Aviation Public Health Initiative

Assessment of Risks of SARS-CoV-2 Transmission During Air Travel and Non-Pharmaceutical Interventions to Reduce Risk

Phase One Report: Gate-to-Gate Travel Onboard Aircraft

Prepared by

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ACKNOWLEDGEMENTS

The findings and recommendations of this report are the independent conclusions of the Harvard T.H. Chan School of Public Health Aviation Public Health Initiative. The APHI team hopes its contents will underscore the importance of following science, to save lives, to reinvigorate economic well-being, and to lead the country and the world to overcome the COVID-19 crisis.

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LIST OF ABBREVIATIONS AND ACRONYMS

A4A	Airlines for America
ACE2	Angiotensin Converting Enzyme 2
ACH	Air Changes per Hour
AIHA	American Industrial Hygiene Association
APHI	Aviation Public Health Initiative
APU	Auxiliary Power Unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
ATP	Adenosine Triphosphate
CAAT	Civil Aviation Authority of Thailand
CAR	Central African Republic
CDC	Centers for Disease Control and Prevention
CFD	Computational Fluid Dynamics
cfm	cubic feet per minute
cm/s	centimeters per second
CO_2	carbon dioxide
DNA	Deoxyribonucleic Acid
EASA	European Union Aviation Safety Agency
ECS	Environmental Control System
GUV	Germicidal Ultraviolet
HEPA	high efficiency particulate air
IATA	International Air Transport Association
l/s/p	liter per second per person
MERS-CoV	Middle Eastern respiratory syndrome coronavirus
MERV	minimum efficiency reporting value
NAS	National Academies of Sciences
nm	nanometer
NPI	Non-Pharmaceutical Intervention
PCA	Pre-conditioned Air
PPE	personal protective equipment
ppm	parts per million
ppmv	parts per million per volume
PRNT	Plaque Reduction Neutralization Test
PUIs	Persons Under Investigation
QAC	Quaternary Ammonium Compound
RH	Relative Humidity
RNA	Ribonucleic Acid
RT-PCR	Reverse Transcription Polymerase Chain Reaction
S&T	Science and Technical
SARS-CoV-2	Severe Acute Respiratory Syndrome Coronavirus 2
SEIR	Susceptible – Exposed – Infected – Recovered
WGS	Whole-genome Sequencing
WHO	World Health Organization
μm	micrometer

1.0   EXECUTIVE SUMMARY

This document summarizes the emerging scientific literature on the effectiveness of selected non-pharmaceutical interventions (NPI) used to control transmission of the novel coronavirus SARS-CoV-2 on board aircraft. Based on modeling of aircraft ventilation systems and current evidence about this novel coronavirus, the report presents recommendations regarding risk mitigation for airlines, airline passengers and crewmembers. The comprehensive strategy proposed incorporates layering NPI to create additive and/or synergistic benefits for reducing the risk of exposure to SARS-CoV-2 during air travel. This layered NPI approach, with ventilation gate-to-gate, reduces the risk of SARS-CoV-2 transmission onboard aircraft below that of other routine activities during the pandemic, such as grocery shopping or eating out.

The global SARS-CoV-2 pandemic is a disruptive force acting on people and business around the globe. The challenge is to develop effective and efficient methods to safeguard concurrently against the disease and open segments of society. The aviation industry is confronting this problem and its manifestations using a science-based approach to integrate new knowledge with existing technologies.

The Harvard T.H. Chan School of Public Health Aviation Public Health Initiative (APHI) grew out of discussions between Harvard faculty members and leaders of the aviation industry. The 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?

From the start, the industry's bedrock tradition of aviation safety paralleled a focused commitment to public health safety. Aviation leaders agreed to the independence of the academic research. The APHI launched in July 2020, approximately four months after declaration of the national COVID-19 emergency. As part of this overall effort, this APHI project advances: 1) Understanding of the novel characteristics of this coronavirus in the unique aviation environment; 2) Strategies to mitigate transmission in the confined space of an aircraft and the indoor spaces of an airport; 3) Behaviors by crewmembers and passengers to protect themselves and others nearby them.

The project is led by the National Preparedness Leadership Initiative, a joint program of the Harvard T.H. Chan School of Public Health and the Harvard Kennedy School of Government, Center for Public Leadership. The APHI academic team includes expertise in industrial hygiene, infectious disease, engineering, environmental, medical, social sciences, and crisis leadership experts. On the aviation side, a consortium of airline operators, aviation industry manufacturers, and airport operators sponsored the project. It is by design an inclusive, multi-disciplinary, multi-

sectoral, and multi-organizational platform, intended to address the unique contours of the current COVID-19 crisis in the aviation industry. The project is a model for how industry and science can work productively together to surmount this disease and its challenges.

The Harvard T.H. Chan School of Public Health Aviation Public Health Initiative is releasing two major reports to address the scope of the aviation journey:

- Phase 1: This document, The Gate-to-Gate journey focused on aircraft.
- Phase 2: The Curb-to-Curb journey focused on airports, scheduled for release in early 2021.

Method

The APHI engaged in the following activities:

1. Review of emerging research regarding the infectious characteristics of SARS-CoV-2 and the resulting effectiveness of selected non-pharmaceutical interventions (NPI) to control its transmission, specifically for this Report, onboard aircraft during the different phases of a journey and in jetways.

2. Analysis of Computational Fluid Dynamics (CFD) modeling and data gathering conducted by aircraft manufacturers, airline operators, and government agencies, compared against independent modeling, in order to test assumptions and integrate findings into comprehensive recommendations based on the best possible evidence.

3. Frequent and in-depth conversational interviews with aircraft manufacturers, airline operators, aviation industry leaders, airline crewmembers and airport operators to assess current operational conditions during the COVID-19 crisis and options for reducing disease transmission through a layered NPI approach.

Findings on Risk Reduction

1. **The Emerging Science on SARS-CoV-2**: The research to characterize SARS-CoV-2 viral production and transmission is still emerging. Therefore, at this stage of the pandemic, scientific judgement combines with evidence-based research. This understanding is applied to determining the best engineering, disinfection and modified human behavior strategies. The metric used to calculate disease transmission of respiratory diseases is dose, namely exposure concentration over time. However, in the case of SARS-CoV-2, that measure is not directly applicable. Rather, a more advanced multi-compartment model applies. The Susceptible – Exposed – Infected – Recovered (SEIR) model describes the situation in which a susceptible population may have been exposed but may not yet be infectious, given the virus requires time to incubate and reproduce. What complicates the calculation is the

susceptibility of the person exposed, the biological dose of virus particles delivered to a target organ and the duration over which the exposure occurs. The infectious dose for SARS-CoV-2 is yet unknown. Particles (detectable, viable, and infectious) are estimated from source measurements, but include many particles that do not cause infection due to viability, infectivity, host defenses, etc. In such situations, the concept of quanta is used (see Section 3.2.6) to describe whatever that unknown number might be, and probability is applied to estimate the likelihood of inhaling an infectious dose, i.e., quanta of infection. Quanta are therefore agnostic about the actual number of particles, but quantifies the number of doses generated by the source under specific circumstances and considering the probability of inhaling an infectious dose. As such, quanta allows quantification of risk reductions for mitigation strategies and calculations of comparative risk for different social activities, and it applies to analysis of disease transmission in the unique circumstances of an aircraft cabin.

2. **The Layered Approach to Risk Reduction:** The NPI (Non-Pharmaceutical Interventions) proposed for risk mitigation of SARS-CoV-2 transmission includes the consistent operation of ventilation systems, disinfection of surfaces, consistent wearing of face masks, and procedures during boarding and deplaning to maximize social distancing among passengers and crewmembers. The efficacy of these combined strategies is given in Table 1.1. Details underpinning the approach are found in the thematic sections of the Report that present the detailed scientific rationale and evidence in support of the strategy. This layered NPI approach serves to reduce significantly the risks of disease transmission in the aircraft environment.

3. **Ventilation Systems on Aircraft:** These sophisticated systems deliver high amounts of clean air to the cabin that rapidly disperses exhaled air, with displacement in the downward direction, reducing the risk of passenger-to-passenger spread of respiratory pathogens. Aircraft ventilation offers enhanced protection for diluting and removing airborne contagions in comparison to other indoor spaces with conventional mechanical ventilation and is substantially better than residential situations. This level of ventilation effectively counters the proximity travelers will be subject to during flights. The level of ventilation provided onboard aircraft would substantially reduce the opportunity for person-to-person transmission of infectious particles, when coupled with consistent compliance with mask-wearing policies.

4. **Crew and Passenger Behavior:** Deterrence of behaviors that increase the likelihood of transmission of SARS-CoV-2 from one person to the next is the most critical factor in enhancing public health safety onboard aircraft. Health attestations and screening for crew and passengers who show symptoms of COVID-19 reduce the likelihood that an infectious individual will board a plane until rapid, reliable, and inexpensive testing becomes available. Face masks significantly reduce transmission and airlines now require passengers to wear

them, with few exceptions. Airlines enforce these policies and place those who do not comply on no-fly lists. Passengers are required to follow orderly procedures for boarding and deplaning in order to reduce congestion. Combined with hand washing, cleaning and abstaining from face touching, crewmember and passenger behaviors are important contributors to aviation risk reduction.

Conclusion

Implementing the layered risk mitigation strategies described in this report requires the assurance of passenger and airline compliance. Substantial progress has been made in that effort. It will help to ensure that air travel, with respect to SARS-CoV-2 transmission, is as safe as or substantially safer than the routine activities people undertake during these times.

The activities any individual chooses to undertake during COVID-19 depends on their personal health assessment and the relative risks and consequence of becoming infected. The findings and recommendations in this report offer the public the opportunity to reach informed decisions about air travel.

Though a formidable adversary, SARS-CoV-2 need not overwhelm society's capacity to adapt and progress. It is possible to gain a measure of control and to develop strategies that mitigate spread of the disease while allowing a careful reopening of sectors of society. There is much to gain by simply following the science. It offers a bounty of information about how people can achieve both public health safety and opportunity.

The project may periodically also issue bulletins and updates, which can be found at the APHI website: https://npli.sph.harvard.edu/crisis-research/aviation-public-health-initiative-aphi/.

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)

2.0   INTRODUCTION

This document is a summary of the current scientific literature on the effectiveness of selected non-pharmaceutical interventions (NPI) used to control transmission of the novel coronavirus SARS-CoV-2. The report presents specific recommendations in the context of air travel that are based on the research to provide effective risk mitigation relating to airline passengers and crewmembers. The essential elements of the approach described relate to layering NPI to create additive and/or synergistic benefits in reducing the risk of exposure to COVID-19 for passengers and crewmembers during air travel.

2.1   TECHNICAL SUMMARY

The report builds upon previous guidance documents, such as *The Runway to Recovery: The United States Framework for Airlines and Airports to Mitigate the Public Health Risks of Coronavirus* (DOT, 2020) issued in July 2020 jointly by U.S. Departments of Transportation, Homeland Security and Health and Human Services and the various COVID-19 related publications issued by the International Air Transport Association (IATA, 2020). While these documents offer sound advice, the efforts of APHI include an examination of critical elements of risk mitigation in relation to NPI that can be combined or "layered" to enhance safety. These include physical engineering controls and ventilation, operational practices and passenger and crew behavior that seek to ensure reasonable and efficacious strategies are available to reduce the risk of SARS-CoV-2 transmission during air travel.

The global pandemic of SARS-CoV-2 and the resulting COVID-19 infections have thrown the disruptive forces acting on the travel sector into sharp relief, drawing attention to the interconnected and hyper-dependent nature of health and business. The dual health and economic crises are disrupting social and commercial activity, with the travel industry affected severely. The APHI team has worked to provide the aviation industry and the general public with science-based evidence that:

1. Seeks to define the risks that congregate settings and air travel in particular, may present.
2. Detail mitigation strategies that seek to minimize the risk of SARS-CoV-2 transmission while traveling by air.

In line with what is known currently about transmission of SARS-CoV-2, there are actions that can be taken by an individual traveler to reduce their risk of infection. In addition, there are actions that can be taken by an airline to reduce the risk of transmission of the virus. Taken together, these activities relate to the biology of the virus, to engineering interventions, to changes to policies and protocols and to human behavior. Adopting a layered approach means that the different interventions can be combined to create a comprehensive strategy that reduces

risk. This supports an evidence-base to inform decision-making at the corporate level as well as at the individual level, when travelers contemplate a journey and how they will prepare for and behave while on a flight.

In order to understand the different modes of transmission for SARS-CoV-2, and better estimate the reduction of transmission, several risk factors need to be understood. Transmission depends on how much virus an infected person might produce when they breathe, talk, laugh, sing, cough and/or sneeze (Ningthoujam, 2020). Any large drops are likely to settle quickly. Smaller-sized drops and aerosols are subject to evaporation or more prolonged dispersion in the air, allowing them to travel some distance.

Ideally, it would be useful to know the number of viral copies across the different sizes of drops and aerosols produced. Some inferences relevant to the COVID-19 situation can be made from laboratory studies undertaken with people suffering from influenza, however they have limited application. The research to characterize SARS-CoV-2 viral production is still in its early stages and uncertainty persists. Therefore, at this stage of the pandemic, scientific judgement combined with evidence-based research is used to determine the best engineering, disinfection and modified human behaviors strategies.

The metric used to calculate disease transmission of respiratory diseases is dose, namely exposure concentration over time. However, in the case of SARS-CoV-2, that measure is not directly applicable. Rather, a more advanced multi-compartment model applies. The Susceptible – Exposed – Infected – Recovered (SEIR) model describes the situation in which a susceptible population may have been exposed but may not yet be infectious, given the virus requires a period of time to incubate and reproduce. What complicates the calculation is the susceptibility of the person exposed, the biological dose of virus particles delivered to a target organ and the duration over which the exposure occurs.

The infectious dose for COVID-19 is yet unknown. Particles (detectable, viable, and infectious) are estimated from source measurements, but include many particles that do not cause infection due to viability, infectivity, host defenses, etc. In such situations, the concept of quanta is used (see Section 3.1.6) to describe whatever that unknown number might be, and probability is applied to estimate the likelihood of inhaling an infectious dose, i.e., quanta of infection. Quanta are therefore agnostic about the actual number of particles, but quantify the number of doses generated by the source under specific circumstances and considering the probability of inhaling an infectious dose. As such, the quanta concept allows quantification of risk reductions for mitigation strategies and calculations of comparative risk for different social activities.

Disease transmission is a complex process in a heterogeneous and mobile population, visiting different types of buildings, traveling in different kinds of public vehicles and finally boarding an

airplane. The challenge is to find ways to reduce this complexity while remaining relevant to the lived experience of travelers. Grounded in biological and physical evidence, disrupting the transmission or substantially reducing the risk of transmission is possible, thereby allowing for some semblance of normal interactions and commerce until an effective vaccine or treatment against SARS-CoV-2 is widely available.

The layered approach to NPI proposed for risk mitigation of SARS-CoV-2 transmission is given in Table 1.1. Details underpinning the approach are given in the thematic sections of the Report and present the scientific rationale and evidence in support of the strategy.

For Phase 1 "Gate-to-Gate" the risk of transmission of SARS-CoV-2 to passengers and crewmembers relates only to the period from when they *leave* the departure airport, by stepping onto the connecting jetway, on the flight and until they reach their arrival airport (whether destination or transfer) and deplane to step off the jetway. The Phase 2 "Curb-to-Curb" report of this Harvard T.H. Chan School of Public Health APHI project covers the risk from passage through the departure airport, to include check-in and security screening, and arrival at the destination airport, to include baggage claim and movement out of the airport building. The Phase 2 report will also examine risks aboard intra-airport transit vehicles, such as buses and trains. Together, these two reports cover the aviation journey for both customers and the workforce.

In gate-to-gate travel, the jetway, the dimensions of the aircraft, load factors and seating arrangements restrict physical separation. When a plane exceeds 60% load factors (percent of seats occupied), it is no longer possible to rely on physical distancing alone to mitigate the risk of virus transmission. While onboard the airplane, three periods need to be evaluated to offset the risk of increased congestion ensure. These periods are boarding, cruising, and deplaning. Each of these segments involves unique activities, such as storing and retrieving luggage, using seat trays while eating, using entertainment systems, standing in the aisle and using the lavatory.

With typical airplane layouts in economy class seating, the majority of passengers are seated facing forward during the cruise portion of the flight; there are some business and first-class configurations in which passengers are seated in backward positions. However, as passengers settle in for departure they will be variously in the aisle, moving through the airplane to locate their seat and store their luggage (with luggage sometimes stowed in a number of locations). Upon arrival, the process is similar, albeit the rush to exit may mean that density is greater than during a staged boarding process.

During all of these periods of activity, and particularly the transitional conditions when physical distancing is compromised, risk of virus transmission will be reduced if surfaces are sanitized, masks are worn, and ventilation is effective. This report addresses the efficacy of these combined

strategies. Particular emphasis is placed on the effectiveness of aircraft ventilation systems, which are able to filter 99.97% of SARS-CoV-2 particles out of air found on aircraft.

Air travel demands the design of effective strategies to mitigate transmission given people are typically in close proximity to one another. These conditions may be exacerbated onboard. Prior to arrival at the airport, at check-in and/or before boarding, passengers may be subject to health screening and testing (see Section 6.0), with those of concern isolated or refused boarding. Passengers can be required to wear an appropriate face covering, typically a mask (see Section 7.0). Upon boarding and deplaning, an orderly process can be implemented to support physical distancing and reduced density (see Section 8.0). In reality, 100% compliance with these measures will be difficult to achieve in all settings. The success of these NPI depends upon educating travelers to the benefits they offer travelers and workers associated with their travel. Compliance and enforcement are essential. Furthermore, transmission is reduced by enhanced cleaning protocols and disinfection of surfaces (see Section 9.0) along with physical engineering controls and ventilation (see Section 10.0). New technologies and innovative techniques are being developed and implemented to meet the continuing challenges posed by the COVID-19 pandemic.

The risk of transmission on an aircraft can be reduced to very low levels with full compliance of the recommended NPI. Few peer-reviewed reports have been published on in-flight transmission of communicable illnesses, including COVID-19. As of September 30, 2020, there were 13 peer-reviewed case studies available for analysis that focused on COVID-19 transmission and exposure mitigation on aircraft. Of these studies, eight were commercial flights and five were evacuation or repatriation flights. Section 2.0 provides a critical account of each case study, including type of flight, number of passengers, number of potential cases, and transmission mitigation procedures reportedly in use.

After detailed analysis of these reports, it is the view of APHI that there have been a very low number of infections that could be attributed to exposure on aircraft during travel. Also, had transmission mitigation procedures, i.e., maintaining appropriate physical distancing prior to travel and use of face masks throughout the trip, been used consistently on these flights a further reduced probability of transmission of COVID-19 during the flights would be anticipated. When masks were used by crewmembers (Yang et al., 2020), no transmission to crew was found. A significant finding from the evaluation of the evacuation flight procedures was that there was no COVID-19 infection among any of the air medical crews, despite the exposure to numerous positive cases. The lack of transmission to air medical crews indicates the effectiveness of the layering approach to reduce the risk of COVID-19 transmission.

