



Published in final edited form as:

J Travel Med. 2025 November 23; 32(7): . doi:10.1093/jtm/taaf090.

Measles transmission risk during commercial air travel

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Abstract

This work is written by (a) US Government employee(s) and is in the public domain in the US.

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†This author's work was supported in part by an appointment to the Applied Epidemiology Fellowship Program administered by the Council of State and Territorial Epidemiologists and funded by the Centers for Disease Control and Prevention Cooperative Agreement Number 1NU38OT000297-03-00

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Protocol registration

Prospero protocol number 16740, accessible at https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=516740

Conflict of interest: The authors have declared no conflicts of interest.

Disclaimer

The findings and conclusions of this report are those of the authors and do not necessarily represent the official position of the Centers for Disease Control and Prevention.

Background: Measles transmission on aircraft has been well-documented, and many countries perform contact investigations after exposure events during air travel. This review summarized and updated available evidence for measles transmission risk during commercial air travel to inform best practices for public health response after such exposures.

Methods: We searched eight databases for articles and pre-prints about measles and air travel published during 2004–2023. Reviewers screened for articles that contained primary data about measles exposure events on commercial flights. Two reviewers used a piloted data extraction template to collect information from each article, including flight characteristics, approach to contact investigation, and outcomes. Risk of bias was assessed using the Mixed Methods Appraisal Tool.

Results: The initial literature search identified 196 articles, of which 19 met the inclusion criteria. These articles described contact investigations performed for ≥ 182 flights, which identified 70 secondary cases associated with 144 index cases. In articles where the contact investigation did not include the whole plane, many secondary cases were seated outside the contact zone, as defined by the investigation. Among secondary cases where vaccination status was known, 73% (40/55) were unvaccinated, and vaccination rates among cases < 18 years of age were especially low (3/18, 17%). Uptake of post-exposure prophylaxis was low in the few articles that reported this information.

Discussion: Measles transmission on aircraft is an established risk, especially for persons that are unvaccinated, and can affect passengers seated outside of the rows immediately around the index case. The available information suggests many barriers to provision of post exposure prophylaxis, and routine vaccination likely remains the best protection against measles outbreaks associated with air travel. However, most studies were designed and reported in a way that did not support robust analysis of the best approaches to contact investigation or the most effective way to prevent secondary cases.

Keywords

Measles; air travel; transmission risk; border health

Introduction

Endemic measles was declared eliminated from the United States in 2000, but imported cases associated with international travel remain an important source of outbreaks.¹ Measles virus is highly contagious, and transmission during air travel has been well documented,^{2,3} despite high rates of air exchange in modern commercial aircraft.⁴ Persons with measles are infectious for up to 4 days before rash onset, so informing contacts of their exposure increases awareness and can prevent ongoing community transmission by encouraging asymptomatic exposed persons to immediately isolate and seek care if they develop prodromal signs. Post-exposure prophylaxis (PEP) is available in the form of vaccination or immunoglobulin administration and is effective if given within 3 or 6 days (respectively) of exposure. Measles cases have increased worldwide in recent years, including in countries like the United States where measles has been eliminated.^{5,6} This is expected to result in

a corresponding increase in the number of exposure events on aircraft during domestic and international air travel that require public health intervention.

U.S. Centers for Disease Control and Prevention (CDC) coordinates aircraft contact investigations after measles exposure events on aircraft. Eligible flights include any domestic or inbound international flight carrying an infectious person, regardless of the length of the flight. Modern aircraft have high rates of air turnover, and airflow is directed from the center aisle(s) to the sides of the plane, thus limiting shared air between passengers seated more than a few rows apart.⁷ For this reason, a common starting point for infectious disease contact investigations is to consider travellers seated within two rows in front of or behind the index case to be exposed.⁴ However, because measles is so transmissible, the size of the contact zone CDC uses for measles has been expanded several times since the United States first began conducting measles aircraft contact investigations in 2005. In the current protocol, the contact definition for large aircraft includes: (i) all passengers seated in the same row as the index case and those seated within two rows in front and behind, (ii) all infants in arms on the plane, and (iii) all cabin crew that served the index case. For smaller aircraft (passenger capacity ≤ 50) or airlines with unassigned seating, all passengers and flight crew are considered contacts. The evaluation of individual contacts is conducted by state, local, and territorial health departments, and decisions about whether to offer PEP are determined by the individual jurisdiction's protocol.

