SPOR Evidence Alliance
Strategy for Patient-Oriented Research
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Strategy for Patient-Oriented Research
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Aircraft environmental control systems (ECS) for preventing SARS-CoV-2 transmission

A systematic review

Date of Literature Search: 12/11/2020
Date of Submission: 1/5/2021

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Suggested citation: Abou-Setta AM, Lam O, Kasireddy V, Askin N, Tricco AC. Aircraft environmental control systems (ECS) for preventing SARS-CoV-2 transmission: a systematic review. January 5, 2021.

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Land Acknowledgement(s)

SPOR Evidence Alliance operates from the St. Michael's Hospital, Unity Health Toronto which is located on the traditional land of the Huron-Wendat, the Seneca, and the Mississaugas of the Credit. Today, this meeting place is still the home to many Indigenous people from across Turtle Island.

The Centre for Healthcare Innovation is stationed on the University of Manitoba's HSC campus, located on original lands of Anishinaabeg, Cree, Oji-Cree, Dakota, and Dene peoples, and on the homeland of the Métis Nation. We respect the Treaties that were made on these territories, we acknowledge the harms and mistakes of the past, and we dedicate ourselves to move forward in partnership with Indigenous communities in a spirit of reconciliation and collaboration.

We are grateful to have the opportunity to work on these lands.

Funding Acknowledgement(s)

This project was jointly funded by the SPOR Evidence Alliance and the World Health Organization.

The Strategy for Patient-Oriented Research Evidence Alliance (SPOR EA) is supported by the Canadian Institutes of Health Research (CIHR) under the Strategy for Patient-Oriented Research (SPOR) initiative.

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Special thanks to Leslie Copstein for helping draft the manuscript.

Declarations of interest

None.

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Background

In humans, coronaviruses may cause respiratory infections ranging from the common cold to severe disease. The 2003 Severe Acute Respiratory Syndrome (SARS), the 2012 Middle Eastern Respiratory Syndrome (MERS) and the 2019 coronavirus disease (COVID-19) are all notable pandemics caused by coronaviruses.

COVID-19 has proven to be more difficult to manage, compared to previous epidemics, for many reasons including its high infectivity rate. The mean reproductive number (R_0), which represents the speed of spread or transmissibility, of SARS-CoV-2 (the virus that causes COVID-19) has been estimated to be around 3.28,[1] which is higher than that for SARS (1.7–1.9) and MERS (<1)[2]. To combat the transmission of SARS-CoV-2, governments and public health organizations/ officials have implemented polices to decrease the disease spread including increased testing, social distancing protocols, use of face masks/ coverings and the number of individuals who can congregate. While there is evidence of effectiveness of such policies, this may not be possible in some situations (e.g., airplanes), where social distancing may not be possible. In addition, airplanes are a closed environment where the air flow is controlled by the onboard Environmental Control System (ECS); an apparatus that guarantees safety and comfort to the occupants of an aircraft, maintaining its interior environment under adequate limits of pressure, temperature, air composition, but also contributes to disinfection[3].

In most commercial airplanes, conditioned air is provided to the cabin through distribution outlets in the ceiling and collected by ducts in the bottom, establishing a laminar airflow. There is little horizontal flow and such standard displacement keeps particles and microorganisms spread under control[3,4].

When operational, the ECS exchanges the cabin air at a rate of 10 to 15 times per hour[4]. Half of the collected air is ejected from the airplane while the other half is continuously recirculated, after going through high efficiency particulate air (HEPA) filters that retain particles and airborne microorganisms[3]. HEPA filters were found to be 99.97% efficient in retaining particles sized from 0.1 µm to 0.3 µm and 100% of larger particles[4,5]. Although SARS-CoV-2 particle size ranges from

0.06 µm to 0.14 µm, droplets and aerosols containing them are larger and supposed to be trapped by HEPA filters[6].

There is no single ECS for all aircraft and they differ slightly in design and function. Additionally, airflow is not consistent to all seats/ sections of the plane and location of an infected individual in relation to the inputs and outputs of the ECS may affect the risk of transmission.
The objective of this systematic review is to identify, critically-appraise and summarize evidence on the effectiveness of maintained, tested, and functional ECS while aircraft passengers are on board in preventing SARS-CoV-2 transmission to air travelers.