The Science and Technical Team conducted nine structured interviews with air carriers to assess their operational procedures and policies as they related to risk mitigation strategies. The team also undertook discussions with flight crew and their supervisors from these airlines to understand better passenger compliance with NPI policies. The team is grateful to the many people from the airlines and airports who gave of their time and shared their experience and insights generously.

2.2   GENERAL APPROACH

The objectives of the research undertaken by the Science and Technical Team led by the Harvard T.H Chan School of Public Health APHI were to determine high-risk areas and activities relevant to the spread of SARS-CoV-2 via droplet, airborne, and/or contact transmission routes on aircraft. Based on these exposure opportunities, science-based mitigation measures to address the perceived risks have been identified. Research-led guidance has been developed to help airlines create targeted risk mitigation strategies to deal with transmission of SARS-CoV-2 as it applies to their operations. The research and recommendations presented in this report are the independent findings of the APHI team. The project benefitted from active interactions among APHI scientists and industry engineers, leaders, and employees, who shared data, experiences, and options in response to SARS-CoV-2. The intent is to provide the industry and the public with science-based mitigation measures to address the risks of air travel through the COVID-19 crisis.

The project focused on assessing the potential for SARS-CoV-2 spread on aircraft through general routes of transmission, namely:

1. Direct contact with infectious droplets
2. Inhalation of infectious aerosols
3. Indirect contact with infectious agents contaminating inanimate surfaces (fomites)

Viruses are small, subcellular agents unable to multiply outside a host cell – they are effectively intracellular parasites (Baron, 1996). The assembled virus (virion) comprises one type of nucleic acid (RNA or DNA) and a protective protein coat. The nucleic acid contains the genetic information necessary to program viral replication in the host cell, while the protein coat protects the nucleic acid and permits attachment of the virion to the host cell. Once the viral nucleic acid has penetrated and thereby infected the host cell, replication of the virus can begin. Viruses are distinct among microbes in their extreme dependence on the host cell to be able to multiply (Baron, 1996).

SARS-CoV-2 is a novel RNA virus, with a protein coat that appears crown-like due to small bulbar projections. Infection with SARS-CoV-2 **causes a disease referred to as COVID-19**. A person in the early phase of their infection with this virus may not display any symptoms and is

said to be **pre-symptomatic**. Other people who are infected yet who do not display symptoms are referred to as **asymptomatic** (Oran & Topol, 2020). Temperature and symptom screening used effectively to detect and isolate persons with SARS-CoV-1 or H1N1 infections are therefore of limited use in the pre-symptomatic phase or in asymptomatic SARS-CoV-2 persons. This presents challenges to individuals, co-workers, friends and others who may unknowingly be in close proximity with a person capable of spreading the virus. Public health officials from the World Health Organization (WHO), Centers for Disease Control and Prevention (CDC) and numerous state and local agencies have emphasized the importance of wearing proper face coverings, practicing proper hand washing techniques, avoiding congregation and adhering to physical distancing as means to reduce risk of transmission.

Implementing context specific layered risk mitigation strategies, with the assurance of passenger and airline compliance, will help to ensure that air travel with respect to SARS-CoV-2 transmission is as safe as or substantially safer than the routine activities people undertake during these times. Technical and scientific evidence alone will however not be persuasive. But set against the millions of passenger hours already accrued during the COVID-19 pandemic, where airlines have established mask-wearing policies and implemented hospital-level cleaning practices, will help attest to the low risk of acquiring COVID-19 while flying. That said, the activities any individual chooses to engage in at this time will depend on their personal assessment of the relative risks and consequences of becoming infected and going on to develop the disease. Until the pandemic subsides, through development of herd immunity via vaccination or prior illness, many potential travelers will fly or not based on their own perception of the risks.

The risk of transmission of COVID-19 on an aircraft can be reduced to very low levels by utilizing various control measures that have been shown to be effective in other settings. Given the status of the current testing regimen and challenges relating to operationalization, the NPI addressed in this report are relevant and applicable to the goal of material risk reduction through mitigation. They are also variously included in the **COVID-19 guidance issued by cognizant authorities**, including WHO, CDC, International Air Travel Association (IATA), European Union Aviation Safety Agency (EASA, 2020), National Academies of Sciences (NAS), Association of Heating, Refrigerating, and Air Conditioning Engineers, Inc. (ASHRAE), and American Industrial Hygiene Association (AIHA). Guidance documents issued by these agencies and organizations reflect best practices derived from experience with other respiratory viruses; for some settings and controls, information is specific to SARS-CoV-2.

Behaviors and Practices to Reduce SARS-CoV-2 Risks on Aircraft

For prospective passengers, confidence in their safety from developing COVID-19 is a factor in their decision to fly (Lamb, et al., 2020). Airlines in the United States have adopted policies and procedures requiring compliance with behaviors to help mitigate the spread of SARS-CoV-2 in

the airport and aircraft settings. Those who violate these procedures may be placed on a no-fly list and barred from flying on the airline concerned. This enforcement is a powerful motivator to support behavioral compliance of passengers and is considered an important measure to help achieve consistent risk reduction and public health-protection behaviors during flights. Supporting behavioral practices to reduce the transmission of SARS-CoV-2 when traveling by air complement other risk-reduction interventions, such as the onboard ventilation and filtration systems and regular disinfection of surfaces. Measures that reduce the risks of disease transmission serve to enhance public confidence. Therefore, actions by the airlines to require compliance by passengers with risk-reducing health measures are important.

For anyone considering flying, it is important to first assess personal risk and make informed decisions accordingly. In the midst of a global pandemic, the possibility of transmission will always exist in a public environment. Therefore, individuals at higher risk should consult with health care providers for specific personalized information and advice.

Compliance with Public Health Safety Protocols

The behaviors of passengers and crewmembers on aircraft, including wearing face masks and hand hygiene, are essential to mitigating transmission of SARS-CoV-2, the virus that causes the disease COVID-19 (Jefferson et al., 2008; Beradi et al., 2020; Ferretti et al., 2020; Prather et al., 2020). Together with other risk-reduction interventions, these measures yield additive benefits, and the resultant "layered" strategy maximizes risk reduction (IATA, 2020). At the outset of the COVID-19 crisis, airlines allowed those onboard to decide voluntarily about whether or not to wear face masks, practice physical distancing, and comply with various protective procedures during boarding and deplaning. Early research on disease transmission on aircraft documented cases in which crewmembers and adjacent passengers acquired the disease when face mask use and other behaviors were not in use (Hoehl et al., 2020; Khanh et al., 2020). Concerns about such transmission prompted airlines to modify onboard policies and procedures and require compliance. By mid- to late summer 2020, individual airlines revised their requirements. Rather than recommending certain practices and allowing those on board to decide whether to comply or not, the airlines adopted policies requiring passengers age two and up and all crewmembers to wear appropriate face masks as a condition to fly. Research on face masks supports their protective role in reducing respiratory disease transmission (Jefferson et al., 2008; Beradi et al., 2020). Likewise, airlines adopted policies and procedures to encourage physical distancing when moving in the cabin while passengers boarded and deplaned the aircraft.

Adoption and Enforcement of Public Health Guidelines

Punctuated by an implicit theme, "If you don't comply, you don't fly," the airlines adopted safety campaigns, developed clear rules and expectations of passengers, and laid out enforcement policies. Airlines now provide instructions regarding health safety and give advanced and fair

warning to passengers who refuse to follow airline public health safety rules, such as properly wearing masks. After reaching the limit of successive warnings, most major airlines make it clear to the public that offenders will be placed on a no-fly list. It is noteworthy that while each airline developed its own protocols, there is overall uniformity in how the airlines address risk reduction for passengers and crew.

The airlines have issued hundreds of no-fly determinations during the COVID-19 crisis. After the limit of successive warnings have been issued, passengers may receive a yellow slip on board or a notification after the flight to signify this designation. In order to avoid in-air conflict, crewmembers may also gently request onboard compliance. If it is not given, notification of service denial occurs only after the flight is completed. The vast majority of passengers and crew conform to mandated protocols. In the most egregious situations, pilots have interrupted a flight and landed in order to discharge a defiant passenger. Though notification procedures vary, the airlines are uniformly unwavering in their stance about compliance. It is a powerful motivator to achieve passenger behavioral compliance, and it is essential for achieving consistent public health-protecting behaviors during flight.

In addition to the face mask policies, most airlines require a **health attestation** prior to boarding. The enforcement policies extend to compliance with physical distancing in the gate area prior to boarding, and include aircraft boarding and deplaning procedures. The airlines vary on their load factors, with some though not all keeping the middle seat on larger aircraft or the aisle seat on smaller aircraft unoccupied. All airlines have policies that address concerns about crowding on aircrafts, in some cases allowing passengers to rebook flights when they learn that their booked flight is at more than 70% capacity.

Safety as a Signal for Potential Fliers

The combination of mandate and strict enforcement will likely be required for the course of the COVID-19 public health crisis. Should fast and definitive pre-boarding viral testing become available, this may change such requirements. Passengers routinely comply with requirements for security screening, seat belt use, and other safety protocols. However, in the U.S. behaviors relating to wearing face masks and/or physical distancing during the pandemic have assumed a level of symbolic significance, translating nonconformity into a statement on politics or injustices, contrary to the science-based recommendations.

For prospective passengers, confidence in their safety from COVID-19 is a key factor in their decision to fly (Lamb et al., 2020). This involves the universal adoption of face masks and enforcement of face mask policies, along with other risk-reducing procedures (Graham et al., 2020). These interventions support public health safety, and trust in their enforcement has become equivalent to trust in the airworthiness of the plane and security from a terrorist threat. As with any activity, such as driving, playing sports, or lifestyle choices, there are risks.

Measures that reduce risk provide assurance. Therefore, actions by the airlines to require compliance with risk-reducing health measures have importance for the public. Of interest, an observed trend in social media postings on the topic of face masks on planes have shifted from videos and stories of transgressors to videos and stories of enforcement. The message is getting out: airlines want to stop potential viral transmission that could result from inconsistent implementation of protective measures. Consistency on the part of airlines, passengers and crewmembers will continue to be critical in both reducing passenger and crew risk and communicating to prospective fliers about mitigation measures that may inform their choices.

Responsible Self-Determination: Societal/Institutional Action and Personal Agency

Two key considerations inform the opening of segments of society during the COVID-19 crisis. They are both contingent on following the science about the novel coronavirus and its transmission. The first is what society and institutions can do to create environments that protect the health of the public and reduce the risks of disease transmission. The second is personal agency, a matter of personal behavior and personal choices. To create a safe health environment, both must be present. The actions taken by airlines and aircraft manufacturers, as described in this report, reflect both societal and institutional actions. The research, implementation of best practices, and combination/layering of effective practices for risk mitigation serve to create a lower-risk environment in the face of the SARS-CoV-2 pandemic.

The decision to fly is typically a personal one. In a public environment, there is always risk of transmission when in the midst of a global pandemic, and how people view that risk will influence their behaviors and choices (Dryhurst et al., 2020). Personal agency relies upon an individual's own decision-making capacity, increased by knowledge regarding disease risks and actions to mitigate risks (Vallacher & Wegner, 1989). These actions include wearing a face mask, maintaining appropriate physical distancing when possible, washing hands properly and avoiding face-touching (Jefferson et al., 2008; Kampf et al., 2020; Li et al., 2020). Exercising agency allows a cautious engagement in routine activities, opening freedoms and quality of life in a responsible manner. It is a formula for taking back some measure of self-determination, while engaging responsibly in an approximation of normal activities, such as taking a flight.

2.3   BACKGROUND ON COVID-19

It is important for the aviation industry to understand the virus and its behavior in order to direct activities to reduce spread and to avoid costly actions that may not materially affect transmission. COVID-19 is an infectious respiratory disease caused by the SARS-CoV-2 virus. It was first recognized in December 2019, when an outbreak of a new type of coronavirus was identified in the province of Hubei, China. The outbreak expanded very rapidly, affecting most countries worldwide. Consequently, on January 30, 2020, the outbreak was declared by the WHO as a Public Health Emergency of International Concern (PHEIC) (WHO, 2020a) and on March 11,

2020, further characterized as a pandemic (WHO, 2020b). As of September 30, 2020, there were 33.4 million cases and one million deaths worldwide, with many millions still suffering severe illness and economic hardship (Asadi et al., 2020; Ferreti et al., 2020; Wolfel et al., 2020). Key elements of the virus and the way it is transmitted are described in the following sections as background to understanding approaches to reducing its spread and in creating safer environments.

2.3.1   Background on SARS-CoV-2 Virology

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is the causative agent of CoV disease 2019 (COVID-19) (Ludwig and Zarbock, 2020). SARS-CoV-2 is a member of the *Coronavirinae* subfamily in the family *Coronaviridae*. Based on genetic and phylogenetic relationships, this subfamily is classified into four genera: α-, β-, γ-, and δ-CoV. Members of the α- and β-CoV genera infect mammals (Ye et al., 2020). Currently, circulating CoVs in human populations include two α-CoVs and two β-CoVs that cause the common cold (Ye et al., 2020). SARS-CoV-2 is a β-CoV (Ye et al., 2020). Several other highly pathogenic human β-CoVs have emerged in the past two decades, namely SARS-CoV-1 and the Middle Eastern respiratory syndrome coronavirus (MERS-CoV) (Ye et al., 2020). Human-to-human transmission via direct or indirect contact and inhalation of respiratory droplets are the main modes of spread of highly pathogenic CoVs viruses (Cui, 2019; Neerukonda, 2020).

SARS-CoV-2 virions are spherical, with a diameter of 60-100 nanometers (nm) conforming to the typical CoV diameter of 125 nm (Jin, 2020). CoVs are named after their crown-like morphology, as observed under the electron microscope, afforded by the surface glycoproteins on the virus (Figure 2.1). They are enveloped positive-sense single-stranded RNA viruses that can cause a wide range of respiratory, enteric (gut), hepatic (liver), renal (kidney), and neurologic diseases in mammals and birds. SARS-CoV-2 utilizes human angiotensin-converting enzyme 2 (ACE2) as a receptor to gain entry into human cells, which it must do to replicate itself (Hoffman, 2020). ACE2 is a type I membrane glycoprotein found on cells in the lungs, heart, intestines, and kidneys (Yan, 2020). Following transmission, the virus replicates inside cells of the respiratory (upper and lower) and gastrointestinal tracts.

Figure 2.1   Structure of the Corona Virus Virion (Source: Holmes, 2020)

2.3.2   Means of SARS-CoV-2 Viral Transmission

SARS-CoV-2 is the coronavirus that causes the COVID-19 disease. The virus is transmitted from person-to-person when respiratory droplets containing the virus are expelled from a contagious person while breathing, vocalizing, coughing, and/or sneezing and subsequently taken up through the mouth, nose, or eyes of a non-infected person; the virus then generally deposits on the lining of the nasal passages or throat (Sungnak, et al., 2020; Zhang, et al., 2020). Three possible pathways of transmission are recognized:

1. *Close contact transmission* can occur when an infectious person sheds droplets that make direct contact with an uninfected person's mucus membranes of the eyes, nose and/or mouth or are inhaled by that person. As a term, "close", is considered to be within 6-feet (1.83 meters). There is convincing evidence of SARS-CoV-2 transmission via droplet and aerosol transmission when people are in close contact (CDC, 2020a). Practices that distance people from one another respond to this mode of transmission.

2. ***Fomite transmission*** can occur when infectious particles that have previously deposited on inanimate objects or surrounding surfaces via airborne droplets or through direct contract with other contaminated surfaces, such as hands and/or tissues, are subsequently transferred to the membranes of the eyes, nose and/or mouth. While very few cases of fomite transmission have been reported (Goldman, 2020; Meyerowitz et al., 2020), this route does not require physical proximity. Transmission by fomites occurs much less often than via close contact. Practices that thoroughly clean and disinfect surfaces mitigate this form of transmission.

3. ***Longer-range or airborne transmission*** refers to the exchange of small, microscopic respiratory droplets that can remain suspended in the air, allowing for subsequent inhalation by an uninfected person; this is widely referred to as aerosolization. Some reports of spread between people in crowded, indoor settings are consistent with long-range transmission; they might also be explained by undocumented close contact. Long-range transmission is thought to occur less often than transmission by close contact. Practices that require a face mask and the provision of highly effective ventilation on aircraft are designed to mitigate disease spread through this mode of transmission.

2.3.3   Symptoms of COVID-19

A SARS-CoV-2 positive person may remain asymptomatic (~40% cases), but among those who are symptomatic, the symptoms of COVID-19 patients may include (CDC, 2020b):

- Fever above 100.4°F (37.7°C), or feeling unusually hot, accompanied by shivering/chills
- Sore throat
- New cough, not related to a chronic condition
- Runny/stuffy nose/nasal congestion (not related to allergies or relieved by antihistamines)
- Difficulty breathing, shortness of breath
- Diarrhea, with or without respiratory symptoms
- Nausea and/or vomiting
- Headache unrelated to chronic condition
- Fatigue
- Muscle aches
- New loss of sense of taste or smell
- New foot sores (COVID-19 toes)
- New rash

Symptoms may appear two to 14 days after exposure to the virus (CDC, 2020b), with a mean of six days, as shown in Figure 2.2. The current understanding is that an asymptomatic individual is approximately 75% as infectious as a symptomatic person in spreading SARS-CoV-2 (CDC,

2020c). It is useful for aircraft crew and the airline workforce who encounter customers to be aware of this list of symptoms, so they can be identified for their own well-being and in order to identify symptomatic customers.

Before Symptom Onset	After Symptom Onset	
Detection Unlikely	PCR - Likely Positive	PCR - Likely Negative
	Antibody Detection	

1 Peak Viral Load and Infectivity

2 Majority of Secondary Infections Occur Prior to this Point

3 Virus Unable to be Cultured in Mild-Moderate Illness Beyond this Point

4 <5% Probability of Culturing Virus in Severe-Critical Illness or Immunocompromised Patients Beyond this Point

5 Longest Duration of Infectious Shedding by Culture Reported to Date

6 Persistent or Recurrent Positive PCR Possible Up to this Point or Beyond (Not Contagious)

Increasing Probability of Infection

Sars-CoV-2 Exposure

Week -2 | Week -1 | Week 1 | Week 2 | Week 3 | Week 4 | Week 5 | Week 6

Day -3 | 3 | 5 | 10 | 15 | 20 | 42+

Symptom Onset

Nasopharyngeal Swab PCR — Sputum PCR — IgM Antibody — IgG Antibody

Figure adapted from: Sethuraman N, Jeremiah SS, Ryo A. Interpreting Diagnostic Tests for SARS-CoV-2. JAMA. 2020;323(22):2249–2251. doi:10.1001/jama.2020.8259 and https://www.gropmod.com/images/585/contagiousness infectivity precautions prevention diagnosis infection isolation

Figure 2.2 Temporal Pattern of Symptom Presentation, Infectivity, and Immune Response Relative to Exposure to SARS-CoV-2

2.3.4 Infectiousness Prior to Symptoms

Evidence suggests that SARS-CoV-2 RNA can be detected in people one to three days *before* the onset of symptoms, with the highest viral loads (as measured by RT-PCR[1]) observed around the day symptoms appear, followed by a gradual decline over time (Pan et al., 2020; Wolfel et al., 2020; He et al., 2020; To et al., 2020). **Transmissibility**, namely the ability of an infected person to spread the virus to another person, has been shown to begin two to three days *before* the appearance of the first symptoms (He, 2020). The duration of RT-PCR positivity generally appears to be one to two weeks for asymptomatic persons, up to three weeks or more for patients

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[1] RT-PCR stands for Reverse Transcription Polymerase Chain Reaction and is a laboratory technique to detect the presence of specific genetic material. It can be used to detect RNA from the SARS-CoV-2 virus.

with mild to moderate disease (Wolfel et al., 2020; He et al., 2020; Zhou et al., 2020), and can be much longer in patients with severe COVID-19 disease (Pan et al., 2020). One case study reported that infectivity of asymptomatic people may be weak (Gao et al., 2020), while another reported that infectiousness may last for as long as 21 days in asymptomatic individuals (Hu et al., 2020). Approximately 40-45% of SARS-COV-2 infections are considered asymptomatic (Oran et al., 2020), although it has been reported that mild or asymptomatic cases could be as high as 80% (WHO, 2020c). This is an important consideration for the aviation industry, as asymptomatic and pre-symptomatic passengers and/or crew could board aircraft and pose a risk. For this reason, strict enforcement of face mask policies are critical, since such cases cannot be identified.

