aircraft. On Flight B, the single index case sat in Business Class and the attack rate for the remaining passengers, 11/12 of whom were sitting within 2 rows was 62%. On Flight C, both index cases were in Business Class and transmitted to flight crew. Seat plans were not available for all flights in the table, but a minority occurred more than 3 rows from any index case; the 2-row rule for contact tracing may need to be re-visited. This review focuses on the epidemiology of actual documented human transmission. Cabin airflows, cabin aerosolization and filtration parameters of aircraft ventilation systems are beyond our scope. The overall published data, as

Table 1. Summary data on peer-reviewed or public health publication of flights with suspected or possible in-flight SARS-CoV-2 transmission from January 2020 to 21 September 2020

Arrival date	Origin–destination transmission levels	Flight # origin–destination aircraft type total Pax	Number Pax likely infected pre-departure	In-Flight transmissions level of likelihood	Quarantine and testing protocols on arrival	Seat location of secondary cases	Masking-result	Comments
Mass transmission events (> 1 secondary case)								
A ² 19-March	Large outbreak on Ruby Princess cruise ship. Almost no local transmission in Australia on date of flight with disembarked passengers	QF 577 Sydney–Perth A330. 28 Pax in business; 213 in economy	13 PCR+ symptomatic index cases came directly from the Ruby Princess. 9 classified as infectious during flight	11 certain transmissions no other plausible exposures	After initial index cases identified, other PAX notified to quarantine. Testing only of those coming forward. 11 Ruby Princess index cases had the same strain not previously recorded (A2-RP) by WGS	Secondary cases all within 12 rows in the mid-cabin 3 secondary cases more than 2 rows away from a primary case	Rare—mass transmission	Proven by WGS. Likely underestimate as no systematic post-arrival testing of asymptomatic flight Pax. Unique sequence likely originated on ship. US passengers on flight had just arrived in Sydney. 5 other primary cases on flight from other ships had different sequences. No investigation of in-flight movements. No other cases symptomatic on arrival. Only 4 cases remained asymptomatic throughout Proven by WGS. 2 index cases and 2 flight attendants identical whole genome sequences, not seen before in Hong Kong Secondary cases both PCR negative D0 and had passed temperature and symptom screening in Dubai. Pre-flight transmission possible
B ³ 2-March	Only 23 total UK and 16 total Vietnam cases prior to flight date.	VN54 London-Hanoi B787 21 Pax in business; 180 in economy	1 PCR+ highly symptomatic index case in Business Class on arrival, contact of a known case (exposed while in Italy)	15 highly likely transmissions. 12 in Business Class (62% attack rate), 2 economy, 1 flight attendant.	All Pax home quarantined, tested on D3, D5 and D13. 15 secondary cases PCR+ by D5.	11/12 Business class secondary cases within 2 rows of index case. Economy cases 15 rows distant	Optional—mass transmission	No investigation of in-flight movements. No other cases symptomatic on arrival. Only 4 cases remained asymptomatic throughout Proven by WGS. 2 index cases and 2 flight attendants identical whole genome sequences, not seen before in Hong Kong Secondary cases both PCR negative D0 and had passed temperature and symptom screening in Dubai. Pre-flight transmission possible
C ⁴ 10-March	Early onset of outbreak in Toronto and Boston visited by index cases.	CX811 Boston-Hong Kong B777 Unknown Pax# in 274 seats	2 Pax (couple) symptomatic on arrival day	2 highly likely transmissions to flight attendants tested after contact tracing of index cases	No arrival quarantine or testing in place. Index cases PCR+ D5 when hospitalized.	Index couple in adjacent business class seats served directly by 1 flight attendant.	Optional—mass transmission	Proven by WGS. 2 index cases and 2 flight attendants identical whole genome sequences, not seen before in Hong Kong Secondary cases both PCR negative D0 and had passed temperature and symptom screening in Dubai. Pre-flight transmission possible
D 20-June wars.vote4.hk/en/cases	All infected Pax originated in Pakistan during peak of transmission.	EK380 Dubai-Hong Kong B777 Unknown Pax# in 360 seats	27 PCR+ all asymptomatic on arrival	2 likely transmissions; PCR+ on D14	Observed quarantine with testing of all Pax on D0 and D14	1 sitting in Row 40 with 5 index cases; 1 in isolated location	Mandatory—mass transmission. Meals served.	Proven by WGS. 2 index cases and 2 flight attendants identical whole genome sequences, not seen before in Hong Kong Secondary cases both PCR negative D0 and had passed temperature and symptom screening in Dubai. Pre-flight transmission possible