Methods

We included randomized trials, non-randomized trials, observational studies and modelling studies on airline travelers (passengers and/or crews on-board an airplane) following emergence of SARS-CoV-2. The non-randomized and observational studies could be single arm or with a control group, including but not limited to prospective or retrospective cohort studies, case-controlled studies, cross-sectional studies, or case reports/ series. We excluded opinion papers, editorials, study protocols and trial registries.

The intervention was any on-board airplane ECS. For single arm studies, and as the intervention arm in comparative studies, it was assumed that the ECS was maintained, tested, and functional while travelers (passengers and/or crews) are on-board (while stationing and/or during flight), unless otherwise stated. A different ECS or a poorly maintained aircraft ECS were valid comparators as well if the ventilation system is not functioning during engine off operations while travelers (passengers and/or crews) are on-board.

The outcomes of interest were on-board SARS-CoV-2 transmission among travelers (passengers and/or crews), fiscal implications (e.g., costs), economic harms (e.g., on aviation, tourism), feasibility and user acceptability (e.g., passenger confidence).

Search strategy for identification of studies

We searched general health and COVID-19-specific bibliographic databases [MEDLINE (Ovid), EMBASE (Ovid), Web of Science (Thompson-Reuters), Cochrane Covid (https://covid-19.cochrane.org/), LitCovid (https://www.ncbi.nlm.nih.gov/research/coronavirus/), and Medrxiv (https://connect.Medrxiv.org/relate/content/181); last search was conducted on December 11, 2020. Lastly, we conducted searches in general purpose databases (e.g., Google), government and public health websites (e.g., WHO) and news outlets for additional unpublished or grey literature. Each database was searched using an individualized search strategy; example of Medline search is available in **Appendix 1**. Finally, the reference lists of relevant narrative and systematic reviews and included studies were hand-searched for relevant citations. We performed reference management in EndNote™ (version X9, Thomson Reuters, Carlsbad, CA, USA).

Study selection

We used a two-stage process for study screening and selection using standardized and piloted screening forms. Two reviewers independently screened the titles and abstracts of search results to determine if a citation met the inclusion criteria. Full texts of all included citations were reviewed independently, and in duplicate. All conflicts were resolved through discussion, consensus or by a third researcher, as required.

Data abstraction and management

One reviewer summarized the findings from included study reports, and a second researcher reviewed the summaries for accuracy and completeness. Discrepancies between the two reviewers were resolved by discussion and consensus. Data management was performed using Microsoft Excel™ 2010 (Excel version 14, Microsoft Corp., Redmond, WA, USA).

Assessment of methodological quality and potential risk of bias

As most of the evidence came from single-arm observational and modelling studies, we assessed the risk of bias and methodological quality, respectively using the tools proposed by Murad et al., 2018[7] and Jaime Caro et al., 2014[8]. If any randomized trials were identified, then we would have assessed the risk of bias of those trials using the Cochrane Risk of Bias Tool.

Results

From the 561 records identified through database searching and other sources, we included nine publications that provided evidence for the key questions **(Figure 1)**; representing seven unique studies[9-15] and two companion publications[16,17]. Most of the included studies reported on evidence from modeling/ simulation studies[10-14] (n = 5). The remaining two studies reported on single-arm, non-comparative observational studies[9,15]. We did not identify any comparative studies in humans. Both single-arm studies were judged to at high risk of bias **(Appendix 2)**. There were moderate to major concerns regarding the quality of the modeling studies as well **(Appendix 3)**. We only identified evidence for 'on-board SARS-CoV-2 transmission among travelers (passengers and/or crews)'. No evidence was found regarding the fiscal implications (e.g., costs), economic harms (e.g., on aviation, tourism), feasibility and user acceptability (e.g., passenger confidence) of different ECS or functional vs. non-functional ECS.

Summary description of included studies in provided in **Tables 1 – 2.** Evidence from the two single-arm studies provide preliminary evidence that with adequate, maximum ventilation through the ECS, the rate of transmission of SARS-CoV-2 is minimal. This is further supported by evidence from the modeling/ simulation studies that show that the design and function of current aircraft ECS decrease the likelihood of transmission. It should be noted that these studies also noted the importance of mask-wearing while on-board. The certainty of the evidence was very low for evidence from both single-arm studies as well as modeling studies **(Table 3, Appendix 4)**.