Other high-income countries where measles is uncommon also take public health action when persons with measles travel while infectious,^{8–10} but the details of the protocols vary by country, and many grant health departments discretion to adjust their approach based on individual circumstances and resource availability. For example, the European Union's RADIGA guidance states that all passengers and crew should be considered at risk but presents a prioritization scheme based on age, vaccinations status, and seating location if resources are limited.⁹ The United Kingdom Health Security Agency advocates a 'warn and inform' approach that focuses on mass communication to all persons potentially affected in lieu of more targeted contact tracing.⁸

The logistics of aircraft contact investigations are complicated, and challenges such as difficulty obtaining timely, accurate contact information from airlines, inability to verify contact vaccination history, and reluctance of contacts to accept PEP may compromise the public health benefit of this activity. There is also a dearth of evidence-based recommendations about how large the area of the aircraft used to define close contact (the contact zone) should be and which contacts should be prioritized for intervention.

Two recent systematic reviews of measles transmission on aircraft covered literature published from 1946–March 2012 (Edelson³) and 2001–2013 (Jost *et al.*²). Jost *et al.* identified 132 index cases that led to 47 secondary cases and found that transmission was more likely if the index case was young or if there were multiple index cases on the same flight. Edelson's review focused on the role of a contact's location in the plane relative to the index case, with the goal of informing the selection of an appropriate contact zone. Among the studies included, the median distance between the index and secondary cases was six rows, with the farthest seated 17 rows away from the index case. Shortly after this study

was published, the maximum passenger capacity for aircraft requiring a whole-plane contact investigation under CDC protocols was increased from 30 to 50.

This systematic review seeks to summarize and update available evidence for measles transmission risk during commercial air travel to inform best practices for conducting measles aircraft contact investigations.

Methods

A CDC librarian designed customized search strategies for eight databases (Medline, Embase, Global Health, Cochrane Library, CINAHL, Scopus, Epistemonikos, and Global Index Medicus), focusing on keywords related to measles transmission and air travel (Box 1, Supplemental Table 1). The search was limited to published articles and pre-prints from 2004–2023. No restrictions were placed on publication language. The resulting article lists were imported into a reference management software (EndNote, Clarivate, Philadelphia, PA) for deduplication. The reference sections of review articles identified in the initial search were reviewed for any additional articles that met the search criteria.

The deduplicated article list was imported into a cloud-based systematic review software (Covidence, Melbourne, Australia), where each article was reviewed and evaluated by two reviewers to determine whether inclusion criteria were met. To be included, articles needed to contain primary data on measles exposure events on commercial flights for which contact investigation was performed. Review articles, editorials without primary data, and modelling studies were not included. Initial screening comprised title and abstract review and, if the article met inclusion criteria or if eligibility could not be determined, full text review was performed. Discordance between the two reviewers about eligibility were resolved through discussion with the larger group until a final determination was reached. Articles that were deemed eligible after full text review were advanced to the data extraction phase.

Two reviewers used a data extraction template to collect information about each article, including flight characteristics, approach to contact investigation, and contact data (vaccination history, disease status, PEP). Some articles were primarily focused on community spread of measles after transmission on a plane; for these articles, we included only data clearly identified as coming from aircraft contacts. We also explored whether articles reported cases as co-travellers of the index case (e.g. household members, same tour group); if they did not, we assumed secondary cases had no association with the index case. If the article described an index case whose itinerary included several flights, but contact investigation was not performed for all, the first country in the index case's itinerary was still listed as the origin. There were several instances where overlap between articles was suspected. If there was enough detail (e.g. flight itineraries, demographic information) to be certain that two articles were describing the same index and secondary cases, these cases were only counted once. If there was uncertainty, the cases were treated as separate.

Because most of the articles included in this review did not have a comparator group, the risk of bias was assessed using the Mixed Methods Appraisal Tool (MMAT).¹¹ If a study included a comparator (non-exposed group), it was considered quantitative non-randomized,

and if it did not, it was considered quantitative descriptive. Studies were considered to include a comparator group if they defined a contact zone and included any outcome data for persons outside that contact zone (even if that outcome data was acquired passively). If a study did not define a contact zone, it was assumed that there was no comparator group. The MMAT questions were used as written, except for question 3.4 ('Are the confounders accounted for in the design and analysis?'), where the answer choices were modified to include 'partial yes' if the study addressed some, but not all, pre-specified confounders. Specific confounders considered included the contact's age, vaccination status, and travel history. Discrepancies between reviewers during the data extraction and risk of bias assessment phases were resolved through group discussion. For question 4.5 ('Is the statistical analysis appropriate to answer the research question?'), if a study was not designed in a way that supported conducting more complex statistical methods, but the manuscript reported basic descriptive statistics (including the number of secondary cases among air travellers and the number of persons exposed), reviewers were instructed to respond 'Yes.'