2.4   CRITICAL REVIEW OF POSSIBLE TRANSMISSION ON AIRCRAFT

Although the CDC has stated that *"the risk of getting a contagious disease on an airplane is low"*, they have developed specific protocols to contact and investigate travelers who may have been exposed to a passenger harboring a contagious disease on a flight (CDC, 2019). The CDC document states that the major contacts of concern are within two rows of the *"Index patient (case)"* and specifies that *"Identifying contacts is based on the disease, how it spreads, and where a passenger was seated in relation to the index patient."* It recommends contact tracing for those individuals seated two rows in front and two rows behind the index case for highly contagious infectious diseases, such as measles and tuberculosis that have recognized airborne or droplet transmission vectors.

Airline travel presents many unique environments and opportunities to come into close contact with possible infectious people and materials. The chance for infectious contact can occur in many locations during a trip, such as in the general population at the origin or destination city, during transit to the airport, in the terminal, at an amenity destination or at the gate, besides being on an aircraft. Specifically, when onboard an aircraft, which is the focus of this Report, there are several physical factors such as very high air exchange rates, limited mobility in cabins and cabin crews that are trained in management processes to identify and segregate ill passengers, that are particular to air travel and likely help to mitigate potential exposure. During 2020, the aviation industry and the government in the United States have engaged in discussions to introduce contact-tracing systems when a case is identified on board a flight. At the time of writing, these proposed policies and practices have not been implemented.

2.4.1   Summary of Case Studies

Few reports have been published on **in-flight transmission of communicable illnesses**, including COVID-19. Indeed, a transmission event is a trigger for development of an academic paper; as such, non-transmissions are likely under-represented in the literature. As of September 28, 2020, there were 13 peer-reviewed case studies, describing 12 flights (two authors

reported on the same flight), that focused on COVID-19 transmission and exposure mitigation on aircraft. Of these studies, seven were commercial flights and five were evacuation or repatriation flights. Table 2.1 summarizes information reported by each case study, including type of flight, number of passengers, number of potential cases, and transmission mitigation procedures reportedly in use.

Each of the 12 flights are described in detail in the following sections, with further information presented in Appendix A. Each published case has however one or more significant limitations that preclude relevance to incidental exposure to an infective person on a commercial aircraft and subsequent infection. For example, the analyses undertaken of the eight commercial flights had the following limitations

- Pre-flight and/or post flight contacts between index cases and secondary cases of infection were not excluded (Chen et al., 2020; Eldin et al., 2020; Hoehl et al., 2020; Khanh et al., 2020; Speake et al., 2020).
- Seating location (or more accurately, the physical distance) of the index cases relative to those that were presumed to be secondary cases was not recorded (Bae, et al., 2020; Khanh et al., 2020).
- The exposure and incubation periods were not properly accounted for (Ng et al., 2020).
- Airborne transmission may have been misattributed, as opposed to likely infection through contact of fomite (Choi et al., 2020).

Several of these trips included passengers who had originated in Wuhan, China (Chen et al., 2020; Ng et al., 2020) or other points of origin that had high numbers of infections in the population at the time of travel. As such, initial infections could have occurred before departure (Bae et al., 2020; Choi et al., 2020). These confounding variables hamper the generalizability of the studies' findings. The study by Choi et al. (2020) indicated that although two pre-symptomatic individuals were present in business class for a 15-hour flight, the only infections that were transmitted were to two cabin crewmembers that serviced the Business Class cabin. This may indicate that no airborne viral transfer occurred to other passengers and the crewmembers' likely exposure was via fomites that they handled during service.

Furthermore, the flights that have been reported to date relevant to the transmission of COVID-19, took place in January, February or March of 2020. During those early days of the pandemic, standardized procedures of mask wearing, increased disinfection of surfaces and improved hand hygiene were not commonly employed, and reports of investigations did not always effectively detail the use of the available protocols. Upon review, it points to the need for greater standardization of data when investigating such events. Furthermore, collecting genetic evidence by sequencing the virus genome, as done by Choi et al. (2020) and Speake et al. (2020) is essential to assessing the true risk of viral transmission on aircraft.

Based on the available scientific evidence, it is the view of APHI that there have been a very low number of infections that could be attributed to exposure on aircraft during travel. Also, had transmission mitigation procedures, i.e., maintaining appropriate physical distancing prior to travel and use of face masks throughout the trip, been used consistently on these flights, a further reduced probability of transmission of COVID-19 during the flights would be anticipated.

The use of masks is an important consideration when drawing conclusions from these studies. The case study with the highest estimated COVID-19 transmission rate (7%) reported that masks were not mandatory during the flight (Khanh et al., 2020). The cases that had the next highest COVID-19 transmission rate (up to 2%) either did not provide masks, or provided masks to passengers on the plane instead of prior to boarding; this posed a risk of transmission among passengers during the check-in and boarding process (Hoehl et al., 2020). Other studies that described the use of masks reported a transmission rate of less than 1%. When masks were employed on commercial flights by infectious cases (Ng et al., 2020; Nir-Paz et al., 2020; Schwartz et al., 2020) close contacts on the aircraft remained uninfected. (Note: The son of one patient in the Ng et al. 2020 study tested positive on quarantine day 3, possibly indicating transfer on the aircraft or possibly exposure prior to boarding.) **When masks were used by crewmembers (Yang et al., 2020), no transmission to crew was found.**

The next most common reported transmission mitigation strategy was the use of **temperature checks and/or medical screening of passengers prior to boarding the flight**. The practice of temperature checking as a pre-boarding screening method has come into question, simply because presymptomatic positive cases may not be exhibiting a fever even though they are infectious. It can be effective at identifying symptomatic individuals so that they might be isolated and prevented from exposing passengers in the terminal or on the flight, though its limitations must be acknowledged. Without quick and reliable pre-boarding viral testing, it will be difficult to distinguish a COVID-19 symptomatic passenger from a passenger experiencing another respiratory illness. Temperature screenings and symptom self-declarations have limitations and can still result in the boarding of symptomatic passengers; therefore, these approaches should not be relied upon as the only implemented transmission mitigation strategy.

The only studies that reported implementing **social distancing outside the flight**, for example at check-in and during onboarding, were evacuation flights. Similarly, case studies on evacuation or repatriation flights were the only ones that reported the use of barriers on the plane to segregate patients; enhanced ventilation on the plane was also noted with cabin ventilation remaining on at all times, including while on the ground and at the gate (Cornelius et al., 2020), and specific decontamination procedures during the flight were also reported. One study described using nearly all the transmission mitigation strategies listed in Table 2.1. This study summarized multiple flights that resulted in the repatriation of over 2,000 individuals flown on

39 flights, all of whom were either COVID-19 positive, persons under investigation (PUI), or individuals who were asymptomatic. These evacuation flights all employed a layered approach to risk mitigation, implementing multiple levels of transmission mitigation strategies. **A significant finding from the evaluation of these evacuation flight procedures was that there was no COVID-19 infection among any of the air medical crews, despite the exposure to numerous positive cases. The lack of transmission to air medical crews supports the effectiveness of the layering approach to reduce the risk of COVID-19 transmission.**

Table 2.1 Summary of Information Found in Case Studies Reporting COVID-19 Positive Passengers

Study [all published in 2020]	Flight Type	Number of Crew/ Staff	Number of Passengers	Potential In-flight Transmission Number & Rate (%)	Transmission Mitigation Strategy					
					Screening Prior to Flight	Masks	Physical Distancing Outside of Flight	Barriers on Plane	Increased Ventilation	Decontamination Procedures during Flight
Chen et al.	C	11	335	1 (<1%)		✓[2]				
Eldin et al.	C	NA	NA	1 (NA)*						
Schwartz et al. & Silverstein et al. [1]	C	NA	~350	0-1 (0 – <1%)*						
Hoel et al.	C	NA	102	2 (2%)*						
Choi et al	C	NA	294	4 (1.4%)*						
Liu et al.	C	16	201	15 (7%)*	T					
Speake et al.	C	NA	213**	8-11 (3.8 – 5.2%)						
Bae et al.	E	18	299	1 (<1%)	T, M	✓[3]	✓			
Ng et al.	E	NA	94	0-2 (0 – 2%)	T	✓[4]				
Cornelius et al.	E	NA	>2,000	0 (0%)***	M	✓		✓	✓	✓
Pongpirul et al.	E	35	377	NA	T	✓	✓	✓		✓
Nir-Paz et al.	E	4	11	0 (0%)	S	✓				

C   Commercial
E   Evacuation/Repatriation
✓   Measure implemented
T   Temperature Screening
M   Medical Screening
S   Negative COVID-19 Test
NA   not applicable

*   Minimum transmission number and rate. Unable to calculate attack rate since not all passengers were tested.
**   Does not include 28 business class passengers since they were not included in analysis.
*** No transmission from index cases to crewmembers.

[1]   Two studies addressed same flight case study.
[2]   Only flight attendants wore masks.
[3]   Masks provided prior to flight.
[4]   Masks provided during flight.

2.4.2 Summary of Past Transmission of Diseases Attributed To Air Travel

Given the volume of commercial flights daily, carrying millions of passengers and crew worldwide, the number of documented incidents of infectious disease transmission occurring on board an aircraft remains infrequent. Outbreaks of respiratory diseases associated with air travel have however been reported, such as severe acute respiratory syndrome (SARS), measles, tuberculosis, and influenza (Olsen et al., 2003; Lei, 2018; Amler et al., 1982; CDC, 1983; CDC, 2004; Mangili & Gendreau, 2005; de Barros et al., 2006). Generally, these diseases are transmitted via aerosols (e.g., measles, tuberculosis) or via multiple routes (e.g., influenza). Each disease differs in the susceptibility of non-infected persons and the degree of infectiousness of the virus concerned. These cases however did not involve use of protective measures, such as wearing a face mask, now being employed. Furthermore, most of these appear to have occurred on aircraft that were likely in-service before 1990 when HEPA filters became standard equipment on most commercial aircraft. Regardless, useful information relevant to the COVID-19 pandemic can be gleaned from such accounts.

While there are occurrences of transmissibility that could inform the current crisis, **SARS** is the most closely related disease to COVID-19. In a SARS-related investigation, passengers and crew on three flights that included an infected person were interviewed. On one flight with a pre-symptomatic SARS case, no infection was documented among the passengers (Olsen et al., 2003). Another flight carried four SARS symptomatic people, with reported potential transmission to one passenger (Olsen et al., 2003). A flight with one symptomatic passenger confirmed SARS infections in 16 persons, two others were diagnosed as probable SARS, and four were reported to have SARS but could not be interviewed (Olsen et al., 2003). Illness in passengers was related to physical proximity to the index (i.e., infected) patient, with illness reported in eight of the 23 persons seated in the three rows in front of the index patient; this compared with 10 of the 88 persons seated elsewhere. Based on the locations of the secondary cases, the report suggested that airborne transmission had occurred (Olsen et al., 2003).

Lei et al. (2018) conducted a meta-analysis of 10 studies with possible **influenza** outbreaks on aircraft. The analysis showed that the risk of acquiring influenza was greater for passengers within two rows of the infected person; the risk was greater the longer the duration of the flight and the total infectivity of the index cases (Lei et al., 2018).

Measles is transmitted via aerosols and is highly infectious (CDC, 2018). However, measles transmission onboard aircrafts is believed to be uncommon (Amornkul et al., 2004; Mangili & Gendreau, 2005), with few case studies describing measles transmission during commercial air travel (Amler et al., 1982; CDC, 1983; CDC, 2004; Mangili & Gendreau, 2005; de Barros et al., 2006). In one of the most recent cases, an infectious individual traveled on six flights (one international flight arriving in Brazil and five local flights within Brazil) over a short period of

time while infected, and the investigation identified just six confirmed cases (de Barros et al., 2006).

Several studies about the in-flight transmission of **tuberculosis** have been reported, with most undertaken in the mid-1990s (MacFarland, 1993; Driver, 1994; CDC, 1995; Kenyon, 1996; WHO, 1998; Wang, 2000). Of these six investigations, two revealed a probable link to onboard transmission. In one case (Kenyon et al., 1996), four of 15 fellow passengers seated within two rows of the index passenger had a positive tuberculin skin test conversion. Overall, transmission of tuberculosis onboard aircraft is a rare event, most likely to happen to those in close proximity to the infectious passenger (within two rows) and/or exposed over a long time (greater than eight hours).

Based on the investigations of outbreaks of other respiratory diseases on aircraft, it appears that transmission on aircraft is relatively infrequent. Where transmission does occur, those close to the infectious passenger are at a higher risk than those seated at some distance. Depending on the transmissibility of the particular disease agent, determining how transmission occurs on aircraft (e.g., aerosol, direct contact, fomite) can be difficult. For example, did the transmission occur prior to boarding, during the use of a public lavatory or on the flight? In none of the published cases of respiratory disease transmission on aircraft did the authors indicate that the reference case(s) or the passengers were wearing protective face masks, as they must do on U.S. airlines today.

In many of the case reports, the difficulty of contact tracing due to lack of contact information was noted. Therefore, it would be beneficial to improve contact information to be able to respond more efficiently to a disease outbreak (Sevilla, 2018).

2.4.3 Potential Transmission of SARS-Cov-2 on a Flight from Singapore to Hangzhou, China: An Epidemiological Investigation (Chen et al., 2020)

An outbreak of COVID-19 among 324 passengers accompanied by 11 crew on a 5-hour flight from Changi Airport, Singapore to Hangzhou, China on January 24, 2020, was investigated (Chen et al., 2020). Though the flight originated in Singapore, it was strictly managed upon arrival in Hangzhou because approximately 100 passengers had departed from Wuhan to Singapore on a flight on January 19, 2020.

On the flight, face coverings were not required. No Personal Protective Equipment (PPE) was provided to the passengers and no barriers were erected on the plane. The flight operated at 89% seating capacity; the middle seat was not left unoccupied. The Boeing 787-9 aircraft was equipped with standard air handling systems.

Upon arrival in Hangzhou, passengers' temperatures were taken before deplaning. All passengers were required to follow medical isolation and observation protocols for at least 14 days. During this time, passengers were asked to take their temperature twice daily and report any upper respiratory symptoms. Crewmembers (n=11), all Singaporean, returned to Singapore on January 26, 2020, and were not part of this investigation.

All infected passengers from the January 24, 2020, flight to Hangzhou were also on the January 19, 2020, flight to Singapore. Three cases reported symptoms before the January 24, 2020, flight: two on January 23, 2020, and one on the day of the flight. On January 26, 2020, all passengers were tested for SARS-CoV-2 by RT-PCR; eight passengers tested positive, six of whom reported symptoms and two of whom were asymptomatic. On January 31, 2020, one passenger reported symptoms and on February 2, 2020, an additional two passengers reported symptoms. All passengers were tested again for SARS-CoV-2 by RT-PCR and no additional cases were identified by February 6, 2020. On February 8, 2020, all passengers not originating from Wuhan were released and the rest were released on February 15, 2020.

All the cases belonged to tour groups while in Singapore, denoted as Tour Groups A, B, C and D. There were 15 members of Tour Group A and 12 of them were confirmed SARS-CoV-2 positive. Therefore, investigators in this study attributed all infections among Tour Group A to activities amongst the tour group members prior to the flight. Three other cases, one from Tour Group B and two from Tour Group C (all asymptomatic) were identified by RT-PCR on January 26, 2020. As such, investigators ruled out transmission during the flight given the incubation time of COVID-19 being inconsistent with that timeline. Investigators concluded there was only evidence that one case, identified on February 2, 2020 and part of Tour Group D, was attributable to transmission during the flight. They reasoned that this case was consistent with the incubation time expected for COVID-19, was the only member of the tour group to become infected and was the only one not to have been on the January 19, 2020, flight from Wuhan to Singapore. This case reported that he removed his mask to eat and drink during the flight and that when he spoke, he had not worn the mask "tightly" and had his nose exposed. This actually implies that the true attack rate was 0.3%.

2.4.4   Asymptomatic Transmission of SARS-CoV-2 on Evacuation Flight (Bae et al., 2020)

A cohort study of passengers on an evacuation flight from Milan, Italy to South Korea on March 31, 2020, was evaluated (Bae et al., 2020). Prior to the flight, medical staff performed physical examinations, medical interviews, and temperature checks on 310 planned passengers; 11 were subsequently excluded from the flight. The investigation followed 299 passengers who boarded the 11-hour flight. During pre-boarding, passengers were kept 2 meters (6.56-feet) apart and were provided with N95 respirators. During the flight, most passengers wore the N95s the entire time, except for mealtimes and restroom use, though they were not required to do so. No other PPE was provided. Physical barriers were not in place during the flight and middle seats

were filled. Information on the airplane's ventilation during the flight and taxiing was not provided. The quarantine status of passengers prior to the flight was not reported.

Upon arrival, all 299 passengers were quarantined and isolated individually at a government facility for 14 days. All passengers were tested for SARS-CoV-2 by RT-PCR on quarantine days one and 14. Of the 299 quarantined passengers, six tested positive for SARS-CoV-2 on quarantine day one and were transferred to hospital for 14 days; these passengers reported no symptoms at any time and were classified as asymptomatic.

One passenger, a 28-year-old woman with no underlying disease, tested positive for SARS-CoV-2 on quarantine day 14 after reporting symptoms on quarantine day eight. She reportedly wore a N95 respirator for the entire duration of the flight except when using the toilet. According to the researchers, she likely contracted the disease on the flight. This was because the woman had been seated three rows away from an asymptomatic passenger, reported that she had self-quarantined and did not leave her dwelling in Italy for three weeks prior to the flight. The remaining passengers (n=292), crew (n=10), and medical staff (n=8) were similarly quarantined and tested negative for SARS-CoV-2 on both occasions; they were released on quarantine day 15.