Discussion

Environment control systems are essential components in modern commercial aircrafts[3]. They are designed to create a stable environment to maximize comfort and safety of flight passengers and crew. Although all modern airplanes have HEPA filters, its use in commercial aircrafts is not mandated, or regulated, by US or European aviation authorities[4]. Furthermore, it is unclear what percentage of operational aircraft use HEPA filters or the cost/ barriers to retrofit airplanes with the purpose to increase ECS disinfection functions against SARS-CoV-2.

The results of this systematic review provide limited evidence that a functional aircraft ECS will minimize the transmission rate of SARS-CoV-2 inside the aircraft cabin. This is accomplished through the cabin airflow design, the use of HEPA filter, replacement of half of the air during each cycle and multiple cycles per minutes.

While the transmission rate is anticipated to be limited, the risk may differ depending on the ECS in use and the location of a passenger's seat in comparison to an infected individual. For example, on computational analysis[11] showed that in the Airbus economy class, the best seat was located next to the window, while in the Boeing economy class, the best seat was the middle seat in the side bank of seats. In another study[13], it was demonstrated that the aerosol exposure risk is typically highest in the row of an index patient; followed by rows in front and behind the index patient. They also concluded that while there is a measurable difference in the middle vs. aisle or window seat, there is little practical difference at these high overall reduction levels. Lastly, the flight deck exposure risk was shown to be extremely unlikely, as the ECS supplies separate air to this portion of the aircraft.

While the potential rate of exposure may be limited using a functional ECS, there are examples of cases linked to possible onboard transmission. For example, Hoehl et al.,[18] reported two cases of probable secondary cases in a flight with seven index cases. It should be noted that no measures to prevent transmission were adopted on that flight and secondary cases were among passengers sit within two rows of distance of the index cases.

In conclusion, while there is currently limited evidence of the effectiveness of ECS to limit the spread of SARS-CoV-2, the available evidence is encouraging. Future research should focus not only on modeling/ simulation but also on real-life evidence of its effectiveness, parameters to increase the effectiveness, and potential harms (e.g., associated costs).

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Figure 1. Modified PRISMA flow-chart