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Table 1. Continued

Arrival date	Origin-destination transmission levels	Flight # origin-destination aircraft type total Pax	Number Pax likely infected pre-departure	In-Flight transmissions level of likelihood	Quarantine and testing protocols on arrival	Seat location of secondary cases	Masking-result	Comments
Chartered Evacuation Flights: Hundreds of flights totalling >200 000 Pax, little published data to date								
E ⁶ 31-March	From Italy at peak 1st wave transmission	Evacuation Milan-Seoul B747 299 Pax	6 PCR+ on arrival Seoul. 11 symptomatic denied boarding	1 likely transmission.	All Pax quarantined and tested on D0 and 14. 6 PCR+ asymptomatics on D0; 1 on D14	No index cases within 6 rows; shared specific lavatory with an index case	Mandatory – 1 likely transmission. Secondary case masked except during meals and in lavatory CDC.	Secondary case quarantined alone for 3 weeks pre-departure, private ground transport, screening/pre-boarding/distancing outside airport terminal by Korean CDC.
F ⁶ 3-April	Italy at peak of 1st wave transmission	Evacuation Milan-Seoul 205 Pax	3 PCR+ on arrival in Seoul.	1 possible transmission.	All Pax quarantined and tested on D0 and 14. 3+ on D0; 1+ on D14		Mandatory (except during meals)—1 possible transmission.	No pre-departure or in-flight detail on 1 possible case. Pre-departure as above.
G ⁷ 20-February	Diamond Princess Pax	Evacuation Tokyo-Tel Aviv Galaxy 6000. 11 Pax 3 crew	2 asymptomatic PCR+ on arrival	No transmission	All Pax quarantined and tested 6 times over 14 days. 0 additional positive at D14.	Index cases were seated in back rows behind everyone else.	Mandatory (crew FFP2, Pax surgical except during 2 meals)—no transmission.	Small cabin, ventilation different from large aircraft
H 17-February	Diamond Princess Pax	Evacuation Tokyo-Travis AFB California B747 300 Pax	14 PCR+ asymptomatic diagnosed pre-departure	No post-arrival data available	All other Pax quarantined on Air Force bases and tested once	PCR+ positives seated in separate area of aircraft	Mandatory	Post-arrival testing not yet published.
I 20-March	Costa Luminosa Pax	Evacuation Marseille-Atlanta 300 Pax	3 known PCR+ enroute; 10 other Pax obviously ill (media reports)	No post-arrival data available	Asymptomatics continued on domestic flights. Disposition of symptomatics and known PCR+ unknown	3 PCR+ separated from others enroute after test results became known	Optional	Post-arrival testing not yet published
Published Flights with Possible Single Transmissions								
J ⁸ 24-January	15 index cases infected in Wuhan prior to 19-January departure or during group tours with others from Wuhan. 0 cases in Singapore that week. Case #16 from Hangzhou.	Singapore—Hangzhou B787 335 Pax	16 PCR+ Pax on first testing D2	1 possible transmission. PCR+ D2	Quarantine and PCR at D2, D12 for all Pax	1 possible case spent 1 hour seated between 4 index cases	Mandatory—1 possible transmission. Possible secondary case took off mask to talk for 1 hour	Possible transmission to #16 on flight with an incubation period of just 2 days. From China not Wuhan but no others in his Singapore tour group positive