Typical airline protocols now require masks to be worn by all passengers and crew, whereas in this case study (Bae et al., 2020), it was voluntary. Had masks been required for the duration of the flight, making exceptions for mealtimes and restroom use, the risk of transmission may have been reduced. The study did not mention the use of masks prior to boarding the plane. It is possible that passengers became infected with SARS-CoV-2 prior to boarding the plane given that there were 11 persons excluded from the flight with whom they may have been in contact.

The ventilation status during boarding and taxiing may have influenced the transmission of SARS-CoV-2; however, this study (Bae et al., 2020) did not provide sufficient information to evaluate this variable. The temperature screenings, physical examinations, and medical interviews of passengers prior to boarding was an effective means of reducing exposure from potentially symptomatic individuals on the plane. The pre-boarding process, which implemented social distancing of 2 meters (6.56 feet) and the use of masks, is a useful approach to reduce risk of transmission. The study did not specify the implementation of off-boarding physical distancing, which might have influenced the risk of transmission.

2.4.5   SARS-Cov-2 Infection among Travelers Returning from Wuhan, China (Ng et al., 2020)

A cohort study of passengers on an evacuation flight from Wuhan, China to Singapore on January 30, 2020, was reviewed (Ng et al., 2020). Prior to the flight (duration unspecified), 97 passengers underwent temperature screenings at check-in and before boarding; three febrile passengers were excluded from the flight. The resulting 94 passengers boarded the flight. The study did not specify social distancing requirements during the pre-boarding, boarding, or off-boarding processes.

Passengers were provided with surgical masks on board the plane, but the study did not provide information on the requirement to use masks during the flight. No other PPE was provided. Physical barriers during the flight were not in place and middle seats were filled. Information on the plane's ventilation during the flight and during taxiing was not provided. The quarantine status of passengers prior to the flight was not reported.

Upon arrival, all 94 passengers were tested for SARS-CoV-2 by RT-PCR. Two positive cases were detected and transferred to a hospital. The remaining 92 passengers were quarantined and isolated at a government facility for 14 days. Passengers were checked for symptoms and fever three times per day. On quarantine day two, four passengers reported symptoms and on day three a further two passengers reported symptoms; all six passengers were hospitalized and subsequently tested negative for SARS-CoV-2 by RT-PCR. Three of the six passengers who were thought to be symptomatic were returned to the government quarantine facility. The remaining 87 non-symptomatic passengers all tested negative by RT-PCR on day six of quarantine and were released from the government facility after the 14-day quarantine.

On day three of quarantine, 76 of 86 non-symptomatic passengers were RT-PCR tested, and one SARS-CoV-2 positive case identified with the person hospitalized; there was one inconclusive test result. The SARS-CoV-2 positive case was a 17-year-old boy who was the son of one of the two positive case passengers who arrived in Singapore. The study determined that the boy's infection was likely due to transmission from his parent. The inconclusive case, a 41-year-old man who underwent multiple RT-PCR tests that remained indeterminate, was transferred to hospital.

Surgical masks were provided to passengers once on board the plane, leaving an opportunity for transmission while boarding the plane. Additionally, the study did not indicate whether the wearing of masks was mandatory. Mandatory use of masks during boarding, for the duration of the flight, and while off-boarding, could reduce the risk of transmission. The ventilation status during boarding and taxiing was not provided. The temperature screening of passengers prior to boarding enabled the identification of three febrile persons who were denied boarding. The study did not specify any social distancing requirements at check-in, prior to boarding, or off-boarding. The lack of physical distancing measures and with masks being provided only upon boarding meant that passengers were at risk of infection with SARS-CoV-2 prior to boarding as they may have been in close contact with one of the three febrile persons denied boarding at check-in.

2.4.6   Probable Aircraft Transmission of COVID-19 In-Flight from the Central African Republic to France (Eldin et al., 2020)

A case study of a passenger who flew a round trip commercial flight from Paris, France to Bangui, Central African Republic (CAR) was reviewed (Eldin et al., 2020). The passenger flew from France to CAR on February 13, 2020, to attend a business conference for six days, which included engaging in presentations with approximately 30 people.

The passenger flew 7 hours from Bangui, CAR back to Paris, France on February 24, 2020, arriving February 25, 2020. The passenger (hereafter, Patient 1) developed symptoms on February 29, 2020, and tested positive for SARS-CoV-2 by RT-PCR on March 6, 2020. A second passenger (hereafter, Patient 2), who was identified as a business partner of Patient 1, flew on the same flight home. Patient 2 exhibited symptoms February 25-29, 2020, and tested negative for SARS-CoV-2 by RT-PCR on March 3, 2020. Both Patient 1 and Patient 2 flew economy class. A third passenger, who was identified as a coworker of Patient 1 and Patient 2, flew on the same flight home in business class and did not exhibit any symptoms.

The study made no mention of the use of masks, social distancing, temperature or medical screening, physical barriers, plane ventilation, or quarantine status of passengers prior to the flight from CAR to France.

The researchers ruled out that Patient 1 contracted SARS-CoV-2 in France before travelling to CAR given the incubation time range and the fact that there were only 15 documented cases in France at the time before travelling. They also determined Patient 1 was unlikely to have contracted SARS-CoV-2 in CAR since all known business contacts from the conference were screened and ruled out. Lastly, they ruled out that Patient 1 acquired infection in France after returning during February 25-27, 2020, since there was no local circulation documented during that time.

The researchers concluded that Patient 1 likely contracted SARS-CoV-2 on the plane back to France, while traveling with a passenger who was diagnosed with COVID-19 11 days later, in Cameroon. This scenario is plausible, since there was no indication of masks being worn during the flight or information on ventilation systems being on during boarding and taxiing. The researchers failed to acknowledge however, the possibility that Patient 1 contracted the virus at the airport during check-in, boarding, or off-boarding, given passengers were potentially not wearing masks and there was no apparent implementation of physical distancing measure.

2.4.7   Mass Air Medical Repatriation of Coronavirus Disease 2019 Patients (Cornelius et al., 2020)

The evacuation protocols implemented by the U.S. Department of Health and Human Services (HHS; Cornelius et al., 2020) for transporting U.S. citizens on evacuation flights from Wuhan, China, and from cruise ships to the U.S. was reviewed. The chartered flights resulted in the repatriation of over 2,000 individuals, all of whom were either COVID-19 positive, PUI, or individuals who were asymptomatic.

On January 29, 2020, the first American citizens were evacuated from Wuhan, China to California via a Boeing 747. In early February, four additional flights were deployed to transport the remaining U.S. citizens from Wuhan, China to the U.S. These charter flights resulted in approximately 800 passengers being repatriated from Wuhan to the U.S.

In early February, 338 U.S. citizens were evacuated from the Diamond Princess cruise ship off the coast of Japan via two Boeing 747s. The Diamond Princess cruise ship was identified as having 712 COVID-19 positive cases out of 3,711 persons aboard the ship. The 338 U.S. citizens evacuated by aircraft were taken to quarantine centers in California and Texas. Of the 338 U.S. citizens, 14 were known positives at the time of transport and five passengers developed a fever while on board the aircraft. Known or suspected cases were taken to treatment facilities upon arrival.

On March 9, 2020, the Grand Princess cruise ship returned to California with 3,533 passengers, including 21 known COVID-19 positive cases. Upon arrival, passengers disembarked the cruise ship and were transported to federal quarantine centers in California, Texas, and Georgia using Boeing 737s. During these flights, two patients became symptomatic requiring hospitalization upon arrival.

Prior to boarding any of the Boeing 737 charter flights, evacuees were screened for signs and symptoms of COVID-19 and determined to be either COVID-positive, PUI, or non-symptomatic. Surgical masks were required for PUI and N95 masks were required for known COVID-19 positive cases. Additional PPE was utilized by crewmembers. Crewmembers in close proximity (less than 6 feet, 1.83 m) to patients receiving medical treatment and monitoring during the flights wore Tyvek suits with booties and a hood, a double layer of gloves, and either a powered air-purifying respirator or a N95 mask with a face shield. Crewmembers outside of the 6 feet range (i.e., pilots and flight attendants) were fitted with a N95 mask and gloves at a minimum, and typically a gown and face shield were worn. The evacuation aircrafts were equipped with plastic sheeting as barriers to isolate areas for segregating and treating patients. The back section of the plane was designated for symptomatic individuals to allow separate egress. Safe work practices were used, which included mandatory aircraft surface decontamination, airflow exchanges, and designated lavatories. The evacuation protocols implemented by HSS (Cornelius et al., 2020) relied and expanded upon previous recommended techniques: CDC's Guidance for Air Medical Transport of Severe Acute Respiratory Syndrome Patients and Guidance on Air Medical Transport for Middle East Respiratory Syndrome Patients (CDC, 2019).

This study represented the largest repatriation of potentially contagious patients in history and was executed without infection of any supporting air medical evacuation crews. As evidenced by the lack of COVID-19 cases among air medical crew, the protocol implemented by HHS for evacuation flights is effective in reducing the risk of COVID-19 transmission.

2.4.8   Commercial Airline Protocol during COVID-19 Pandemic: An Experience of Thai Airways International (Pongpirul et al., 2020)

The case describes the implementation and feasibility of the Thai Airways International protocol implemented during the COVID-19 pandemic from the perspectives of passengers and air

crewmembers on repatriation flights (Pongpirul et al., 2020). The researchers surveyed a total of 377 passengers and 35 air crewmembers from two repatriation flights operated by Thai Airways International using a Boeing 777 aircraft. Both flights were to Bangkok, Thailand, with one flight being 9.25 hours in duration from Sydney, Australia and the other being 11.5 hours in duration from Auckland, New Zealand.

The researchers reviewed and summarized information gathered via an online questionnaire survey of 377 Thai passengers and conducted in-depth interviews with 35 air crewmembers to determine their perspectives of the Thai Airways International protocols during the COVID-19 pandemic. Thai Airways International implemented their protocol in compliance with the COVID-19 risk score developed by the Civil Aviation Authority of Thailand (CAAT). This risk score is based on number of COVID-19 cases from country of departure, proportion of seats to be occupied by passengers, flight duration, and use of HEPA filtration. Based on the level of COVID-19 risk, the CAAT risk score determines eligibility to fly to Thailand and provides requirements relating to PPE of crews and pilots, and temperature checks of passengers.

The researchers received a 22.5% passenger response rate. The passenger survey responses confirmed the receipt of surgical face masks, face shields, and disinfecting gel alcohol. The passengers estimated that there were 1.59, 1.41, and 1.26 meters (5.21, 4.63 and 4.13 feet) physical distancing at the check-in counter, pre-boarding area, and in-flight, respectively. Passengers had their temperature taken prior to the flight and reported getting their temperature taken one to two times during their flight. As part of the protocol, the cabin areas were divided by disposable curtains into five designated areas, namely the:

1) "Clean area" was located at the front of the plane, designated only for crews with PPE.
2) "Buffer zone" was designated as a dressing area for crews.
3) "Passenger area" was designated for passenger seating with had seating arrangements for the adjacent seat to be empty except for when passengers were seated next to declared family member.
4) "Quarantine area" located in the last three rows of the plane was designated for passengers or crewmembers with unanticipated symptoms identified onboard.
5) "Lavatories" at the front of the plane, designated for crew only.

The protocol implemented various disinfection procedures, such as lavatory disinfection after each use, alcohol gel provided to all passengers and the disinfection of aircrafts after flights. Upon arrival in Bangkok, all passengers were tested for COVID-19 by RT-PCR and quarantined in a government-provided hotel for 14 days.

Aircrews expressed concerns regarding occupational exposure for themselves and their family members, but their concerns seemed to be alleviated after experiencing the repatriation flights. The

aircrews estimated that there were 1.5 to 2 meters (4.92-6.56 feet) physical distancing at the check-in counter, pre-boarding area, and boarding line. Aircrews reported 1-2 meters (3.28-6.56 feet) physical distancing was not practical in-flight. The aircrews commented on the 'buffer zone', where crew would change, because crews with advanced PPE would cross paths with those using simpler means. Aircrews also determined that providing passengers with surgical masks, face-shields, and cleaning hands with alcohol gel prior to boarding was impractical because several passengers had many carry-ons.

The researchers acknowledge the limitations of their study, in particular: a low survey response rate; inaccuracy of self-reported data based on passengers' perceptions, and the nature and response of Thai passengers might not reflect other ethnic origins. The study suggested that passengers reported that in-flight temperature checks, and varying degrees of physical distancing at check-in, boarding, and in-flight was possible. The Thai Airways protocol was largely well received by both passengers and aircrews.

2.4.9   Lack of COVID-19 Transmission on an International Flight (Schwartz et al., 2020)

A study of a flight from Wuhan to Guangzhou, China then from Guangzhou, China to Toronto, Canada was reviewed (Schwartz et al., 2020). There were 350 passengers on board a 15-hour flight that landed in Toronto on January 22, 2020. A 56-year-old man arrived at a Toronto emergency room with a fever and cough one day after returning from a 3-month visit to Wuhan, China; he had developed a dry cough during the flight. Ambulance and hospital personnel wore appropriate PPE after learning of patient's travel history. The patient had a medical history of controlled hypertension, his maximum temperature was 38.6°C, oxygen saturation was 97% on room air, and respiratory rate was 22 breaths per minutes without any signs of distress. Laboratory results showed mild thrombocytopenia, normal hemoglobin concentration, and normal white blood cell count, creatinine concentration of 81 µmol/L, normal alanine aminotransferase, and normal lactate concentration. His chest X-ray showed patchy bilateral, peribronchovascular, and ill-defined opacities in all lung zones. The patient's wife developed a cough the following day. Both of their throat and nasopharyngeal swabs were found positive for COVID-19 by PCR.

Twenty-five other passengers were identified as close contacts as they were seated within 2 meters (6.56 feet) of the symptomatic case during the flight, in addition to flight crewmembers and one close contact upon arrival in Toronto. For 14 days following the flight-positive case, local public health officials monitored daily close contacts. On January 29, 2020, seven days after landing in Toronto, one close contact developed a cough but had a negative test result for SARS-CoV-2 throat and nasopharyngeal swab. Passengers identified as non-close contacts were asked to self-monitor and contact public health officials if they began experiencing any symptoms. Five of these people developed symptoms that are commonly associated with COVID-19 but also received negative throat and nasopharyngeal results. There were no secondary cases after the prolonged air

travel exposure, indicating that perhaps transmission was mitigated by mild symptoms and masking during the flight.

2.4.10 Absence of In-flight Transmission of SARS-CoV-2 likely due to use of Face Masks on Board (Nir-Paz et al., 2020)

On February 20, 2020, 11 Israeli citizens from the Diamond Princess cruise ship off the coast of Japan were repatriated back to Israel (Nir-Paz et al., 2020). The ages of the passengers ranged from 42 to 76 years. The passengers had at least one negative RT-PCR test for SARS-CoV-2 before boarding the aircraft. Two of the 11 passengers were spouses of COVID-19 patients admitted to hospitals in Japan, prior to travelling. All passengers were transferred in a dedicated bus directly from the cruise ship to the plane.

During the flight, staff wore filtering face piece masks and had minimal interaction with the passengers except to distribute two meals. The 11 passengers wore either surgical or N95 masks and had to replace their mask every 3 hours of the 13.5 hours flight. Most passengers took their mask off to eat and drink for both meals that lasted around 15 minutes each. They were also able to move around the cabin freely and use the aircraft bathrooms, with most keeping their masks on.

Once in Israel, all passengers were isolated for 14 days and retested. Two of the 11 tested positive for SARS-CoV-2; a 76-year-old male and a 62-year-old female. They were both spouses of COVID-19 patients in Japan, leading the study to conclude that they may have contracted the virus prior to boarding the plane. The woman who tested positive was also found positive by viral cultures four days after arrival. Both cases remained asymptomatic. The passengers that tested negative continued to test negative on six consecutive tests during the 14-day quarantine period, even after being in close contact on the flight with the two positive cases. Assuming that the two cases acquired their infection prior to the flight, then there were no secondary cases after the prolonged air travel exposure, indicating that perhaps mild symptoms and mandatory masking mitigated transmission during the flight.

2.4.11 Assessment of SARS-CoV-2 Transmission on an International Flight and Among a Tourist Group (Hoehl et al., 2020)

This case followed a group of 24 tourists who flew on a commercial flight from Tel Aviv, Israel to Frankfurt, Germany (Hoehl et al., 2020). None of the 24 people had received a diagnosis of COVID-19 prior to the flight; however, seven days prior to the flight, the group had contact with a hotel manager who was later diagnosed with COVID-19. There were 102 passengers on the 5-hour and 40-minute flight, including the group of 24 tourists. In Frankfurt, the tourist group received throat swabs and were questioned about symptoms, contacts, and prior testing results. All results from the IgG antibody test were confirmed with a plaque reduction neutralization test (PRNT).

Of the 24 tourists, seven tested positive for SARS-CoV-2 on arrival in Frankfurt in a throat swab sample via RT-PCR. Four of the seven experienced symptoms on the flight, two were pre-symptomatic, and one was asymptomatic for the remainder of their infection. Of the other 78 passengers on the flight, the study was only able to interview 71. One passenger tested positive by RT-PCR four days after the flight but did not recall experiencing symptoms; this passenger had a positive antibody test seven weeks after the flight and their PRNT result was positive.

Within 14 days after the flight, seven other passengers reported symptoms of COVID-19. One passenger reported headache, muscle ache, and hoarseness that started within five days after the flight. A serum sample from this passenger was collected nine weeks after the flight and detected SARS-CoV-2 IgG (antibody), and the PRNT yielded a borderline result. None of these seven passengers reported having contact with COVID-19 positive persons before the flight.

Six to nine weeks after the flight, serum samples were collected from six other symptomatic and five asymptomatic passengers. All serum samples tested negative for antibodies, except for one borderline IgG test result, which had a negative PRNT result. One symptomatic passenger was not considered a transmission case from the flight since they had had previous contact with COVID-19 patients. Some 46 asymptomatic passengers were not tested. According to the study, there were two likely COVID-19 transmissions on the flight potentially associated with the seven index cases.

The study did not specify any physical distancing requirements before the flight. The lack of physical distancing, in addition to the dereliction of masks use, may increase the risk of transmission of SARS-CoV-2 among passengers prior to boarding the flight. Due to these conditions, it is possible that passengers became infected with SARS-CoV-2 prior to boarding the plane from not wearing a mask and being in proximity to any one of the seven index cases. The two likely COVID-19 flight transmissions may have occurred due to the lack of masks being worn on the plane.

2.4.12   In-Flight Transmission of Severe Acute Respiratory Syndrome Coronavirus 2 (Choi et al, 2020)

This study evaluated viral genetic sequencing from respiratory samples from a cluster of four SARS-CoV-2 positive patients who were on the same flight from Boston, Massachusetts to Hong Kong, China (Choi et al, 2020). The authors identified the cluster from reviewing a database of 1,110 public records of laboratory-confirmed COVID-19 patients in Hong Kong, China recorded from January 23, 2020, through June 13, 2020. The four-patient cluster (Patients A-D) was determined to be associated with a 15-hour commercial flight carrying 294 passengers that departed from Boston on March 9, 2020 and arrived in Hong Kong March 10, 2020.