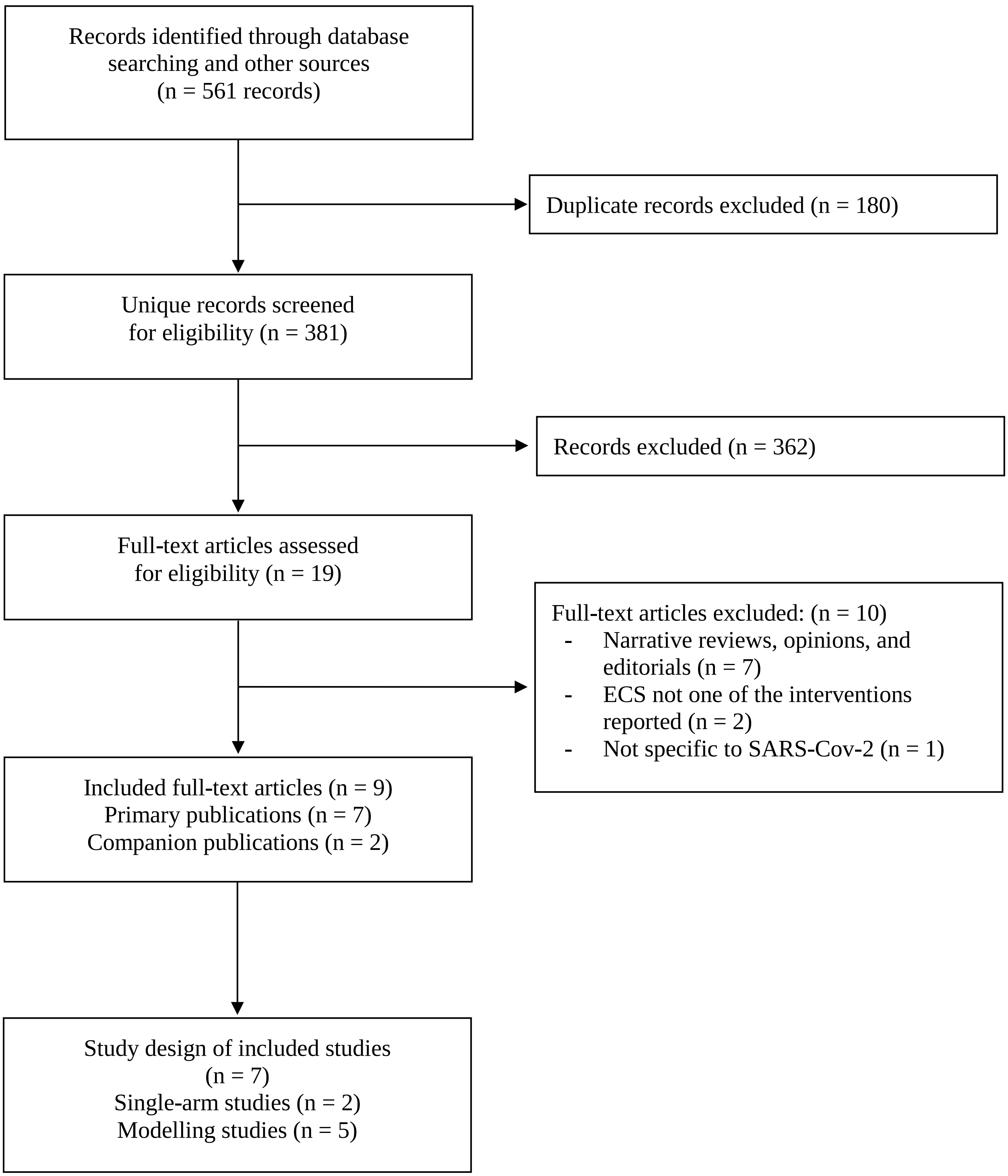

Table 1. Summary of observational studies.

Study	Summary of results
Chen 2020[9]	Study reporting on the repatriation of overseas Chinese nationals. To maximize ventilation, during the flight, the maximum amount of ventilation under the premise of safety was applied. During ground operation and maintenance, the aircraft auxiliary power unit was used for ventilation, and the use of the bridge load air supply was avoided. Upon arrival, cabin doors and cargo hold were opened for ventilation prior to maintenance work began, and natural ventilation time was extended. All personnel subsequently tested negative (three times) for COVID-19.
Zhang 2020[15]	Among 4492 passengers and crew bound for Beijing, 161 were positive for COVID-19. Two confirmed have been infected in the aircraft; overall attack rate was 0.14. The air circulation pattern on the aircraft was side to side (laminar); air entered the cabin from the top, circulated across the aircraft, and exited the cabin near the floor. It is suggested that this circulation pattern can effectively prevent respiratory infectious disease in aircraft cabins.

Table 2. Summary of modelling studies.

Study	Summary of results
Dai 2020[10]	Along with mask wearing in the aircraft cabin, natural ventilation (or normal mechanical ventilation) can ensure that the infection probability is less than 1%.
Desai 2020[11]	Computational analysis of typical intercontinental aircraft ventilation systems to determine the seat where environmental factors are most conducive to human comfort with regards to air quality, protection from orally or nasally released pollutants (e.g., CO2 and coronavirus), and thermal comfort levels. Air velocity, temperature, and air pollutant concentration emitted from the nose/mouth of fellow travelers were considered for both Boeing and Airbus planes. Airbus seat had a higher temperature, lower CO2 concentration, and lower air velocity. Unlike first class and business class, there was a tradeoff between a warmer seat and poorer circulation. The best seat in Airbus economy was both warm and had good circulation. The Boeing seat performed less well in all these areas. - In Airbus economy class, the best seat was located next to the window. - In Boeing economy class, the best seat was the middle seat in the side bank of seats.