Results

Literature search

The initial literature search identified 194 articles and two additional relevant articles were identified from the reference sections of review articles (Figure 1). Eighty-five duplicate articles were removed and 111 articles advanced to the screening phase. Of those, 77 were excluded based on title and abstract review and 34 continued for full text review. Of those, 15 articles were excluded (10 because they were modelling studies or studies without primary contact tracing data, and five because the exposure setting was not a commercial flight or it was unclear if exposure occurred on the plane), and 19 met the inclusion criteria and were included in the systematic review.

Exposure events and approaches to contact investigation

The 19 articles described at least 182 flights where some form of measles contact investigation was performed (three articles did not clearly describe the number of flights investigated¹²⁻¹⁴; Table 1) in response to 144 index cases. Most reports included only one or two flights (median = 1.5, mode = 1) and focused on a single outbreak or series of related outbreaks. Two reports^{15,16} were aggregate analyses of all measles contact investigations performed in a single country over a defined period. Flight duration was often not reported (13/19, 68%) but ranged from 40 minutes to 19 hours when reported. Except for the two aggregate articles, each study included 1–3 index cases.

Five articles (5/19, 26%) did not describe the contact definition used for the investigation. Among those that did define a contact zone, eight (8/14, 64%) indicated that this contact zone was selected based on national guidance (4 from Australia, two from the European Union, and two from the United States) and 1 indicated that practical considerations forced them to deviate from guidelines. Six articles (6/14, 43%) defined the contact zone as the entire plane. Seven articles (7/14, 50%) defined the contact zone as all passengers seated within two rows in front of and behind the index case, with or without the inclusion of

other higher-risk groups (infants, cabin crew). One (1/14, 7%) aggregate study reported different contact definitions depending on the size of the plane.¹⁶ Among articles where the contact zone did not include the entire plane, five (5/8, 63%) reported limited outcome data for secondary cases that occurred outside their defined contact zone, but none performed systematic follow-up for travellers outside the contact zone.

Outcomes

Seventeen articles (17/19, 89%) reported at least one secondary case. Together, these 17 articles reported a total of 70 secondary cases, of which 49 (70%) occurred in persons within the contact zone defined by the study and 21 (30%) occurred in persons outside the contact zone. No articles explicitly reported whether secondary cases had been co-travellers of index cases; however, most articles had context clues within their narrative description of case investigations suggesting that the index and secondary cases were not travelling together.

Only two articles reported any analysis beyond descriptive statistics. Hoad *et al.*¹⁵ reported the risk of acquiring measles if seated within two rows of an index case as 0.68% among passengers seated within two rows in front of or behind the index case. Nelson *et al.*¹⁶ reported lack of immunity (or unknown status) and presence of multiple index cases as factors that increased the odds of a contact developing measles (adjusted odd ratios: 18.9 and 9.1, respectively).

Only one article reported demographic information or vaccination history for non-cases, and this article did not report any secondary cases.¹⁷ Of the 41 secondary cases for which age was reported, 56% (n = 25) occurred in children < 18 years old. The vaccination status of 15 secondary cases (15/70, 21%) was either unknown or not reported in the article. Among the 55 secondary cases whose vaccination status was reported, 73% (n = 40) were unvaccinated. Among the 15 secondary cases that were considered vaccinated, 11 (73%) were reported as either having two doses or being 'fully vaccinated' and four (27%) had received at least one dose or were described as 'partially vaccinated.' Among the 32 secondary cases where both age and vaccination status were known, vaccination rates were 17% (3/18) among children and 36% (5/14) among adults. Of the 15 paediatric cases reported to be unvaccinated, six were among infants < 12 months old, who may not have been eligible for vaccination, depending on the vaccine recommendations in their country of origin. One article reported age and vaccination status of secondary cases separately; the secondary cases from this article were considered to be of unknown age for calculation of vaccination rates by age group.

Seven articles mentioned offering PEP to some contacts, but none of the articles specified how many of these contacts were considered eligible for PEP. Three did not provide any information about how many contacts actually received PEP^{12,15,18} The remaining four^{14,16,17,19} reported a combined total of 23 contacts receiving some form of PEP; while these articles did not report the number of contacts that were offered PEP, the number receiving PEP represented < 1% (23/3062) of the total contacts identified in these articles. Challenges reported included difficulty reaching contacts within the required 6-day window, inadequate information to assess pre-existing immunity, and low uptake among eligible contacts.