The study did not specify any use of masks, physical distancing, quarantining, temperature or medical screenings, or ventilation requirements before, during, or after the flight. The authors were

unable to determine the attack rate of the virus since not all passengers were tested after the flight. Using public records data, the authors were able to obtain detailed information on the four cases determined to be associated with the flight.

Of the four cases, two patients were passengers (Patients A and B) and two were crewmembers (Patients C and D). Patients A and B were a married couple, who both sat in window seats in business class, with one seated in front of the other. Patients A and B both developed symptoms on March 10, 2020, and were diagnosed with SARS-CoV-2 by March 15, 2020. Prior to the flight, and within the 14-day incubation period, Patients A and B visited Toronto and Ontario, Canada (February 15 through March 2, 2020); New York, U.S. (March 2-5, 2020), and Boston, U.S. (March 5-9, 2020). The couple was classified as imported cases to Hong Kong.

Patients C and D were flight attendants during the flight and identified via contact tracing by the Hong Kong government and the airline as being close contacts of Patients A and B. Patient C was a Hong Kong-based business class flight attendant who served Patients A and B during the flight. Patient C was asymptomatic and determined to be SAR-CoV-2 positive on March 17, 2020. Patient C also stayed in Boston, U.S. from March 5-9, 2020 prior to the flight.

Patient D was a Hong Kong-based flight attendant on the same flight as Patients A, B and C. Patient D became symptomatic on March 18, 2020 and was diagnosed with SARS-CoV-2 on March 21, 2020. No other information was provided on patient D's travel prior to the flight or contact with other patients during or after the flight.

The authors determined the viral sequencing from the upper respiratory samples of Patients A-D to yield near full-length viral genomes that were 100% identical and phylogenetically grouped to clade G.[2] None of the other 189 viral sequences deduced from samples collected in Hong Kong during January 21, 2020 through to May 12, 2020 belonged to clade G. Additionally, the researchers determined the virus sequences related to Patients A-D were isolated to Toronto, New York City, and Massachusetts, making it plausible those Patients A and B acquired a similar virus during their visit. These findings suggest that the virus was transmitted during air travel from index cases, Patients A and B, to Patients C and D.

The researchers stated that the 15-hour flight was the only location where all four patients were in close proximity for an extended period. There was no information provided on control measures for virus transmission implemented before, during or after the flight. According to the timeline and contact tracing identifying close contacts, it is plausible that the transmission of SARS-CoV-2 from Patients A and B to Patients C and D occurred on the flight. Given that there is no

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[2] Clade is a term to denote related organisms descended from a common ancestor; clade G is a variant of the SARS-CoV-2 genetic sequence widely distributed globally.

information on any precautionary measures being employed, it is possible that the proper use of such measures could have prevented this transmission.

2.4.13 Transmission of Severe Acute Respiratory Syndrome Coronavirus 2 during a Long Flight (Khanh et al., 2020)

An outbreak of COVID-19 among 201 passengers accompanied by 16 crew on a commercial 10-hour flight from London, United Kingdom to Hanoi, Vietnam on March 1-2, 2020, was investigated (Khanh et al., 2020). Prior to the flight, all passengers underwent thermal imaging and completed a self-declaration of any symptoms. No passengers were excluded from the flight based on these screening results.

Prior to the flight, one passenger traveled to Italy and Paris with her sister. This passenger (Case 1) began to experience symptoms (cough and a sore throat) two days prior to her flight. Case 1 underwent the screening process, failed to report any symptoms on the self-declaration form, and boarded the flight. Case 1 was seated in business class, among 21 other passengers, and continued to experience a sore throat and cough during the flight. On March 5, 2020, three days after her arrival, Case 1 went to a hospital in Hanoi and tested positive for SARS-CoV-2 via PCR. The sister of Case 1, who had traveled to Italy and France prior to the flight also tested positive for SARS-CoV-2.

Upon learning the status and travel history of the index case (Case 1), local health staff began the process of contact tracing. All flight crew, 16 (100%) were successfully traced, quarantined, interviewed, and tested. Most passengers, 168 (84%) were successfully traced, quarantined, interviewed, and tested. There were 33 (16%) passengers who were not contacted since they had transited to other countries. Of the 184 crew and passengers traced, 15 additional COVID-19 cases were identified; this indicated a transmission rate of at least 7% (15 cases/217 crew and passengers). The number could be higher if any of the remaining 33 passengers ended up being SARS-CoV-2 positive. These 15 secondary cases met all of the following inclusion criteria for being a probable secondary case, namely:

1) They experienced signs/symptoms 2–14 days after arrival or they were SARS-CoV-2 positive by PCR 2–14 days after arrival in the absence of signs/symptoms.
2) In-depth investigation did not reveal any potential exposure to SARS-CoV-2 before or after the flight during the incubation period.
3) They had shared cabin space with a probable index case during the flight.

Of the 15 secondary cases, 12 passengers were from business class (where case 1 sat), one was a crewmember serving the economy class, and two passengers were in the economy class. Cases were defined 2-14 days from the flight, within the 14-day incubation period. The researchers determined the attack rate of the virus in business class to be 62% (13 cases out of 21 passengers).

The authors determined that 11 of 12 (92%) passengers ≤2 m (6.56 feet) away (≤2 seats away) from case 1 were SARS-CoV-2 positive, whereas 1 of 8 (13%) passengers >2 m (6.56 feet) away (>2 seats away) were SARS-CoV-2 positive. These calculations resulted in a risk ratio of 7.3 (95% CI 1.2-46.2). The researchers also determined that of the 12 additional cases in business class, 8 (67%) developed symptoms, with a median symptom onset of 8.8 days after arrival. The authors determined sitting in business class, where case 1 sat, to be the biggest risk factor for transmission of COVID-19.

Current typical airline protocols require masks to be worn by all passengers and crew; however, there were no mandatory mask protocols during this time. If masks had been required during the duration of the flight, making exceptions for mealtime and restroom use, then the risk of transmission may have been reduced. Additionally, the authors acknowledged that aerosol or droplet transmission from case 1 might have occurred outside of the airplane, such as at the airport terminal, in a pre-departure lounge, during the boarding process, in lines to immigration, and/or in baggage claim. The study did not specify any physical distancing parameters implemented before or after the flight. The lack of physical distancing, in addition to not wearing masks may have increased the risk of transmission of SARS-CoV-2 among passengers before and/or after the flight. **As evident by this case study, thermal imaging and self-declaration of symptoms cannot be the only control measures implemented to prevent transmission of COVID-19.**

2.4.14 Flight-Associated Transmission of Severe Acute Respiratory Syndrome Coronavirus 2 Corroborated by Whole-Genome Sequencing (Speake et al., 2020)

This study evaluated an outbreak of COVID-19 among 213 economy class passengers who flew a 5-hour commercial flight from Sydney to Perth, Australia on March 19, 2020. Passengers comprised of travelers transitioning from Sydney to Perth after arriving from one of three oversea cruise ships and international flights, as well as domestic travelers. It was determined after the flight that two of the three cruise ships had an outbreak onboard. The study utilized epidemiologic analyses in conjunction with whole-genome sequencing (WGS) to evaluate potential transmission of SARS-CoV-2 during the flight. In addition to evaluating potential in-flight transmission, the researchers utilized statistical analyses to test the hypothesis that the risk for flight-associated infections was independent of seat assignments.

According to interviewed passengers, masks were rarely used during the flight and there was no information provided on masks worn before or after the flight in the terminal or during the boarding process. The study did not specify any social distancing, temperature or medical screenings, or ventilation requirements before, during, or after the flight. At the time, COVID-19 PCR testing was only offered to persons experiencing symptoms. There was no testing conducted prior to the flight.

Investigations of COVID-19 transmissions during this flight began after March 21, 2020, when the Western Australian Department of Health was notified that six passengers aboard the flight had tested positive for SARS-CoV-2 by PCR. These six passengers had recently disembarked from cruise ships that had docked in Sydney on March 18 and 19, 2020. After the initial six PCR-positive cases were identified, all close contacts were informed and directed to quarantine. There were 64 passengers from the flight that experienced symptoms, 29 passengers were determined positive and 35 passengers were determined negative by PCR. There were no cases reported among crew.

Among the 29 confirmed passenger cases, onset of symptoms occurred between March 15 to April 1, 2020. Of the 29 confirmed cases, 13 had been on the Ruby Princess cruise ship, four were on the Ovation of the Seas cruise ship, two were on the Sun princess cruise ship, five were international travelers, and five were domestic travelers. Two cruise ships, Ruby Princess and Ovation of the Seas, were retrospectively identified as experiencing a SARS-CoV-2 outbreak. Of the 29 PCR-positive cases, there was sufficient viral RNA available for 25 of the 29 to generate a sequence, with 100% coverage obtained for 21 samples and partial coverage for 4 samples. The WGS yielded a phylogenetic tree for 21 complete genomes to determine the viral lineage, which resulted in 17 cases that were A.2 sequences and 4 cases that were B.1 sequences. Utilizing the GISAID international database, the researchers linked the A.2 sequence to a cluster from the Ruby Princess cruise ship (sequence hereafter "A2-RP"). The A2-RP was not previously identified in the GISAID database prior to the outbreak on the cruise ship.

To determine flight-associated transmissions, the researchers defined primary cases as being "passengers with SARS-CoV-2 who had been on a cruise ship with a known outbreak in the 14 days prior to illness onset and whose specimen yielded a virus genomic sequence closely matching that of the ship's outbreak strain" and/or "any passenger whose illness began prior or within 48-hours after the flight's departure." Secondary cases were defined as "passengers with PCR-confirmed SARS-CoV-2 infection who had not been on a cruise ship with a known SARS-CoV-2 outbreak within 14 days of illness onset and whom symptoms developed >48 hours after and within 14 days of flight." The researchers defined flight-associated secondary cases as "international passengers who arrived in Sydney March 19, 2020 or domestic Australia travelers who had not been on a cruise ship in 14 days before illness and whose specimens yielded WGS lineage not known to be in circulation at their place of origin but closely matched lineage of a primary case on the flight." Lastly, suspect possible flight-associated cases were defined as "persons who had recently been on a cruise ship with no known onboard SARS-CoV-2 transmission and specimen yielded lineage related to that of passengers with primary cases on flight," or "domestic passengers who had not been on a cruise ship but for whom WGS information was unavailable."

Of the 29 PCR-positive cases, 18 were classified as primary cases. Thirteen of the primary cases were from the Ruby Princess cruise ship and had the A2-RP sequence, nine of which were classified as infectious during the flight. Four of the primary cases were from Ovation of the Seas cruise ship and had the B.1 sequence, one of which was classified as infectious during the flight. One of the primary cases was a traveler returning from the U.S. who was classified as infectious during the flight and had the B.1 sequence. Utilizing epidemiological analyses and WGS, the researchers identified 11 secondary cases that had symptom onset during March 22, and April 1, 2020. Of these 11 secondary cases, eight were classified as flight-associated, all with the A2-RP sequence, unique to the Ruby Princess cruise ship outbreak. The remaining three cases were classified as possible flight-associated cases due to the B.1 viral sequence results. The authors determined infection from sources outside of the flight to be unlikely since SARS-CoV-2 risk was low in both New South Wales and Western Australia during the time of the flight. Additionally, two of these possible flight-associated cases had recently disembarked from the Sun Princess cruise ship, which had no reported outbreak. The third possible flight-associated case did not have a specimen and was therefore considered suspect.

The researchers reviewed the seating location of the 11 infectious primary and flight-associated cases to determine the spatial distribution of transmission. There were six primary infectious cases located in the mid cabin and five in the aft cabin. Of the six primary infectious cases in the mid cabin, three were symptomatic passengers who had disembarked from the Ruby Princess and were seated together in the same row, all with the A2-RP sequence. The remaining three primary infectious cases in the mid cabin comprised of one pre-symptomatic passenger from the Ruby Princess with A2-RP lineage, one traveler from the U.S. with B.1 lineage, and one passenger from Ovation of the Seas with B.1 lineage. There were five infectious primary cases in the aft cabin, all of which were from the Ruby Princess cruise ship and had the A2-RP sequence. The researchers determined a significantly higher risk for secondary infection among passengers in the mid cabin (11 cases of 112 passengers) in comparison to secondary infection among passengers in the aft cabin (zero cases of 101 passengers; $p<0.005$). The researchers also evaluated the influence of window seating on infection and found that seven of eleven secondary cases had window seats. More specifically, they determined the secondary attack rate among mid cabin passengers in a window seat (seven cases of 28 window-seated passengers) was significantly greater than non-window seats (four cases of 83 non-window-seated passengers, $p <0.007$). With regards to the spatial distribution of infection, the researchers found that three of the eleven secondary flight-associated cases were outside of the usual distance parameters of two rows front and behind from primary cases. The researchers noted that secondary infections from infectious passengers was not uniform and suggested that the lineage of the virus and settings of the different airplane cabins may influence infection.

Flight-associated transmissions might have been reduced or eliminated had there been temperature and medical screening implemented to prevent the boarding of symptomatic, infectious, primary

cases. Additionally, the use of masks before, during, and after the flight might have reduced the spread of aerosols and transmission. As noted by the authors, there was no information provided on passenger movements in the airport, gate, and aboard the aircraft. There was no mention of physical distancing or the use of masks at the airport; therefore, it is possible that transmission could have occurred in the airport before or after the flight. The spatial clustering of secondary cases in the mid cabin of the plane suggest, however, that transmission occurred during the flight.

2.5 SUMMARY OF AIRLINE PRACTICES: INTERVIEWS WITH AIRLINES

Airline personnel from nine airlines were surveyed using semi-structured online interviews and a questionnaire issued to staff (see Appendix C) to understand how airlines were adapting their operations and services toward increased health and safety to mitigate SARS-CoV-2 transmission during air travel. Of the nine airlines, seven participated in an interview, six completed the questionnaire and four did both. Personnel included those from corporate strategy to ground operations, aircraft and flight safety, crew management, environmental health and safety, chief medical officers and members of COVID-19 working groups; most had around 20-years' service with the airline concerned with only a few less than five years. The main findings are given in the following account, with further details available in Appendix D, with summaries by airline (coded for anonymity).

2.5.1 Airlines' Face Mask Policies and Enforcement

Face masks or face coverings help prevent inhalation or expiration of particles that may contain virus, and their efficacy varies by type of mask and how it is worn (see Section 7.2). All nine airlines had a strict policy or mandate in place for passengers and crewmembers to wear a mask that fully covers their nose and mouth, secured at the chin, and worn throughout the travel journey. The only exceptions were children under two years, who should not wear a mask according to current CDC face covering guidance (CDC, 2020d). Only two of the nine airlines considered cases with medical exceptions, for which these airlines had a standard process in place with a third-party medical partner. All nine airlines used their websites to communicate their face mask policy, with announcements/notices at check-in, at the gate and onboard.

> *"…included in our gate announcement, we remind passengers that the mask must also be covering their nose and mouth, and we also make an announcement on board, the flight attendants do…"* (Airline #1)

> *"… it's included during the check in process where customers are asked to acknowledge that they have seen the health questions as well as our mask requirement for the airport and onboard … a series of both airport and onboard announcements, … all of our customer-facing employees are empowered to enforce this policy."* (Airline #2)

All nine airlines prohibited masks with holes, vents, valves, openings, or made from mesh materials. In addition, face shields cannot be worn without wearing a mask underneath. One airline updated their policy to prohibit powered air purifying respirators (PAPRs) or breathing apparatus that enclose the face or the head. For passengers without a mask or with a non-compliant mask, all nine airlines provide one. Airlines have surgical-style or disposable masks available for crewmembers and passengers. A few airlines have branded masks or face shields available for crew or are considering offering face shields to their flight crew.

> *"...we've restricted face mask types to either the surgical mask or to the cotton mask that would be worn, not N95 mask, and not a gaitor or a neck gaitor or a bandana… not a valve mask either."* (Airline #3)

All nine airlines deny boarding to passengers without a mask and have a process to handle non-compliance during a flight. Flight attendants and pilots remind people to wear their masks, and issue warnings to non-compliant passengers. The warning process varies among the airlines, albeit most provide three warnings, verbal and written; a final warning is issued before filing a report or instituting a flight ban. Such no-fly bans remain in place for a defined period, which can be a year, for the duration of the passenger's passport, or until the airline's mask policy subsides; the latter is the most common ban among the airlines examined. Only one airline indicated that non-compliance could lead to a permanent no-fly ban on the airline. Overall, the airlines reported having good compliance, but on average, an airline may handle up to 15 reports per day where passengers had not complied but have fewer than 65 people listed on a no-fly ban.

> *"What we have done though is ensure that we are enforcing the mask policy. So essentially we have a three strikes or you are out, so we tell you about it before you get on board the aircraft, once you do get on, we reiterate it from both the captain and attendants, and if you take it off during flight, you can only do that if you're eating or drinking…"* (Airline #3)

> *"For in flight, we've actually adopted a three strike policy. … at the third time they actually provide them this face mask policy enforcement card… if there is no further compliance from the passenger then the flight attendant brings up an in-flight incident report and reviews the situation … we have been basically suspending travel …for a period of a year."* (Airline #6)

The only time a passenger onboard is permitted to remove their mask briefly is while eating and/or drinking. Most airlines have limited the beverage and snack service on board, and/or have suspended it altogether on shorter flights, and/or suspended offering food for purchase. Some airlines only offer or sell bottled water or have available a pre-sealed snack bag for customers, which can be self-served or provided upon request. One airline has straws available upon request.

"... limiting the number of touchpoints you have with a customer ... having a customer self-serve ...[passengers] use a drink service as an opportunity to not wear a mask for the majority of a flight." (Airline #1)

2.5.2   Health Screening of Crew and Passengers

Airlines have implemented health-screening measures for employees. Seven out of the nine airlines had instituted a health attestation process for crewmembers, either daily, monthly or a one-time acknowledgement process to check daily that they are fit for duty and not experiencing any of the symptoms associated with COVID-19. Employees are asked to be vigilant for any of these symptoms, according to CDC guidance (see Section 2.3.3): chills; cough; sore throat; persistent headaches; nausea and/or diarrhea; loss of smell and/or taste; fatigue and/or muscle pain; shortness of breath and/or difficulty breathing; elevated temperature of 100.4°F (38°C) or higher. The other two airlines relied on crew self-monitoring and on following protocols to not present for work if they have symptoms.

"...if you feel sick then you shouldn't be at work, ... make sure that your fever is not greater than 100.4 degrees, ...check themselves against the sense that ... they're okay to enter the workplace. (Airline #6)

Having a temperature of 100.4°F (38°C) or higher is considered a fever and is one of the symptoms that can be easily monitored at home and at the airport. Temperature checks are conducted by five of the airlines at airports and/or headquarters, some using contactless devices or thermal cameras. The monitoring is conducted at least daily and as often as before each flight, and in some cases before a training session. Many airlines ask pilots and flight attendants to monitor their temperature at least twice daily, and some airlines check before each flight.