Study	Summary of results
Harvard 2020[12]	Aircraft ventilation systems disperses exhaled air with displacement in the downward direction. This level of ventilation effectively counters the proximity travelers will be subject to during flights. The level of ventilation provided aboard aircraft will substantially reduce the opportunity for person-to-person transmission of infectious particles, when coupled with consistent compliance with mask-wearing policies. When the aircraft environmental control system is fully operating, the mask-wearing passenger in the nearest seat to a masked infectious person will have a substantially reduced exposure. In other words, the estimated dose inhaled by an adjacent passenger over a few hours of exposure is likely to be less than the amount necessary to cause a secondary infection.
USTRANSCOM 2020[13]	Fluorescent aerosol tracers and real time optical sensors, coupled with DNA-tagged tracers to measure aerosol deposition, were used to conduct an aircraft aerosol experimental validation test in Boeing 777-200 and 767-300 airframes. Tracer aerosols were released from a simulated infected passenger, in multiple rows and seats, to determine their risk of exposure and penetration into breathing zones of nearby seats. The results showed a minimum reduction of 99.7% of simulated virus aerosol from the index source to passengers seated directly next to the source. An average 99.99% reduction was measured for the 40+ breathing zones tested in each section of both airframes. Rapid dilution, mixing and purging of aerosol from the index source was observed due to both airframes' high air exchange rates, downward ventilation design, and HEPA-filtered recirculation. Contamination of surfaces from aerosol sources was minimal, and DNA-tagged tracers agreed well with real-time fluorescent results. The application of a surgical mask provided significant protection against micron diameter droplets released during the cough simulations and reductions greater than 90% were measured. Results of this study suggest that aerosol exposure risk is minimal even during long duration flights, but typically highest in the row of an index patient. Rows in front and behind the index patient have the next highest risk on average. While there is a measurable difference in middle vs aisle or window seat, there is little practical difference at these high overall reduction levels. Flight deck exposure risk is extremely unlikely, as the environmental control system supplies separate air to this portion of the aircraft.

Study	Summary of results
Yan 2020[14]	Simulation investigating cough flow and its time-dependent jet-effects on the transport characteristics of respiratory-induced contaminants in passengers' local environments. Transient simulations were conducted in a three-row Boeing 737 cabin section, while respiratory contaminants were released by different passengers with, and without, coughing and were tracked by the Lagrangian approach. The results indicated that there were significant influences of cough-jets on passengers' local airflow field by breaking up the ascending passenger thermal plumes and inducing several local airflow recirculation in the front of passengers. Cough flow could be locked in the local environments (i.e. near and intermediate fields) of passengers. The cough-jets were found to have long and effective impacts on contaminant transport up to 4 s, which was 8 times longer than the duration of cough and contaminant release process (0.5 s). Also, compared to ventilated flow, cough flow had considerable impacts on a much wider size range of contaminants (up to 200 μm) due to its strong jet-effects.

Table 3. Rating the certainty in evidence from single-arm studies and modeling/ simulation studies.

GRADE domain	Judgement	Concerns about certainty domains
Methodological limitations of the studies	Both single-arm studies were at high risk of bias. In one study[9], only the crew were tested, while in the other study[15], tests from asymptomatic passengers were results not reported. All five modeling/ simulation studies[10-14] were deficient in the reporting of validation (internal and/ or external) and/ or assessment of uncertainty on the models.	Serious
Indirectness	The low transmission rate is used as an indirect measure of success of the airplane ECS in the single-arm studies. Due to the nature of modeling/ simulation studies, this is an indirect evaluation of a real-life situation that has not been validated in human studies.	Not serious, borderline
Imprecision	Number of events in all the included studies were low.	Serious
Inconsistency	Results of all the included studies were consistent in that transmission rates were low.	Not serious
Publication bias	Not enough studies to determine if publication bias is possibly present or not.	Not suspected

Appendix 1. Medline Search strategy (run on Nov 19, 2020 and Dec 11, 2020).
Database: Ovid MEDLINE(R) and Epub Ahead of Print, In-Process & Other Non-Indexed Citations and Daily

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1 exp Coronavirus/ or exp Coronavirus Infections/ (50299)
2 (coronavir* or corona vir* or OC43 or NL63 or D614G or 229E or HKU1 or hcov* or ncov* or covid* or sarscov* or sars-cov* or sarscoronavir* or sars-coronavir* or 2019ncov* or 19ncov* or novel cov* or 2019novel cov* or ((novel or new or nouveau) adj2 (pandemi* or epidemic* or outbreak*))).mp. (91816)
3 (exp pneumonia/ or (pneumonia* or sars*).mp.) and (wuhan or hubei).mp. (3269)
4 COVID-19.rx,px. or severe acute respiratory syndrome coronavirus 2.os. (34944)
5 or/1-4 (96387)
6 limit 5 to yr="2019 -Current" (75206)
7 aviation/ or exp aircraft/ or aerospace medicine/ or air travel/ or airports/ (28369)
8 (aircraft* or airplane* or aeroplane* or airport* or aeroport* or airline* or jet or jets or jetliner* or plane or planes or airbus or airship* or aircrew* or flight* or inflight* or aviat* or cabin crew* or skycap* or flyer* or cockpit*).mp. (248059)
9 ((air* or fly*) adj5 (crew* or pilot* or commander* or cargo or passenger* or travel* or transport* or journey* or trip or trips or personnel* or captain* or officer* or copilot* or engineer* or steward* or attendant* or hostess* or purser* or destination* or departure* or arrival*)).mp. (12184)
10 or/7-9 (259762)
11 ventilation/ or confined spaces/ (6168)
12 (ventilat* or airflow* or (air* adj2 (exchang* or cabin* or flow* or condition* or clean* or filtrat* or filter* or purif* or qualit* or circulat*)) or microclimat* or micro-climat* or aircondition* or hepa filter* or ((sealed or closed or enclosed) adj2 (space* or cabin*))).mp. (239306)
13 or/11-12 (239655)
14 6 and 10 and 13 (48)