In addition to 70 secondary cases exposed on aircraft, four articles^{19–22} also reported 10 secondary cases that were believed to have occurred in the airport, rather than on the plane (reported separately in Table 1). These included seven cases in other travellers that were at the airport at the same time as the index case, but not on the same flight, and three secondary cases among airport workers. One study that reported secondary cases among flight crew also reported seven tertiary cases among airline or airport staff.²⁰

Risk of bias assessment

Five articles (5/19, 26%) were classified as having a comparator group for the purposes of the risk of bias assessment, while the remaining 14 (14/19, 74%) did not (Table 3). Ten articles (10/19, 53%) did not provide enough information to answer at least one of the MMAT questions.

The most common deficiency identified among the five articles with a comparator group was lack of complete outcome data; three articles (3/5, 60%) did not have complete outcome data (defined for this question as at least 80% outcome reporting), while the remaining two articles did not provide enough information to assess data completeness. All five articles were rated ‘partial yes’ for the question about whether confounders were accounted for in the design and analysis. The most common confounders that articles collected information on were contact age (4/5, 80%) and contact vaccination status (5/5, 100%), though in some cases, this information was only reported for secondary cases and not for all contacts. No study reported information about contacts’ travel history.

The most common issues noted among articles without a comparator group were in response to the questions about response bias and appropriateness of statistical methods. In response to the question ‘Is the risk of response bias low?’ reviewers answered ‘No’ for four articles and ‘Can’t tell’ for seven articles. In response to the question about whether the statistical methods were appropriate, reviewers responded that the methods were not appropriate to answer the research question for seven articles.

Discussion

While endemic measles transmission has been eliminated from the United States, disease translocation and onward community transmission by persons travelling from endemic areas remain a threat to public health.¹ Transmission events that occur on aircraft have the potential for outsized impact because contacts are likely to disperse, potentially spreading the virus to communities across the country. This literature review identified relatively few published reports of secondary transmission on aircraft (70 secondary cases associated with 182 aircraft exposure events in the published literature over a 20-year period), but measles exposure on aircraft still represents a risk, especially for unvaccinated persons. Reports of secondary cases in airports^{19–21,23} and at final destinations^{12–14,18,21,23–26} further highlight the impact that travel-associated cases can have on an under-vaccinated population.

Many articles included in this review did not explicitly define a contact zone. Among those that used a contact definition that was limited to persons seated within two rows in front of or behind the index case, 71% (5/7) reported secondary cases outside of the contact zone,

suggesting that this approach may not be adequate to identify passengers at risk. However, no articles provided thorough, systematic follow-up for passengers seated throughout the plane, so it is difficult to determine whether a whole-plane contact investigation is warranted for every measles exposure or if some intermediate contact definition (>2 rows, but less than the entire plane) might be appropriate. Consideration should also be given to whether a different approach is needed if multiple cases are identified on the same flight.

At least 57% of the secondary cases documented in this review occurred among persons who were unvaccinated. International travellers are considered at high-risk for measles exposure and transmission, and they should be encouraged to consider vaccination before travel if they are not already fully vaccinated. U.S. CDC recommends that infants aged 6–11 months should receive one dose of MMR and persons aged ≥ 12 months should receive two doses of MMR separated by at least 28 days prior to international travel.²⁷ The availability of PEP options for susceptible contacts has the potential to amplify the benefits of contact tracing for measles, compared to many other infectious diseases. However, very few articles reported detailed data on the number of contacts offered PEP or the proportion that accepted. Among the four articles that reported PEP uptake,^{14,16,17,19} the number of contacts that accepted PEP was very low, and public health officials encounter many implementation barriers, most notably difficulty identifying and reaching contacts within the required timeframe. While PEP may be a valuable tool in certain circumstances and improving the timeliness of the notification process may allow it to be offered more widely, there are logistical considerations that prevent it from being the primary strategy to address measles exposure on aircraft. For this reason, routine and pre-travel vaccination remain the most effective method to prevent measles transmission on aircraft.

Most articles about measles transmission during air travel report data collected during contact investigations, which carry inherent limitations. Most contact investigations only include persons considered at the highest risk of exposure, without a low-risk comparison group, making it impossible to calculate odds ratios or make inferences about the appropriateness of the contact zone the authors used. Aircraft contact investigations often have low response rates for a variety of reasons, including difficulty obtaining accurate contact information for passengers and availability of resources to conduct follow-up. Among studies that considered the whole plane exposed, follow-up often consisted of a notification sent to all passengers, with a request to respond only if they developed symptoms, leaving these studies vulnerable to non-response bias. Many authors took a narrative approach to describing the investigation and therefore did not include the methodological detail necessary to fully assess their methods, as reflected in this article by the high proportion of domains marked ‘Can’t tell’ in the MMAT. This lack of a standardized method of reporting made the data difficult to aggregate to calculate response rates or odds of infection among exposed contacts. In particular, the lack of consistent reporting of denominator data and the reliance in many cases on passive follow up makes it difficult to quantify risk. Because measles has a variable incubation period, it can be difficult to rule out the possibility that cases were exposed in the community or the household setting before the flight. Since most papers did not explicitly control for other exposure risk factors (high rates of community transmission or ongoing contact between index cases and secondary cases outside the flight), it is possible that some infections that were classified

as secondary cases associated with air travel were actually contracted in other, non-aircraft settings. Information regarding the implementation of PEP was especially limited, making it impossible to quantify the relative importance of different barriers to PEP implementation.