"We've scanned our team members over 1.2 million times with a really low number of individuals that we are detecting a temperature. We're using CDC 100.4 degrees or in some locations, there's an executive order to finding the fever or temperature that we should be scanning for, but it's almost more of a pass fail with the devices that we're using." (Airline #1)

"...our temperature screening process is really focused at our headquarters and in our hot spots…. any place with three COVID positive cases within seven days we deem as a hotspot ... it's very rare that we're picking up anything on the temperature screening." (Airline #4)

The airlines that do not monitor temperatures at the airport ask employees to check their temperature at home. If their temperature is 100.4°F (38°C) or higher, or if staff present with other COVID-19 related symptoms, the employee is advised not to present for work and go to their

healthcare provider. For employee health declarations, using an App or other type of reporting, airlines can capture the symptoms an employee reports. For example, one of the airlines mentioned that fever was the highest reported symptom.

Other types of health screening were discussed with the airlines, including the monitoring of oxygen saturation, which could be a secondary screening on persons presenting with a high temperature. Currently none of the airlines was conducting oxygen saturation monitoring of employees or passengers, although some inflight medical kits do include oximeters to handle incidents.

Testing for SARS-CoV-2 was not practiced routinely by airlines, due largely to the lack of availability of tests and the high associated costs. Five of the airlines do provide testing for asymptomatic employees as an option, or as part of a testing program, or have testing available for flights where a destination requires it. Some on-the-spot testing programs have a more targeted approach in accord with the reported prevalence of a virus in a location, if mandated by a destination, or is reserved for the pilot staff only. Increasingly and most recently, five airlines started to offer rapid tests for passengers through third-party vendors at select airports, and/or at-home mail-in test kits, and/or onsite at select locations.

Health screening was also conducted for passengers. All the nine airlines incorporated a health attestation process at check-in, via their website, an App, or at airport kiosks. Most of these asked passengers to confirm that they are not exhibiting symptoms of COVID-19; that they have not been diagnosed with COVID-19; and that they have not had a known exposure to anyone who has tested positive or a person exhibiting symptoms in the past 14 days. They are also asked whether they have checked their temperature prior to travel and asked not to travel if their temperature is 100.4ºF (38°C) or higher. Passengers are also advised that they must wear a mask or face covering throughout the entire flight.

In addition to the health attestation, two airlines check the temperatures of passengers before boarding, and will not allow a person with a temperature of 100.4ºF (38°C) or higher to board. There is interest in implementing SARS-CoV-2 testing for passengers on certain routes by a few airlines, with one airline already offering rapid tests for passengers at select airports.

All airlines were prepared to handle incidents should a passenger start exhibiting COVID-19 symptoms onboard. Flight attendants follow standard procedures and protocols listed in the flight manual, or in other standard guidance for handling such cases. In addition, more than half of the airlines have a third-party medical assistance partner they can consult. All aircraft have medical kits onboard, some have more specialized kits that include N95 respirators, protective PPE, and oximeters in two of the airlines' medical kits.

2.5.3 Physical Distancing during Boarding, Cruising, and Deplaning

Airlines have adopted a suite of measures to limit touch points and support physical distancing at check-in, the gate and in the cabin while boarding and deplaning. Most had adopted touchless check-in and boarding via an App. Most airlines had installed Plexiglass screens at check-in counters and kiosks. All airlines made announcements to remind passengers to practice physical distancing at the gate, during the flight and while boarding and deplaning. Two airlines noted that reminders and updates to the announcements are made with some frequency to improve their effectiveness. Different types of signage have been used to remind customers to keep their distance from one another, as well as to visualize the recommended proximities of at least 6 feet (1.83 m) between travelers. In terms of signage, jet-bridges had visual aids and floor decals for distancing across the airline areas.

> " ... make announcements during onboarding, asking the customers to create space and to not huddle in the gate area, ... floor markers and wall markers in some of the jet bridges to remind customers of the space that they should be keeping between themselves and other customers.." (Airline #1)

> "...through some visual aids that we've installed, as well as announcements and of course trying to kind of chunk up the number of people per boarding zone." (Airline #3)

The boarding and deplaning processes had been modified to better control congestion in jet-bridges and the cabin aisles. Eight out of the nine airlines were boarding from the back to the front in small groups of three to five rows, or groups of 10 persons, or groups of eight rows at a time. Some airlines also explain the modified boarding and deplaning processes on their website.

> "...some of the boarding schemes that we're evaluating right now are, how do we get people on the plane in a way that is more spread out ... we're trying to determine what's the right approach going forward, and what is the exact right algorithm to assign group numbers to get people on a plane in a way that's a little bit more dispersed ... (Airline #1)

> "... we did modify our boarding process.... it does rely upon the operations agent, the gate agent to make good clear announcements to make sure that customers understand the boarding process has changed" (Airline #4)

For deplaning, almost all the airlines exited row by row, which they announce during the landing process. But most airlines noted that the modified deplaning process is more difficult to control, as most passengers still attempt to stand up as soon as the plane is parked at the gate.

"... we're trying to get our customers to stay seated when they're deplaning ... getting them to deplane a little bit more slowly, ... it's something we're going to have to work on how do we get that behavior to change (Airline #1)

"... additional information for our customers, whether it be on a seat back TV screens, for example, so upon landing it will it queue up a brief commercial or a brief kind of reminder for the deplaning processes, 'Please remain seated until the front row in front of you deplanes'." (Airline #7)

The lower load factors airlines are experiencing have helped to maintain physical distancing in the cabin, as well as while boarding and deplaning. Three of the airlines continue to block the middle seat to provide more spacing between travelers. For capacity control on seating, one airline caps non-revenue flying and stand-by boarding while another offers to rebook passengers where a flight has a 70% loading factor. Several airlines do not block the middle seat and noted that there is no evidence currently on how blocking seats might help to reduce COVID-19 infections. In order to attract customers and reinstate trust, all nine airlines have loosened the flight change policies, most have eliminated fees altogether, and a couple have eliminated change fees permanently.

2.5.4   Aircraft Cleaning and Disinfection

The airlines' disinfection processes have changed significantly in order to reduce any contaminated surfaces or fomites inside the cabin. All airlines have added additional cleaning, prioritizing between flights highly touched areas, and adding additional disinfection overnight or when there is enough time between flights or "turns." Between turns, most disinfection activities require wiping down the high touch areas, lavatories, and galleys. Deeper cleaning is done mostly overnight and often includes use of electrostatic spraying (see Section 9.2.1).

Seven of the airlines have implemented electrostatic spraying of disinfectants, which should reach most areas inside the cabin. Some airlines perform electrostatic spraying at least once per day, or between flights, when having at least two to six hours or more. The other two airlines are not undertaking electrostatic spraying and have instead implemented use of fogging disinfectants overnight or once a week. In addition to antiviral spraying, three airlines have incorporated antimicrobial spraying, ranging from a weekly application to once a month. In order to carry out these extensive cleaning protocols, almost all airlines have included additional cleaning training.

"... before onboard the aircraft, we do go through an extensive cleaning process ... we've done really two significant enhancements. One, ... we've increased just the number of touch points on the aircraft. ... The other ... has been the electrostatic spraying, which I think there's been a lot about that in the media...." (Airline #3)

Two of the airlines have also incorporated ATP (Adenosine Triphosphate) testing of cleaned surfaces as a quality control measure. This has been done using an ATP handheld device after cleaning, which has helped to find priority areas. Several airlines are also undergoing cleaning certification programs, and reviews of cleaning products.

> *"...we do spot checks with ATP testing, which is the same type of testing used in the hospital. And so we'll do spot checks ...we do the elbow grease scrubbing of surfaces first, before we do the electrostatic, we know that the electrostatic alone is not going to do it, so we wipe everything down with cleaner or disinfectant. And then we follow up with the electrostatic spray ... then we let that dry on its own."* (Airline #5)

> *"So we've actually added an extensive amount of round time to our turns in order to allow us to go through the process. ... We're no longer provisioning things like pillows and blankets on the vast majority of our turns...."* (Airline #3)

The airlines are using EPA approved disinfectants (see Section 9.2 and Table 9.2) to kill the SARS-CoV-2 that are also compatible for use in an air cabin environment, as recommended by the aircraft manufacturers. Among the disinfectant chemicals most commonly used by the airlines are chlorine dioxide, quaternary ammonium, and lactic acid, among others. A couple of airlines are using antiviral coatings or are considering their use.

Strict government security restrictions limit the quantities of liquids and gels passengers can bring on board aircraft. In addition, in order to avoid customers bringing household cleaning products that can damage the aircraft, several airlines are actively limiting what passengers can use for disinfecting surfaces and hands. Five of the airlines have alcohol-based disinfecting wipes available for passengers, upon request, or are handing them out upon boarding to ensure customers use cabin-compatible products to disinfect their seating area.

Some airlines are looking into new technological applications for disinfection, particularly UV (see Section 9.2.2) and UV-C (see Figure 9.4) and use of thermal treatments inside the cabin. One of the airlines is piloting a UV cart that disinfects as it moves along the cabin. Other airlines are using or testing UV handheld devices on the flight deck where chemical application is not appropriate.

> *"... we do UV disinfection of the aircraft...think of a beverage cart that has wings that protrude out over the seats, and it also has an extension that goes up towards the ceiling that would also capture the overhead bins. ... with this unit, we are able to hit the lavs..., the galleys, ...the cabin, ...using a 254 range"* (Airline #7)

"we're looking at thermal, heating aircraft to a certain temperature… waiting for their studies to come out because there's a lot of things that need to happen to heat up to a certain temperature and sustain that." (Airline #6)

2.5.5   Healthy Air in the Cabin: Ventilation During Different Stages

An aircraft cabin has inherently a high airflow volume and high-quality air filtration during cruising, which are managed through the environmental control system (ECS) that also controls the temperature and cabin pressurization. All nine airlines mentioned having high air exchange rates of approximately every 2 to 3 minutes (20 to 30 ACH) while cruising, a rate that is similar to, or even higher than the recommended air exchange rates for an operating room in a hospital.

"…we've accomplished a fair amount of work on understanding onboard air quality, being so important to our customers…." (Airline #3)

The ECS air supply when flying is bleed air, or air that is compressed and sent to the air conditioning units, known as A/C packs. The ECS has been designed to recirculate some of the air inside the cabin. Air recirculation happens mostly when cruising, where about 40% to 50% of the cabin air is recirculated and filtered through a high-efficiency particulate air filter, also known as a HEPA filter. All the airlines interviewed have aircraft that are equipped with HEPA filters, and one of the airlines has increased the replacement frequency of their HEPA filters.

"For the most part, onboard air is composed of approximately 50% fresh air from the engine-driven pneumatic system and 50% recycled air, the recycled air goes through every circulation system through HEPA filters. We began by increasing the frequency by which we maintained and replace the HEPA filters." (Airline #3)

Once an aircraft is on the ground, the source of air supply can come from various sources, it is then mixed and distributed to the cabin. One source is through the airplane auxiliary power unit (APU) with the engine in operation, which consumes fuel and can generate noise and emissions at the airport. The air supply may also come from airport ground sources (jet-bridge or cart), known as pre-conditioned air (PCA) that supplies the cabin with fresh air, usually outside air, but at a more reduced flow. Whether the airline owns or controls the ground-based systems varies by airport. In many cases, the air that is being supplied by jet-bridge or cart, is managed by the airport. One of the airlines has been conducting air quality studies in their fleet and at different flight stages, to understand when the risk of SARS-CoV-2 might be higher inside the cabin.

"We then began sampling onboard air at the various stages of flight from the boarding process to …, push back, taxi out, climb, cruise, descent, landing, ride, and deplaning… as a proxy for clean air we only measured particles, fine particles 0.3 to 25 microns in

size. And we collected all that data internally with LTE equipment with personnel. And we also then sample various public spaces, grocery stores, big box retailers, office environments, various places people encounter every day and what we conclusively found is that the onboard air systems, especially in use of the HEPA filters has inherently and exponentially less particles of that size than the places we encounter every day." (Airline #3)

In order to increase ventilation during ground time, several airlines have opted to keep the APUs and ECS running. About half of the airlines interviewed kept engines on or turn on the APUs in order to maintain good air quality conditions on the ground while deplaning and boarding.

"...we have the ability to be self-sufficient on the ground so we can generate both electricity and bleed air, ... There's a tradeoff there,... because when you run the APU, fuel burns, and that costs. But very early on, we did advocate for our flight crews to go ahead and use the APU while we're on the ground for both boarding and deplaning ... to mitigate that concern" (Airline #7)

Other airlines prefer, or have to use, other ground air sources if they are unable to run the APUs, or if an airport does not allow it. Ground air sources are preconditioned air, such as PCA from the jet-bridges, as shown in Figure 2.3, or mounted on carts. Air filtration on the ground is important for airlines as it improves the air quality in the gates and cabins. The ground air may be equipped with filters with minimum efficiency reporting value (MERV) for filtering outside air, or in the case the air source comes from indoors and needs to be recirculated. One of the airlines mentioned that they have updated the filtration in their gates from MERV 8 to 14, which is typically found in laboratory or hospital settings.

"... in normal ground operations we're using jet bridge or air cart. The airline has chosen to not run the APUs at the gate" (Airline #3)

" (the PCA) it's drawing in air from the outside, and then going through a pump, and then bringing it into the aircraft. ...several years ago we made an investment on all units (PCA), or, or jet bridge units so that everywhere we land we have a system that blows air into the airplane... it's either heating, venting or cooling. In the case that we don't have that pre-conditioned air, we will use the aircraft's APU, which is great because then it's going through HEPA,... going through the system filter. I would just say after you push back, if you have a tarmac delay before you take off, the pilot should have either engines running or APU running, running that air through filtration..." (Airline #5)

Figure 2.3   Example of a Jet-bridge Mounted PCA Unit and Yellow Hose Supplying Air to the Aircraft Parked at the Gate (Source: Munich Airport, retrieved from https://www.munich-airport.com/a-fresh-breeze-thanks-to-pca-1229006#)

One of the airlines noted that the ground pre-conditioned air is not recirculated, so it is 100% fresh air from outside the aircraft that comes into the cabin. Another airline mentioned that when running the APU, the air has a recirculated percentage, as it is outside air that is initially compressed at high temperatures. It is then passed thorough the A/C packs in the ECS to be cooled down, is unfiltered as it enters the cabin, then a certain percentage of cabin air is recirculated and passed through the HEPA filtration, while the rest is vented.

3.0   ROUTES OF TRANSMISSION

The relative contribution of the various routes of transmission of SARS-CoV-2 (see Section 2.2) is uncertain. It is likely, however, that all three routes, i.e., large droplet/direct contract, fomite and small droplet/aerosol, each play a role. As such, the actual setting of any exposure will play a critical role in the transmission event. As the scientific community identifies and understands the unique characteristics of the novel coronavirus, that knowledge can inform strategies to reduce disease transmission during air travel. This research supports the importance of the layered approach to enhance public health safety.

One study (Jones, 2020) attempted to evaluate the relative importance of the different routes in a healthcare setting. In this study of healthcare providers (HCP), a risk assessment/exposure modeling effort concluded that large droplet and small droplet/aerosol transmission routes outweighed the fomite route. Contributing respectively 35%, 57%, and 8.2% of the probability of infection, on average, without use of PPE, the study determined that 80% of the aerosol exposure occurred when the HCP was near patients (Jones, 2020). Recent studies demonstrated the likely transmission via the small droplet/aerosols route. Studies detected SARS-CoV-2 RNA in air and surface samples located at a distance from infected patients (Chia, 2020; Guo, 2020; Liu, 2020; Santarpia, 2020). Lednicky (2020a) reported the collection of infectious virus in air samples located nearly 5 meters (16.4 feet) away from the infectious patient. Estimates of viable viral concentrations were determined by assessing the Median Tissue Culture Infectious Dose (TCID50) and found that it ranged from 6 to 74 TCID50 units/L of air (Lednicky, 2020b). Other studies, utilizing epidemiological information from an outbreak at a choir group practice (i.e., extended exposure time, high density per area, close contact and low ventilation rates, etc.), concluded that aerosol transmission was the likely route of transmission (Miller, 2020).

3.1   PARTICLE DYNAMICS OF SOURCE EMISSION

3.1.1   Particle Size Distribution

Respiratory viruses are released into the environment in respiratory fluid droplets via breathing, vocalizing, sneezing and/or coughing. These respiratory droplets are made up primarily of a variety of salt, proteins (mucin) and surfactants. Understanding the size range of respiratory droplets released during various activities, and how evaporation may affect them, is critical to understanding virus transport via the aerosol route. The release of particles during these activities is also dynamic, as environmental factors (e.g., airflow, relative humidity, temperature) will influence particle size and virus survival (Vejerano & Marr, 2018). A number of studies have evaluated the number and size of particles expelled during various activities (e.g., breathing, talking, sneezing, coughing). Studies of coughing and sneezing demonstrated that these activities yield relatively large droplets (approximately 50 μm or larger) (Yang et al., 2007; Zayas et al.,

2012; Lindsley, 2012; Lindsley, 2013; Han, 2013; Bourouiba et al., 2014; Lindsley, 2016; Scharfman et al. 2016).

Particle size is critical to inhalation and deposition in the human respiratory tract. Smaller particles are potentially more infectious for a variety of reasons, including the vast numbers of particles generated, the ability to remain airborne for longer periods of time and to travel further from the source, and to penetrate deeper into the respiratory tract. Those particles most readily inhaled and deposited in the respiratory tract are in the range 1 to 5 micrometer (μm). Particles sized 1 μm are optimal for deposition deep within the lung (alveoli), while progressively larger respiratory particles tend to impact in larger airways. Particles much less than 1 μm (i.e., 0.1 to 0.3 μm) often fail to deposit at all, being exhaled in the next breath. Inhalation and deposition are subject to probability, with some larger particles reaching the lower lung by chance, while some smaller particles may conversely deposit higher up the respiratory tree (Hinds, 1999).

Studies have evaluated the number and size of particles expelled during various activities, e.g., breathing, talking. One study conducted by Morawska (2009) measured total particles released using an aerodynamic particle sizer (APS) and reported 80-90% of droplets expelled were smaller than 1 μm within the aerosol mode, in the range of 0.1 to 1 μm (with the precise location dependent on ambient relative humidity [RH]); at a lower concentration, droplets were at 1.8 μm). This study reported that speech produced additional particles in distinct modes of 3.5 to 5 μm, which became more pronounced during sustained vocalization (Morawska, 2009). These results are in agreement with those reported by other research groups (Papineni & Rosenthal, 1997). Morawska (2009) concluded that expelled respiratory particles are generated at near 100% RH and quickly evaporate when expelled; furthermore, evaporation of respiratory particles to their equilibrium droplet size, where it is not gaining or losing water vapor to the surrounding environment often occurs in less than 1 second (Morawska, 2009). Based on the composition of respiratory fluid, it is expected that exhaled respiratory particles will evaporate to approximately 30 to 50% of initial size (Nicas, 2005).