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Table 1. Continued

Arrival date	Origin-destination transmission levels	Flight # origin-destination aircraft type total Pax	Number Pax likely infected pre-departure	In-Flight transmissions level of likelihood	Quarantine and testing protocols on arrival	Seat location of secondary cases	Masking-result	Comments
K ⁹ 9-March	14 cases/day in Israel. 100 cases/day Germany.	Tel-Aviv-Frankfurt B737 102 Pax	7/24 in same tour group visiting Israel. PCR+ on arrival. Group had contact with confirmed COVID case prior to flight.	1 unproven transmission. 1 non-tour group member self-reported PCR+ test at D4; not tested at D0 and had IgG at 7 weeks. Another non-group member IgG+ at 9 weeks (no previous testing)	No quarantine for non-tour group members	Proposed in-flight cases seated in same or row between index cases	Optional—1 unproven transmission	Authors denote as likely transmission. Few details on epidemiologic background of Pax
L 30-March	#12 spent 2 months in New York at outbreak peak prior to flight. <10 daily cases in Taiwan.	CI 11 JFK-Taipei 340 Pax	11 symptomatic Pax PCR+ on arrival	No proven transmission. Possible case #12 PCR+ D15 developed symptoms D7.	Negative PCR at D14 in all other Pax	Unknown	Mandatory—no likely transmissions	In-flight transmission cannot be ruled out but high-risk pre-flight exposure
Published High-Risk Flights with no Evidence of Transmission								
M ¹⁰ 22-January	Peak of Wuhan outbreak	Wuhan-Toronto 350 Pax	2 PCR+ (couple) 1 symptomatic/1 asymptomatic on flight.	No transmission	Home quarantine of Pax within 2 rows with 14 days close monitoring for symptoms by public health	Not applicable	Optional—no transmissions.	No post-arrival PCR testing of asymptomatic Pax or Pax within 2 rows of couple.
N-R 16, 21, 23-June and 3-4-July (5 flights) www.vote4.hk/en/causes	Almost all Pax originated in Pakistan during peak of transmission.	EK380 Dubai-Hong Kong B777. Unknown Pax# per flight. 360 seats available per flight	10, 19, 13, 9, 7 PCR+ on arrival. 0, 1, 4, 1, 0 symptomatic on arrival; rest asymptomatic.	No transmissions on any of the 5 flights	Observed quarantine with testing on D0 and D14	Not applicable	Mandatory—no transmission was documented with robust testing of all Pax at D14. Meals served.	All Pax had passed temperature and symptom screening in Dubai 4 hours earlier

Abbreviations: WGS = whole genome sequencing; Pax = passengers; Pax# = number of passengers; D0 = flight arrival date; D2 = two days post-arrival, etc.

incomplete as it is, support the concept of proximity to a SARS-CoV infected person as a key factor in in-flight transmission.

Masking

On Flights A–C, with mass transmission events, masking was not mandated in any way and, according to the published reports, was rarely practiced. On Flight D, with 25 passengers PCR+ on arrival but with rigid masking, there were only 2 transmissions and 1 was seated in Row 40 next to 5 index cases. On flights N–R with the rigid masking policies (meals served) of Emirates Airlines, no secondary cases were identified on Day 14 screening despite 58 passengers who were PCR+ on a total of 5 flights of 8 hours each with ~1500–2000 passengers. In-flight masking became mandatory in Canada on 4th June and in Australia on 22nd July. Even with the incomplete contact tracing and testing to detect secondary cases available, aggregate figures on in-flight transmission before and after masking would be informative.

Future Directions

The absence of large numbers of confirmed and published in-flight transmissions of SARS-CoV-2 is encouraging but is not definitive evidence that fliers are safe. Limited data dissemination to date, which may be partly related to current economic or political circumstances, has resulted in only a slow return towards a normal volume of commercial flights. The circumstances for robust study have been too few among the disruption of the pandemic to know with precision the risk and factors needed to quantitate transmission under widely varying circumstances. At present, based on circumstantial data, strict use of masks appears to be protective. Structured prospective studies to quantitate transmission risk on flight with rigid masking protocols are now most pressing. At the same time, those with robust data on in-flight transmission in the days prior to on-board masking should come forward and publish these data.

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Conflict of interest

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