Our study has several limitations. First, due to the date range restriction, we may have missed papers published prior to 2004. Second, we may have missed papers not listed in one of the eight databases searched. Third, because we were not able to identify meaningful outcome variables that were consistently available across most manuscripts, we were not able to conduct a meta-analysis. This also meant that we had to adapt the MMAT methodology, which is intended to be applied to analysis of specific outcome variables, to apply to the study methods more generally.

Based on the findings of this systematic review, CDC's currently recommended approach to measles aircraft contact investigations is likely to capture a majority of secondary cases but may miss exposed passengers seated outside of the defined contact zone on larger flights. Many questions remain about the best way to manage measles exposure risk on aircraft, including questions about the best approach to contact investigation (size of contact zone, target vs broad outreach, etc.) and the most effective ways to prevent secondary cases. These questions are difficult to answer using the existing literature and may be better addressed through a prospective study specifically designed to collect the types of data necessary to directly answer specific epidemiological and operational questions.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgements

The authors thank Joanna Taliano, librarian at the Stephen B. Thacker CDC Library, for her assistance in developing the search strategy and performing the searches. We would also like to thank Argelia Figueroa and Katherine Warren for their support during the development phase of this project.

Funding

This work was supported in part by an appointment to the Applied Epidemiology Fellowship Program administered by the Council of State and Territorial Epidemiologists and funded by the Centers for Disease Control and Prevention [Cooperative Agreement Number 1NU38OT000297-03-00 to E.S.].

Data availability statement

Data available upon request.

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Box 1

Example search strategy for a systematic review of measles transmission on aircraft, 2004–2023.

1	Measles/OR Measles virus/OR Rubella/OR Rubella Virus/OR (Measles OR rubella OR rubeola).mp.
2	Aircraft/OR Air Travel/OR (airplane* OR air plane* OR aircraft* OR air craft* OR airline* OR air line* OR (passenger* ADJ5 plane*) OR (air* ADJ5 passenger*) OR (travel* ADJ5 plane*) OR (onboard ADJ5 plane*) OR (on-board ADJ5 plane*) OR (conveyance ADJ5 plane*) OR commercial plane* OR commercial jet* OR fuselage* OR (air ADJ2 travel*) OR in-flight).mp.
3	Travel Medicine/OR Aerosols/OR Air Pollution, Indoor/OR Air Microbiology/OR (Transmi* OR infect* OR expos* OR contact* OR aerosol* OR airborne OR air-borne OR droplet* OR outbreak* OR cluster* OR case* OR investigat*).mp OR tm.fs
4	1–3/AND
5	Limit 4 to yr = '2004–2023'
6	exp animals/NOT exp humans/
7	5 NOT 6