The distance airborne particles travel in the air is dependent on their size, the air velocity, and the velocity at which the particles are expelled. The greater the indoor air velocity (i.e., more air movement compared to stagnant air) and the velocity at which particles are expelled (e.g., coughing results in higher velocities than breathing), the further the particles can travel. In indoor spaces, air velocities can typically range from 5 cm/s to 20 cm/s (Lin & Marr, 2020). The velocity of particles expelled from normal breathing is estimated to be approximately 1 m/s, talking approximately 5 m/s, with coughing much higher at around 10 m/s and sneezing at 50 m/s (Xie, 2007). It is clear that the physics of respiratory particles released from coughing, sneezing, and breathing is complex. Studies from MIT suggested that clouds of moist air and particles generated allow respiratory particles to travel considerable distances, approximately 7 meters (23-feet) or more regardless of particle size (Bourouiba, 2020). Even considering simple particle physics, large

particles (30 μm) may travel nearly 2 meters (6.56-feet) in low velocity indoor environments and considerably further in indoor air with higher velocities for smaller particles (5 μm). Even at low air velocities, particles could potentially travel hundreds of meters (Lin & Marr, 2020).

3.1.2   Particle Emission Rate

The emission rate of particles is dependent on the activity concerned, e.g., breathing, talking, with higher emission rates for speaking compared to breathing. Emission rates measured by particle counts (e.g., Aerodynamic Particle Sizer [APS] devices) range from approximately 1 to 50 particles per second with emissions increasing the louder the speech (Asadi, 2019). Morawska (2009) reported as many as 330 particles per second in the 0.8-5.5-μm range upon sustained "aah" vocalization. Studies using other measurement techniques (e.g., laser light) revealed an average droplet emission rate of around 1,000 particles/second during speech, with peak emissions as high as 10,000 particles/second (Anfinrud, 2020).

The emission rates of particles during speaking have be shown to be two to 10 times as many particles as in a single cough (Papineni, 1997; Chao, 2009; Morawska, 2009). When comparing emission rates during talking and breathing, Morawska (2009) showed that talking and breathing for two minutes released half as many particles as 30 seconds of continual coughing. Similarly, Chao (2009) reported counting aloud (counting 1 to 100) released at least six times as many particles as an individual cough. The volume of speech also affects the emission rates. In one study, the particle emission rates during speech was positively correlated with amplitude, ranging from one to 50 particles per second (0.06-3 particles per cm3) for low to high voice amplitudes respectively (Asadi, 2019).

Some individuals may have the potential to emit respiratory aerosol at an order of magnitude greater rate than their peers (Asadi, 2019). This phenomenon might contribute to "super-spreader" events where large numbers of individuals are infected at a single event. There is evidence (Stein, 2011) with several respiratory infections that approximately 20% of cases are responsible for 80% of those infected – and conversely, 80% of infectious sources are much less infectious, accounting for transmission to only the remaining 20% of those infected. In a description of a super-spreader event, a single infector seems to have infected over 80% of the individuals at the event (Hamner et al., 2020). Multiple large-scale epidemiological studies of COVID-19 infections indicate that fewer than 20% of infected individuals are responsible for infecting as many as 80-90% of the cases (Adam et al., 2020; Bi et al., 2020). Super-spreading events are likely to be caused by a combination of factors, including high generation rates of infectious droplets, indoor environmental conditions conducive to transmission (e.g., poor ventilation), and large numbers of susceptible persons exposed.

Figure 3.1 The Wells Evaporation-falling Curve of Droplets (Source: Wells, 1934)

3.1.3   Viral Load

For respiratory secretions, the numbers of virus that are dispersed into the environment is dependent on the amount of virus in the volume of the particular fluid, namely the **viral load**, in the case of SARS-CoV-2, from the nasopharynx, trachea, bronchi and/or alveoli. Reported values for viral load in the mouth range widely from 10^2 to 10^{11} copies per mL of respiratory fluid. Viral loads vary over the course of the disease, tending to peak at or just before the onset of symptoms (Pan, 2020; To, 2020; Wolfel, 2020) and becoming undetectable about two weeks after onset of symptoms for severely/critically ill and immunosuppressed patients (Pan, 2020; To, 2020; Walsh, 2020; Wolfel, 2020). It is likely that for those with less severe disease, infectivity decreases more rapidly and to near-zero after 10 days (Rhee, 2020). A reasonable assumption for an average viral load is in the range of 10^7 copies per mL (Pan, 2020). Currently, there is no definitive data on whether viral load is lower in asymptomatic compared to symptomatic individuals; however, several studies conclude that asymptomatic carriers could have viral loads comparable to those of symptomatic carriers (Lee, 2020; Mattar, 2020; Ra, 2020; Walsh, 2020). It has been estimated that approximately 40-45% of SARS-CoV-2 infections are asymptomatic (Oran, 2020). A major limitation is that detection by viral RNA does not correlate with viable or infectious virus, presumed to be some fraction of total RNA in the samples. Culture of viral samples on tissue culture is presumed to correlate better with infectivity.

The number of infectious virions to total viral particles is not known, given each viral RNA copy is unlikely to be infectious. In a study of influenza virus, it was estimated that this ratio was approximately 10^3 to 10^4 (ratio of total influenza viral particles to infectious virus) (Milton 2013; Fabian 2009). While the ratio of RNA copies to infectious virions is not yet known for SARS-CoV-2, the ratio may very well be similar to that of influenza.

3.1.4 Virus in Respiratory Aerosols

While the frequency of transmission by different routes remains unknown (e.g. large droplets, contaminated surfaces and/or aerosols), transmission via surfaces may be less frequent than previously considered (Goldman, 2020). While viable SARS-CoV-2 can be detected in laboratory studies where surfaces have been contaminated with virus intentionally (van Doremalen, 2020), in a study where samples collected from patient rooms were PCR-positive for SAR-CoV-1 viral RNA, no viable virus was detected (Dowell, 2004). Several recent studies have identified viral RNA on surfaces (Santarpia 2020b, Chia 2020), but similar studies have failed to detect infectious virus in samples that were positive for viral RNA (i.e., PCR detection of RNA vs. viral cell culture; Colaneri 2020a, Colaneri 2020b). These results suggest that surfaces may not be contaminated with infectious virus and indicate that transmission from environmental contamination may be unlikely in real-world conditions if standard cleaning procedures and precautions are followed. Therefore, in order to assess the risk of transmission through modeling efforts, the focus is on aerosol transmission as opposed to transmission via contaminated surfaces (i.e., fomites).

Researchers have collected aerosol samples from rooms occupied by infectious patients and measured exhaled breath aerosols to determine the size of infectious aerosols. To date, several studies have detected SARS-CoV-2 in air samples collected in hospital settings. Researchers in China reported the detection of SARS-CoV-2 RNA in aerosols in two size ranges (0.25 to 1 μm and >2.5 μm) (Liu, 2020). Consistent with these results, Santarpia (2020) detected RNA in samples in three size ranges (<1, 1-4, >4.1 μm) and was able to culture infectious virus in the two smaller size fractions (Santarpia, 2020). These results are consistent with data identifying infectious respiratory virus-like influenza in small particle sizes (Yan, 2018). Compared to viral RNA detection, culturing virus in cultured cells from air samples is closer to the in-real-life setting, i.e., measuring airborne virus infectiousness for humans. However, it is not the same and differences include the fact that inhaled virus in humans are subject to structural defenses and immunity, innate and adaptive, including potentially protective cross-immunity from past infections with non-COVID seasonal coronaviruses.

Another technique to identify whether infectious virus is expelled during breathing and speaking is to recruit infected volunteers to breath directly into a sampling device, often referred to as exhaled breath studies. Milton et al. (2013) detected influenza viral RNA in 43% of the coarse particle (>5 μm) and 92% of the fine particle samples collected from infectious volunteers. While no

exhaled breath studies have yet been reported with SARS-CoV-2, tests on COVID individuals are underway to characterize oral/nasal emission rates of viral particles/droplets (Milton, 2020).

Given a typical viral load, not all particles will contain virus. If one assumes an average virus RNA load of 7 x 10^6 copies per milliliter of mucus secretions, the probability that an initial 50 μm diameter droplet prior to dehydration contains at least one virion is ~37%. For an initial 10 μm droplet, this probability drops to 0.37%, and the probability that it contains more than one virion, if generated from a homogeneous distribution of oral fluid, is negligible (Stadnytskyi, 2020). However, small particles that result from the evaporation of larger particles will contain the original number of viruses.

Environmental conditions, such as the stresses of aerosolization, temperature, humidity and exposure to ultraviolet light (e.g., sunlight) affect the infectivity of viruses, both those that are aerosolized and those deposited on surfaces. In the indoor environment, humidity levels appear to influence viral viability for a number of viruses, including influenza and SARS-CoV-1. Although the environmental dynamics of SARS-CoV-2 have not been fully characterized, it can be assumed that its behavior is similar to SARS-Co-1 and other enveloped viruses. In laboratory-based studies, the two SARS viruses had similar viability in aerosols and on surfaces (van Doremalen et al., 2020). In studies of other animal coronaviruses, considered to be surrogates for SARS-CoV-2, tests conducted across a range of temperature and RH conditions showed that coronaviruses are viable longer at 20% RH compared to 50% RH and 80% RH over a range of temperatures (Casanova et al., 2010). Consistent with studies of SARS-CoV-1 and SARS-CoV-2, studies of MERS-CoV also suggest that the survival of coronaviruses decreases dramatically in hotter and drier conditions (Pyankov 2018). While the mechanism that RH plays on virus viability is not completely understood, Lin and Marr (2020) proposed that at low RH viral viability is enhanced due to the inability of solutes such as sodium chloride to act before respiratory droplets evaporate completely. While much research still needs to be conducted, the data on the impacts of humidity suggest that coronaviruses, such as SARS-CoV-2, may remain infectious longer in aircraft cabin environments due to the low humidity. When considering the effects of sunlight, it is estimated that the half-life of SARS-CoV-2 would be dramatically reduced (half-life of 6 minutes) when exposed to simulated sunlight (Schuit, 2020).

Based on the available evidence, it is clear that infectious droplets are emitted during breathing and other respiratory activities. These droplets range in size, but the vast majority of them are 1 μm or slightly below. While most particles will probably not contain infectious virus, enough particles are generated with the potential to transmit infections via the aerosol route.

3.1.5   Particle Transport and Deposition

SARS-CoV-2 is capable of infecting a range of cell types, from bronchial cells in the lungs to conjunctival cells in the eyes, with ACE-2 receptors enabling virus to enter the cells (Sungnak et.

al., 2020). SARS-CoV-2 replicated similarly to SARS-CoV-1 in the alveolar epithelium but more extensively in the bronchus (Hui, 2020). These results indicate that large droplets entering the eyes (or transferred from contaminated hands) could be a potential source of infection. The results also indicate that SARS-CoV-2 can infect conducting airways, more so than SARS-CoV-1, which may explain the greater transmissibility of this virus over SARS-CoV-1 (Hui, 2020).

Deposition of particles that are respirable (i.e., capable of being breathed in) is dependent on particle size. The most frequently generated particles that could contain infectious virus following evaporation are in the particle size range 0.1-1 µm that has the lowest potential for deposition in the respiratory system. Generally, less than 40% of particles in this size range that enter the respiratory system actually deposit, as opposed to those that are breathed in and then expelled (see Figure 3.2). This suggests that many particles in the size range generated during breathing and speaking, even if breathed in by another individual, will not deposit in the respiratory system. HEPA filters clean particles of this size efficiently.

3.1.6   Infectious Particles vs. Quanta of Infection: The Case for Using Quanta

As with almost all other respiratory airborne infectious pathogens, there is still limited understanding of what constitutes an infectious dose for a COVID-19 case. Previous studies of SARS-CoV-1 and human common cold coronaviruses suggest that the infectious dose capable of causing disease in 50% of the population (ID50) is approximately 280 viral particles (Watabanbe, 2010). To date, the infectious dose for COVID-19 has not been determined. Given this data is not known, aerosol science researchers have for many years attempted to bridge this gap in knowledge by using the concept of "quanta."

William Wells introduced the term *quanta* to represent the minimum dose of airborne organisms necessary to cause infection in the host. For pathogens that are transmitted via the aerosol route, an infectious dose can be defined by an infectious quanta emission rate (quanta per hour). Wells postulated that not all inhaled particles containing respiratory aerosols would result in infection and therefore defined a quantum of infection as the number of infectious respiratory aerosols required to infect 63% of susceptible people (Wells, 1955). Based on the concept of quanta, an equation was developed, the Wells-Riley equation (Riley, 1978). The equation can be used to assess the probability of infection of a susceptible population where factors relevant to transmission are understood – such as the length of exposure, ventilation rate in the indoor space, and the pulmonary ventilation rate of susceptible individuals. The Wells-Riley approach does have limitations. For example, the model assumes air is well mixed, such that quanta are evenly distributed in the spaces shared by an infectious person and susceptible hosts. Applying the Wells-Riley model when case and host are in close proximity may underestimate transmission depending on how rapidly viral emissions are dispersed. In the confines of an aircraft cabin, where a potential case is wearing a mask, oral and nasal exhalations are introduced into a turbulent airflow that is rapidly dispersed and flushed from the environment.

Figure 3.2 Regional Deposition of Particles in the Upper and Lower Airways based on the Aerodynamic Diameter of Particles (Source: Hinds, 1999)

Quanta emission rates are calculated typically based on a retrospective review of a transmission event, where factors relevant to transmission (e.g., length of exposure, conditions of the space) are reasonably well known. Essentially, the quanta concept approaches the study of transmission retrospectively from the end result, namely the infection rates, rather than prospectively based on particle numbers or even culturable virus concentrations. The quanta emission rate can be dependent on a number of factors, including the amount of aerosol generated by specific activities (e.g., breathing, standing, singing, exercise) and the infectious state of the infector (e.g., asymptomatic, pre-symptomatic, symptomatic). The concept of quanta and the Wells-Riley equation have been used extensively in analyzing ventilation strategy and its association to airborne infections in clinical environments (Nardell et al., 1991; Fennelly & Nardell, 1998; Escombe et al., 2007).

Several studies have been conducted to estimate quanta emission rates of SARS-CoV-2. Buonanno and colleagues estimated quanta emission rates for activities, including resting, oral breathing (0.36 quanta/hr), heavy activity (oral breathing, 2.4 quanta/hr), speaking with light activity (4.9 quanta/hr), and singing or speaking loudly (31 quanta/hr) (Buonanno 2020a, Buonanno 2020b). Other investigators have estimated quanta mission rates for specific outbreaks. Hota et al. (2020) calculated an emission rate based in the healthcare setting of 0.225 quanta/hr, which is consistent with the value mentioned for resting activities. Miller et al. (2020) calculated a very high emission rate of 970 quanta/hr for singing loudly based on a super-spreader outbreak that occurred at a chorus rehearsal where 53 members of the group were confirmed or strongly suspected of having contracted COVID-19. As the estimates of quanta emissions are generally

based on retrospective reviews of transmission events, the results are consistent with other available scientific evidence, such as the studies that report higher generation of particles when speaking loudly. Additionally, the SARS-CoV-2 estimates are reasonable give quanta values reported in the literature for other infectious disease (e.g., SARS-CoV-1: 28 q/h; influenza: 15-128 q/h; measles 5,580 q/h) (Riley 1978; Liao 2005; Knibbs, 2012).

Recent studies have estimated emission rates ranging from two quanta per hour (breathing at rest) to 970 quanta per hour (singing) (Buonanno, 2020a; Bounanno, 2020b; Miller 2020). This information can be used to assess the probability of infection of a susceptible population when factors relevant to transmission are understood – such as the length of exposure, ventilation rate in the indoor space, and the pulmonary ventilation rate of susceptible individuals.

Several important factors influence the infectivity of aerosols. For example, each droplet or respiratory particle may not carry one or more infectious virions in it. Importantly, one copy of RNA does not represent one viable infectious virus, much less one quantum (successful infection). If that were the case, it would assume infection would occur for each pathogen (RNA copy, in the case of SARS-CoV-2) received by the exposed people. Therefore, researchers have introduced a conversion factor, c_i, defined as the ratio between one infectious quantum and the infectious dose expressed in viral RNA copies. The conversion factor for SARS-CoV-2 is unknown; however, studies with other coronaviruses have estimated that value to be somewhere between 0.01 and 0.1 (Buonanno, 2020a; Bounanno, 2020b).

Estimating infectious dose is useful for comparing pathogens as being more or less infectious, but any estimate is based on many assumptions. A viral dose assumes airborne viruses are uniformly infectious across all conditions, whereas influenza, for example, appears to be more infectious in conditions of low absolute humidity (Lowen & Steel, 2014). It also assumes average host susceptibility, but differences in innate, learned, and adaptive immunity among individuals and populations are well known (Lowen & Steel, 2014). For mathematical models of infection, modelers often estimate source strength and infectious dose – although Wells' quanta concept remains a useful way to model transmission without committing to an actual dose number.

Table 3.1	**Summary of Estimated Quanta Generation Rates for SARS-CoV-2**	
Quanta/hr	**Location/Activity/Source**	**Reference**
0.225	Healthcare workers, COVID-19 patients	Hota et al., 2020
0.36	Oral breathing, light activity	Buonanno et al., 2020b
2.4	Oral breathing, heavy activity	Buonanno et al., 2020b
4.9	Speaking light activity	Buonanno et al., 2020b
31	Singing or speaking loudly, light activity	Buonanno et al., 2020b
>1	Low: Person at rest	Buonanno et al., 2020a
>100	High: Person speaking and walking slowly	Buonanno et al., 2020a
970	Singing loudly	Miller et al., 2020

Particles (detectable, viable, and infectious) are estimated from source measurements, but include many particles that do not cause infection due to viability, infectivity, host defenses, etc. Quanta are agnostic about the actual number of particles but quantifies the number of doses generated by the source under specific circumstances and considering the probability of inhaling an infectious dose.

Figure 3.3   Summary of Epidemiologic Estimates of Quanta Based on Outbreak Investigations

3.1.7   Environmental Stability

In order to understand the duration of survivability of SARS-CoV-2 researchers have studied both aerosols and virus-containing droplets on surfaces. van Doremalen et al. (2020) have conducted stability studies with SARS-CoV-2 in the laboratory environment. The ability to characterize the stability of these virus-containing aerosols or fomites is important in assessing risk as well as determining the efficacy of various cleaning and disinfection protocols. van Dormalen et al. (2020) carried out aerosol studies at 65% RH and 21-23°C, and surface viability at 40% RH and 21-23°C. Similar aerosol studies conducted at RH levels ranging from 40 to 88% generally agree with the results presented by van Doremalen et al. (2020; Smither, 2020). These studies were conducted in laboratory environments with ideal and/or known conditions (i.e., air temperature, humidity). It is known that temperature, humidity and UV light (i.e., sunlight) impact virus survival. In one study using simulated sunlight, the virus was inactivated within 20 minutes on surfaces (Ratnesar-Shumate, 2020). These studies are discussed further in Chapter 9, Disinfection and Cleaning.