Appendix 2. Study quality for cohort studies.

Dom-ains	Leading explanatory questions	Chen 2020	Zhang 2020
Selection	1. Does the patient(s) represent(s) the whole experience of the investigator (centre) or is the selection method unclear to the extent that other patients with similar presentation may not have been reported?	No	No
Ascert-ainment	2. Was the exposure adequately ascertained?	Unclear	Yes
	3. Was the outcome adequately ascertained?	No	Yes
Causality	4. Were other alternative causes that may explain the observation ruled out?	Not applicable	Not applicable
	5. Was there a challenge/rechallenge phenomenon?	Not applicable	Not applicable
	6. Was there a dose–response effect?	Not applicable	Not applicable
	7. Was follow-up long enough for outcomes to occur?	Unclear	Yes
Reporting	8. Is the case(s) described with sufficient details to allow other investigators to replicate the research or to allow practitioners make inferences related to their own practice?	Yes	Yes
Overall Risk of Bias		**High risk of bias**	**High risk of bias**

Appendix 3. Study quality for modelling studies.

Domains	Questions	Dai 2020	Desai 2020	Harvard 2020	US-TRANSCOM 2020	Yan 2020
Model structure	1. Are the structural assumptions transparent and justified?	No to minor concerns	No to minor concerns	No to minor concerns	No to minor concerns	No to minor concerns
	2. Are the structural assumptions reasonable given the overall objective, perspective and scope of the model?	No to minor concerns	No to minor concerns	No to minor concerns	No to minor concerns	No to minor concerns
	3. Are the input parameters transparent and justified?	No to minor concerns	No to minor concerns	No to minor concerns	No to minor concerns	No to minor concerns
	4. Are the input parameters reasonable?	No to minor concerns	No to minor concerns	No to minor concerns	No to minor concerns	No to minor concerns
Validat-ion (ext)	5. Has the external validation process been described?	Not reported	Reported	Not reported	Not reported	Reported
	6. Has the model been shown to be externally valid?	Moderate concerns	No to minor concerns	Moderate concerns	Moderate concerns	No to minor concerns
Valid-ation (int)	7. Has the internal validation process been described?	Not reported	Not reported	Not reported	Not reported	Not reported
	8. Has the model been shown to be internally valid?	Moderate concerns	Moderate concerns	Moderate concerns	Moderate concerns	Moderate concerns
Uncert-ainty	9. Was there an adequate assessment of the effects of uncertainty?	Major concerns	Major concerns	No to minor concerns	Major concerns	Major concerns
Transp-arency	10. Was technical documentation, in sufficient detail to allow (potentially) for replication, made available openly or under agreements that protect intellectual property?	No to minor concerns	No to minor concerns	No to minor concerns	No to minor concerns	No to minor concerns

Overall quality		**Major concerns**	**Major concerns**	**Moderate concerns**	**Major concerns**	**Major concerns**

Appendix 4. Summary of findings.

Outcome	Effect	Number of studies	Certainty in the evidence
SARS-CoV-2 transmission among travelers (passengers and/or crews)	All studies (single-arm and modeling/ simulation studies) showed low transmission rates with functional ECS but were at high risk of bias (single-arm studies) or had moderate to serious concerns about their study quality (simulation studies).	Two single-arm studies and five modeling/ simulation studies	Very low certainty ⨁◯◯◯
Fiscal implications (e.g., costs)	-	No included studies reported on this outcome.	-
Economic harms (e.g., on aviation, tourism)	-	No included studies reported on this outcome.	-
Feasibility	-	No included studies reported on this outcome.	-
User acceptability (e.g., passenger confidence)	-	No included studies reported on this outcome.	-