Database: Medline (OVID) 1946-
Results: 51
Date of search: 06 December 2024

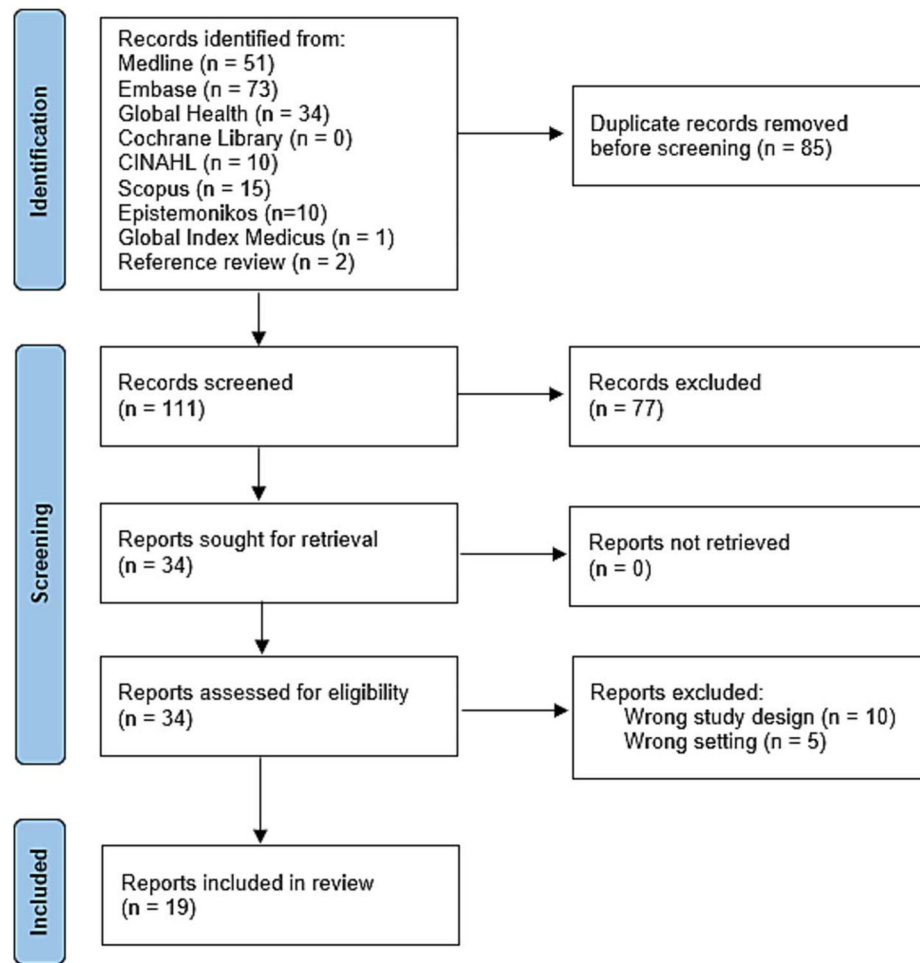


Figure 1. PRISMA diagram showing the screening process for articles included in a systematic review of measles transmission on aircraft, 2004–2023

Table 1
Characteristics and results of articles included in a systematic review of measles transmission on aircraft, 2004–2023

First author, publication year	Flight year	Origin & destination	N Flights (Duration)	Measles at origin	Index cases	Index case clinical signs at time of travel ^a	Contact definition	Secondary cases (Exposed) ^d	Secondary cases (Unexposed) ^b	Secondary case information ^c	Post-exposure prophylaxis	Notes
Amornkul <i>et al.</i> , 2004 ¹⁷	2000	Japan → United States	1 (7 hours)	No/unknown	1	Fever, cough, conjunctivitis; rash Day 0	Whole plane	0 of 276 contacted	N/A	N/A	Given to 4 contacts	
McKeever <i>et al.</i> , 2004 ¹²	2004	India → United States	1+ (NR) ^d	No/unknown	1	Not reported	Not reported	1	N/A	Vaccinated	Offered, no data on uptake	
de Barr os <i>et al.</i> , 2006 ¹³	2006	Maldives → Brazil	NR (NR)	Yes	1	Rash Day –1; other symptoms not reported	Not reported	2 of 118 contacted	N/A	One adult, one child; both unvaccinated	NR	
Cocoros <i>et al.</i> , 2010 ²⁸	2010	Switzerland → United States	1 (NR)	No/unknown	1	Not reported	Within two rows + infants	1 of 29 contacted	0	NR	NR	
Coleman & Markey, 2010 ¹⁹	2008	China → Australia	2 (NR)	No/unknown	1	Fever, cough; rash Day –1	Two rows	0 of 39 contacted	2	Both vaccinated children (siblings)	Given to 8 contacts	Additional secondary case exposed in lounge
Beard <i>et al.</i> , 2011 ¹⁸	2010	South Africa → Australia	1 (12 hours)	No/unknown	1	'Prodromal symptoms'	Two rows	3	1	All unvaccinated adults	Offered, no data on uptake	
Hoskins <i>et al.</i> , 2011 ²⁹	2011	Singapore → New Zealand	2 (4, 7.5 hours)	No/unknown	3	Rash Days –4 to 0; other symptoms not reported	Two rows	3	5	1 vaccinated adult, 2 unvaccinated adults, 3 unvaccinated children, 2 adults with unknown vaccine status	NR	Many cases outside two rows, but can't rule out exposure in airport during 9.5-hour layover
Zipprich <i>et al.</i> , 2011 ²²	2011	Malaysia → United States	1 (NR)	Yes	1	Fever; rash Day 2	Not reported	5	N/A	2 infants and 3 children, all unvaccinated	NR	Additional secondary case in a customs official
Kantele <i>et al.</i> , 2012 ³⁰	2012	Thailand → Finland	2 (NR)	Yes	3	1: fever; rash 2: fever 3: fever, cough	Whole plane	1 of 580 contacted	N/A	Vaccinated child (possibly exposed in Thailand)	NR	
Kodagoda <i>et al.</i> , 2012 ²³	2011	Malaysia → United States	1 (NR)	Yes	1	Fever; rash Day 2	Not reported	2	N/A	1 infant, 1 child, both unvaccinated	NR	All cases in the article also reported in Zipprich <i>et al.</i> ^e

First author, publication year	Flight year	Origin & destination	N Flights (Duration)	Measles at origin	Index cases	Index case clinical signs at time of travel ^a	Contact definition	Secondary cases (Exposed) ^a	Secondary cases (Unexposed) ^b	Secondary case information ^c	Post-exposure prophylaxis	Notes
Hoad <i>et al.</i> , 2013 ¹⁵	2007–2011	NR → Australia	49 (1–13.5 hours)	No/unknown	45	Case definition required rash Days –4 to 4	Two rows	9 of 1082 attempted to contact	11	3 fully vaccinated, 2 partially vaccinated, 9 unvaccinated, 6 unknown	Offered to contacts on 5 flights; no data on uptake available	Attack rate within two rows = 0.0068. Over half of cases identified through other channels and later connected to the flight. Transmission more likely on planes where index case was young or there were multiple index cases)
Nelson <i>et al.</i> , 2013 ^{16f}	2008–2011	Many → United States	108 (0.6–16.8 hours)	No/unknown	74	Case definition required rash Days –4 to 4	Dependent on plane size	9 of 2673 attempted to contact	N/A	1 vaccinated, 7 unvaccinated, 1 unknown; 7 were infants/children	Given to 11 contacts	Factors increasing odds of contacts developing measles included lack of immunity and presence of multiple index cases
Nyangoma <i>et al.</i> , 2014 ¹⁴	2013	China → United States	2+ (NR)	No/unknown	2	1: fever, coryza, cough, rash Days –5 to 2: fever, cough, conjunctivitis, rash Day –3	Two rows + infants + cabin crew	0 of 74 attempted to contact	0	N/A	Given to 1 contact	
Nic Lochlainn <i>et al.</i> , 2016 ²¹	2014	Philippines → United Kingdom	1 (NR)	No/unknown	1	Rash Days 1–2	Whole plane	4	N/A	3 infants, 1 child, all unvaccinated	NR	4 additional secondary cases exposed in the airport (2 passengers, 2 airport workers)
Barrett <i>et al.</i> , 2018 ²⁴	2016	Romania → Ireland	1 (NR)	Yes	1	Fever, rash (day not reported)	Whole plane	1	N/A	NR	NR	Imported case → community transmission with 40 confirmed cases
Huang <i>et al.</i> , 2019 ²⁰	2018	Taiwan → Japan	1 (NR)	No/unknown	1	Fever, cough; rash Day –2	Two rows	2	2	2 cabin crew, 2 passengers	NR	4 additional secondary cases exposed at passport

First author, publication year	Flight year	Origin & destination	N Flights (Duration)	Measles at origin	Index cases	Index case clinical signs at time of travel ^a	Contact definition	Secondary cases (Exposed) ^a	Secondary cases (Unexposed) ^b	Secondary case information ^c	Post-exposure prophylaxis	Notes
Thole <i>et al.</i> , 2019 ³¹	2017	Romania, Italy → Germany	2 (NR)	No/unknown	2	1: Rash Day -4 2: Rash Day 3	Whole plane (born after 1970)	2	N/A	NR		control or while shopping; 7 tertiary cases among airline/airport staff
Bitzegeio <i>et al.</i> , 2020 ²⁵	2018	Within Europe, including Germany, Denmark, Sweden	5 (<2 hours)	No/unknown	2	1: unspecified prodromal signs, rash Days -2 to 2; rash Days -2 & 3	Whole plane	5 of 476 attempted to contact	N/A	3 vaccinated adults, 2 unvaccinated adults	NR	
Lu <i>et al.</i> , 2020 ¹⁶	2017	China → United States	2 (NR)	No/unknown	2	Rash Day 0	Not reported	1	N/A	1 vaccinated adult (cabin crew)	NR	Secondary case was also the index case for another aircraft contact investigation because they worked while infectious

^a Rash days defined based on Day 0 as the onset day; e.g. rash Day -4 is 4 days before onset and rash Day 4 is 4 days after onset.

^b Contacts were defined as exposed vs. unexposed based on the contact definition employed during the study. If the article did not provide a contact definition, all contacts were considered exposed. Where available, the number contacted is provided as the denominator. If this information was not reported, the number of persons on the plane or the number that the investigators attempted to contact is provided instead, if available. No article provided denominator information for the unexposed category.

^c Infant defined as ≤12 months old. Child defined as >12 months to < 18 years. Secondary cases identified as cabin crew without an age provided were presumed to be adults.

^d NR=not reported

^e Because all cases from this article are also reported in Zipprich *et al.* 2011, they were not included in total case counts or in Table 2 to avoid duplication.

^f Based on location and timeframe, this article is suspected to include cases also reported in Cocoros *et al.* 2010, Zipprich *et al.* 2011, and Kodagoda *et al.* 2012. Because this could not be definitively determined, deduplication was not attempted.

Age and vaccination status of secondary measles cases described in articles included in a systematic review of measles transmission on aircraft, 2004–2023

Table 2

	Infant/child	Adult	Age unknown ^a	Total
Vaccinated ^b	3 (17%)	5 (28%)	7 (21%)	15 (21%)
Unvaccinated	15 (83%)	9 (50%)	16 (47%)	40 (57%)
Vaccination status unknown	0	4 (22%)	11 (32%)	15 (21%)
Total	18	18	34	70

^aNelson *et al.*¹⁶ reported one vaccinated secondary case, seven unvaccinated, and one unknown and separately reported that seven secondary cases were children. Because there was insufficient information to determine the vaccination status of the seven children, they were classified as ‘age unknown’ for the purposes of this table.

^bIncludes all secondary cases that had received any number of vaccinations, regardless of whether they had completed a full vaccine series.

Table 3
Risk of bias assessment of articles included in a systematic review of measles transmission on aircraft, 2004–2023^a

Studies that included a comparator group						
First author, publication year	Are the participants representative of the target population?	Are measurements appropriate regarding both the outcome and exposure?	Are there complete outcome data?	Are the confounders accounted for in the design and analysis? ^b	During the study period, did exposure occur as intended?	
Coleman <i>et al.</i> , 2010 ¹⁹	Yes	Yes	No	Partial yes	Yes	
Beard <i>et al.</i> , 2011 ¹⁸	Yes	Yes	Can't tell	Partial yes	Yes	
Hoskins <i>et al.</i> , 2011 ²⁹	Yes	Yes	No	Partial yes	Yes	
Hoad <i>et al.</i> , 2013 ¹⁵	Yes	Can't tell	Can't tell	Partial yes	Yes	
Huang <i>et al.</i> , 2019 ²⁰	Yes	Yes	No	Partial yes	Yes	
Studies that did not include a comparator group						
	Is the sampling strategy relevant to address the research question?	Is the sample representative of the target population?	Are the measurements appropriate?	Is the risk of nonresponse bias low?	Is the statistical analysis appropriate to answer the research question?	
Amornkul <i>et al.</i> , 2004 ¹⁷	Yes	Yes	Yes	Yes	Yes	
McKeever <i>et al.</i> , 2004 ¹²	Can't tell	Yes	Can't tell	Can't tell	No	
De Barros <i>et al.</i> , 2006 ¹³	Can't tell	Yes	Can't tell	Can't tell	Yes	
Coconos <i>et al.</i> , 2010 ²⁸	Yes	Yes	Yes	Can't tell	Yes	
Zipprich <i>et al.</i> , 2011 ²²	Can't tell	No	Can't tell	Can't tell	No	
Kantele <i>et al.</i> , 2012 ³⁰	Yes	Yes	Yes	No	Yes	
Kodagoda <i>et al.</i> , 2012 ²³	Can't tell	Can't tell	Yes	Can't tell	No	
Nelson <i>et al.</i> , 2013 ¹⁶	Yes	Yes	Yes	Yes	Yes	
Nyangoma <i>et al.</i> , 2014 ¹⁴	Yes	Yes	Yes	No	Yes	
Nic Lochlainn <i>et al.</i> , 2016 ²¹	Yes	Yes	No	Yes	No	
Barrett <i>et al.</i> , 2018 ²⁴	Can't tell	Yes	Can't tell	Can't tell	No	
Thole <i>et al.</i> , 2019 ³¹	Yes	Yes	Yes	No	No	
Bitzegeio <i>et al.</i> , 2020 ²⁵	Yes	Yes	Yes	No	Yes	
Lu <i>et al.</i> , 2020 ²⁶	Yes	Yes	Yes	Can't tell	No	

^a Risk of bias was assessed using the Mixed Methods Appraisal Tool [Hong et al., 2018].

^b Potential confounders considered included the presence of co-travellers, disease burden at each contact's origin, contact age, and contact vaccination status. Studies were scored as 'partial yes' if they addressed some, but not all, of the confounders.