Table 3.2 Environmental Stability of SARS-CoV-2 Virus on Various Surfaces		
Surface Material	Time until not Viable (hr)	Half-life (hr)
Air (aerosol)	3	1
Copper	4	1
Cardboard	24	4
Plastic	72	7
Stainless steel	72	6

3.1.8 Duration of Shedding

Evidence suggests that SARS-CoV-2 RNA can be detected in people one to three days *before* the onset of symptoms, with the highest viral loads (as measured by RT-PCR) observed around the day symptoms appear, followed by a gradual decline over time (He, 2020; Pan, 2020; To, 2020; Wolfel, 2020). The duration of RT-PCR positivity generally appears to be one to two weeks for asymptomatic persons, up to three weeks or more for patients with mild to moderate disease (He, 2020; Wolfel, 2020; Zhou, 2020) and much longer in patients with severe COVID-19 disease (Pan, 2020). This means that a positive test can serve to exclude passengers without symptoms.

4.0   VENTILATION REQUIREMENTS ASSOCIATED WITH AIRCRAFT

The airline cabin is a unique setting given its rigorous requirements for maintaining critical control of its environment and the compact seating arrangements in passenger aircraft. Ventilation, essential in all enclosed spaces for basic respiratory needs, also supports thermal comfort and dilutes and removes gaseous and particulate contaminants from breathing zones. The aircraft Environmental Control System (ECS) is designed to meet these needs and must be able to operate in extremes of temperature, ambient air quality, and air pressure.

Travelers and crewmembers have long expressed potential concerns regarding the air quality inside commercial aircraft cabins (NRC, 1986; NRC, 2002). However, much of that concern is likely due to not having a clear understanding of the way aircraft ventilation systems operate. The cabin environment must be safe and comfortable for occupants, given extreme external environmental conditions. Pressurizing the cabin to meet the metabolic requirements of passengers and crew, means that ventilation must be sufficient to dilute contaminants and odors as well as dissipate the heat emanating from people, entertainment systems, galleys and avionics. Specific industry guidance, Federal Aviation Regulations and international regulations are in place to help ensure acceptable conditions of cabin safety, air quality and thermal comfort are always maintained inside the aircraft. This includes the need to provide adequate control of potential airborne transmission of infectious diseases, including SARS-CoV-2 virus within the aircraft environment.

The current pandemic demands a critical evaluation of the interaction of the ventilation system components and their performance through the different phases of air travel, from boarding the aircraft to deplaning upon arrival. Since individual airlines are not required to audit actual ventilation performance it is strongly recommended that airlines adopt voluntary programs to ensure OEM recommendations are being met during all phases of travel.

The aircraft ECS is different from ventilation systems used in most other settings, such as typical buildings and road vehicles, in that it is absolutely essential in enabling the aircraft to operate in the extremes of outside air temperature, ambient air quality, and air pressure encountered while flying. Given the rigorous operating specifications, the ECS can be optimized to reduce the potential risk of exposure to airborne viruses; this analysis is discussed in Section 10.0. The description given here largely apply to narrow body and wide body commercial transport aircraft of recent design; older regional jets or turboprops will not incorporate all these ventilation systems.

The aircraft components include the onboard ECS powered by engines or the auxiliary power unit (APU). When the plane is at the gate, a ground air supply system may be used to provide conditioned air to the cabin. While aircraft systems are generally similar across airplane models

and manufacturers there are a variety of ground preconditioned air units (PCAs). Both the onboard and ground systems have variable settings of airflow rates and thermal conditions. Operating parameters for the ECS, APU, and PCAs are determined by air carriers, with PCA settings (flow/pressure) in practice set for the type of aircraft.

The following sections discuss the various elements of ventilation on the "Gate-to-Gate" journey and evaluates how they may affect potential risk of infection.

4.1   AIRCRAFT VENTILATION SYSTEM AND VENTILATION RATES

Ventilation standards for the aircraft cabin vary by country, following the regulations and guidelines of the corresponding international and national aviation authorities. In the USA, the minimum ventilation rates in an aircraft cabin is mandated by FAA regulations, while the ANSI/ ASHRAE Standard 161-2018 (ANSI/ASHRAE, 2018) guidance defines the requirements for air quality in the aircraft and specifies methods for measurement and testing. The FAA established FARs to guide the operation of commercial airliners. FAR 14 CFR 25.831 states that *"the cabin ventilation system must provide at least 0.55 lb. (0.25 kg) of fresh air for each passenger per minute"*. This is equivalent to 4.7 L/s/p at 8000-feet and a cabin temperature of 22°C (72°F). The NRC report (NRC, 1986) states, *"This ventilation rate is also specified by the joint design regulation FAR/JAR Part 25 for crewmembers to perform their duties without undue discomfort or fatigue and to provide reasonable passenger comfort."* The ASHRAE standard specifies ventilation requirements for maintenance of air quality within commercial aircraft.

As detailed in Table 4.1, ventilation requirements can vary based on whether an aircraft is in flight or on the ground. As such, it does not discriminate between specific activities that may be occurring at various times i.e., boarding, deplaning, and when seated. With these regulations and standards, the cabin is supplied with outside air and highly filtered "clean air" providing air exchange rates significantly in excess to those found in well-ventilated offices and retail spaces (see Table 4.2). **The high air exchange rates utilized in aircraft ventilation systems mean that any contaminant introduced into the cabin should be flushed out much faster than would occur in other types of spaces, i.e., in the order of two to five minutes.**

Table 4.1	Aircraft Ventilation Rates, at Standard Temperature and Pressure, Specified by ASHRAE-161 during Various Operational Phases	
Air Source	**Air Volume in L/s/person**	**Air Volume in CFM/person**
ECS Minimum Outside Air	3.5	7.5
ECS Minimum Total Air	7.1	15
ECS Recommended Total Air	9.4	20
APU Minimum Outside Air	3.5	7.5
PCAs Minimum Total Air	9.4	20

ASHRAE   American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
L/s/person   liter per second per person
CFM/person   cubic feet per minute per person
ECS   Environmental Control System
APU   auxiliary power unit
PCA   pre-conditioned air

ANSI/ASHRAE Standard 161-2018

A major difference between the aircraft environment and the ground environment relates to the atmospheric pressure that must be maintained inside an aircraft. Modern aircraft cabins are generally pressurized to an altitude that will be maintained between 6,000 and 8,000 feet relative to sea level pressure, even if the aircraft is flying at much higher altitudes. Multiple aircraft systems must work together seamlessly to meet the strict environmental needs required while flying. This starts with the propulsion system (engines) where a small portion of ingested low pressure outside air is withdrawn after compression, which is called 'bleed air'; the compressed and therefore hot bleed air is allowed to expand from high pressure to lower pressure through the ECS, which conditions the pressurized air and supplies it to the cabin. Due to extreme dilution encountered out of doors and the harsh environment encountered at elevations above sea level, the outside air is virtually virus-free upon its' intake to the ventilation system.

Heat exchangers and air cycle machines (ACM) constitute the refrigeration component of the ECS that cools the hot (by compression) gases upon intake of the bleed air. There may be multiple ACMs (sometimes referred to as PAC or PACK, for "Passenger Air Conditioning Kit"). The ECS and its associated control system works to temper and regulate the air to heat or cool the cabin air based on the thermal requirements in the cabin environment.

Another integral component of the aircraft ventilation system is the high efficiency particulate air (HEPA) filter used to filter particles out of the portion of air recirculated from the cabin; this recirculated component of the air stream is then mixed with fresh ambient air via the bleed air and the ECS temperature conditioning/filtration systems. During flight, approximately 50% of the air delivered to the cabin may be recirculated after it passes through the HEPA filters.

The HEPA filters remove, at a minimum, 99.97% of the particulate matter from the return air. This high level of filtration ensures that the air supplied to the cabin is virtually free of particulate matter, including bacteria and viruses.

4.2 AIR DISTRIBUTION AND CIRCULATION – ENGINES ON AND ECS OPERATING

The air supplied to the cabin to dilute occupant generated gaseous and particulate emissions is a mixture of outside air, and HEPA-filtered recirculated air set to remove particles and aerosols of all sizes with efficiencies greater than 99.97%.

Figure 4.1 Typical Cabin Air Distribution System (NRC, 2002)

As shown in Figure 4.1, a common architecture exists for delivering outside air and filtered recirculated air, extracted air from the galley, lavatories, and cabin. Typically, air is supplied and exhausted relatively equally through air inlets distributed along the cabin to avoid overheating or overcooling at any specific location. Personal Airflow Outlets (PAOs) or "gaspers", common for short-haul rather than long-haul aircraft, and while not the main source of air allow limited and fine tuning of air to an occupant's breathing zone. Although the air mixes locally in the cabin, the air supply and air exhaust flow rates are generally well matched along the length of the cabin to minimize net flows along the length of the aircraft. Distribution of the air to the cabin can occur through diffusers located in the center of the ceiling in the aisles, above the windows, or along the overhead baggage compartments. Wide-body aircraft will use multiple ceiling diffusers across the

width of the cabin. Air is removed from the cabin through vents near the floor along the interior sidewalls of the aircraft. The air is introduced into the cabin, removed for recirculation, and exhausted in a manner that minimizes row-to-row and within row air and contaminant transfer. Figure 4.2 illustrates the airflow diffuser locations and the flow pattern that is generally achieved in a cabin. Studies performed using various experimental techniques and by modeling using computational fluid dynamics (CFD) show that gaseous and particulate contaminants released by occupants have minimal row-to-row and seat-to-seat dispersion before being removed from the aircraft cabin (Yang et al., 2018).

Figure 4.2   A pictorial diagram of the cabin air ventilation strategy including supply air diffuser locations in the aisle ceiling, along the wall of the cabin below the overhead baggage compartment and the individual air outlets sometimes referred to as Personal Airflow Outlets (PAOs) or "Gaspers"

4.3   AIR SUPPLY WHEN AN AIRCRAFT IS ON THE GROUND

When an aircraft is on the ground, the ventilation requirements can be met using an onboard APU, which is a small turbine mounted in the tail cone of the aircraft supplying electric power to the aircraft (see Figure 4.3). Unfiltered outside air is drawn in through the APU, compressed and supplied to the ECS packs. The APU is normally operated to supply electrical power and air when the aircraft's main engines are not running (e.g., when the aircraft is sitting at the gate) or are not running at speeds able to generate the necessary bleed air or electric power.

Figure 4.3   APU of Boeing 787 Dreamliner APU Exhaust

To save fuel and in accord with local regulations including airport requirements, and where available, airlines may use external PCAs when at the gate or on the ramp. The PCA provides thermally conditioned ventilation air to the aircraft through hose connections to the aircraft during aircraft and cabin preparation, boarding and deplaning operations. In some configurations, the PCA also provides conditioned air to the jet bridge. One such type is a low-pressure ground cart supplying air to the aircraft downstream of the onboard air packs; this is essentially a conventional air conditioner on a mobile cart, as shown in Figure 4.4.

Figure 4.4   Ground Cart Combined Air-Conditioning and Power Unit

With this method, outside air is supplied only to the cabin air supply system, not to the pneumatic system, and no in-line filter is used. Due to the very low personnel density and extremely high dilution that will occur in the ambient environment surrounding an aircraft parked at the gate, the air can be considered to be virus free. The temperature of the air is adjustable and controlled by the cart. The flow rate is fixed but is typically almost equal to the normal total output of the onboard air packs. A variation of the low-pressure ground cart is operated by replacing the air conditioner with a heater; this approach is more economical and is typically used when only warm air is needed. Some airports (and airlines, in cases where airlines have physical control over gate power decisions) have begun to install fixed, low-pressure systems at each gate to replace the low-pressure ground carts. Rather than use an air conditioner mounted on a cart, the fixed system uses an air conditioner that is permanently mounted on the ground, attached to the jet bridge or in the terminal building (see Figure 4.5). These PCAs are connected manually to the aircraft by a flexible duct. The fixed system connects to the aircraft in the same manner as the low-pressure ground cart. A hose connected to a ground-based PCA system will supply air through the aircraft's air duct systems.

Figure 4.5 A Pre-Conditioned Air (PCA) System Attached to a Jet Bridge

By current ventilation standards, the amount of outdoor and total supply air per person from bleed air systems is at least 7.5 liter/second/person (L/s/p) outdoor air, 9.4L/s/p total air when using onboard bleed air, and 9.4L/s/p total supply air when connected to ground-based equipment. **The APUs and the ground PCAs have variable settings and can be operated on appropriate settings during boarding/deplaning to accommodate passenger loads, as some airlines already do. At these times, passengers could be in closer proximity to other passengers than when seated in rows, and increasing ventilation would increase exchange rates and further dilute any particles in the air, including viruses.**

4.4 IMPLICATIONS OF VENTILATION FOR SEGMENTS OF AIR TRAVEL

Within the "Gate-to-Gate" air travel continuum, a number of distinct "segments" can be identified that present unique exposure microenvironments relevant to the potential risks that might be encountered with infectious viruses. Five segments have been identified, each of which may experience different rates of air ventilation, as well as opportunities for physical distancing. Appropriate mitigation strategies will therefore need to be tailored to each phase to minimize the risk of SARS-CoV-2 transmission. The segments are:

- Boarding and waiting for departure
- Ascent
- Cruise
- Descent
- Deplaning

Table 4.2   The "Gate -to-Gate" Segments of Air Travel

Segments	Passenger Activities	Ventilation System	Implications	Response by Airline
Boarding	On jet bridge and in aisle, talking, storing luggage, cabin door(s) open	PCAs or APUs	Open door, standing and open storage bins disrupt airflow	Airlines managing boarding process to maintain physical separation. Some have increased ventilation Duration 10-30 minutes
Ascent	Seated, (most) facing forward, quietly talking or silent	ECS	Full thrust reduced air flow briefly	Short duration - no concern
Cruise	Same as above, with some movement of passengers and crew in aisle	ECS	Fully operating ventilation system; low relative humidity	Airlines reduce service to minimize movement in the aisles
Descent	Same as above, with restricted aisle movement	ECS	Engines at cruise idle may reduce air flow	Usually short duration 10-20 minutes
Deplaning	Movement in the aisle retrieving luggage, Cabin door(s) open	PCAs or APUs	Open doors, standing and open bins decreases distances and disrupts air flow	Airlines managing deplaning to maintain physical separation. Some increase ventilation Duration a few to ~30min

PCA   Pre-conditioned Air
APU   Auxiliary Power Unit
ECS   Environmental Control System

The following sections discuss ventilation air systems for the five segments of the "Gate-to-Gate" journey and evaluates how they may affect potential risk of infection relevant to transmission of SARS-CoV-2.

It has been known for some time that ventilation rates may differ across different flight segments. The 1986 National Research Council reported that reduced airflow during the boarding and deplaning segments might be problematic specifically in terms of the spread of infectious diseases (see side bar).

Following the 2002 NRC report, the FAA sponsored a Cooperative Agreement entitled 'National Air Transportation Center of Excellence for Research in the Intermodal Transport Environment' (RITE). Within RITE the Airline Cabin Environment Research (ACER) Center was formed as a collaborative enterprise involving academia, industry and government. Cabin air quality studies were conducted to address several of the unanswered questions stemming from the 2002 NRC Report, key among them adequacy of ventilation. Researchers from ACER universities collaborated in an air quality study examining 179 commercial flights where portable air-monitoring sensors recorded CO_2 and other parameters.

CO_2 concentrations have long been used as a ventilation indicator for indoor environments, i.e., to estimate the outside air delivery rate (Persily, 1997; Emmerich & Persily, 2001). Further, it has been proposed that CO_2 levels in indoor air provide an estimate of the risk of airborne infection transmission (Rudnick & Milton, 2003). Ventilation in an aircraft cabin is distinctly different from almost all other indoor environments. While highly efficient filters do not remove CO_2, they do remove suspended particles. While elevated CO_2 levels may indicate a passenger is inhaling a higher proportion of exhaled breath from other passengers, it does not necessarily indicate higher risk of exposure to airborne pathogens. On the other hand, higher levels of CO_2 during boarding and deplaning indicate that the amount of outside air per passenger (the source of CO_2) has decreased. If this reduction in outside air is not compensated by a proportionate increase in highly filtered air, then these conditions at these times where aisles are congested represent periods where risk of SARS-CoV-2 transmission could be higher.

The study reported (NRC, 2002) of CO_2 levels across 179 commercial flights provided important insights into ventilation rates during the various segments of a flight including boarding, cruise and deplaning (Cao et al., 2019). The average CO_2 concentrations were 1353 +/-290 ppmv (mean, SD) and the estimated outside airflow rates were 5.77 +/-2.09 L/s/p across all flights. The results

indicated that 96% of observations met the minimum recommended outside airflow rates for acceptable air quality (3.5 L/s/p) during flying phases. Statistical analysis indicated that the ventilation rates during the boarding phases were significantly lower than the others. These findings are of particular interest because low ventilation in other settings has been associated with increased rates of disease transmission and increased upper respiratory symptoms.

Figure 4.6 summarizes the distributions of CO_2 concentrations (left panel) and infers the outside air being supplied (right panel) to the cabin, with comparison to the ASHRAE 161 guideline. Represented as box plots, display time averages for the five segments across all flights are given, with maximum, median, minimum and interquartile values.

Figure 4.6 CO₂ Concentrations and Outside Air Supply to Cabin, Compared to FAA FAR Regulation and ASHRAE Guideline

(a) Shows that CO_2 concentrations were the highest during the boarding phase, with a median of 1539 ppmv and an interquartile range (IQR) of 407 ppmv. CO_2 levels during climbing were lower compared to that during the boarding phase. The median CO_2 concentration was 1304 ppmv during cruise, the lowest among all phases. During descent and deplaning, a slight gradual increase in CO_2 levels was observed. The high CO_2 levels during the boarding phase indicated inadequate ground ventilation by APU or gate-based ventilation systems. The figure also infers the ventilation (outside air) rates in L/s/p with a reference to the FAA FAR.

(b), calculated ventilation rate was significantly lower in the boarding phase compared to all the other flight phases (p<0.0001). The ventilation performance gradually improved during ascent, and reached a peak ventilation at the cruising phase, with a median of 5.51 L/s/p and an IQR of 1.91 L/s/p. (Cao et al., 2019)

It was clear from this study (Cao et al., 2019) that commercial aircraft were often under-ventilated during the ground segment. In the absence of contaminants and respiratory pathogens, brief transient times when passengers and crew experience lower ventilation levels are not of concern. **However, given the risk of airborne transmission of SARS-CoV-2 in the confinement of an aircraft cabin, reduced ventilation would be a concern.** International and national airworthiness authorities asking manufacturers to enable the air system to be on maximally when people are onboard.

Recently, members of the APHI team measured CO_2 levels, along with temperature and RH on four commercial flights. The data from two of those flights is shown in Figure 4.7, give the CO_2 levels near a passenger sitting in the rear section of economy on two narrow body aircraft. These measurements informed the scenarios modeled and reported in Chapter 10.

CO_2 levels were observed to follow the well-characterized trends reported previously and summarized earlier. Comparing the outbound flight to the return flight, there was a factor of three to five increase in the CO_2 levels during both boarding and deplaning. On the BOS-ORD flight, it was likely that the carrier was complying with its directive (issued in July 2020) to maintain high ventilation during ground operations. On the ORD-BOS flight, cabin temperature exceeded 80°F (not shown), an indication that conditioned air was not being provided to the cabin. On approach to Boston's Logan airport, the CO_2 levels increased by a factor of about three, and remained so throughout the deplaning process that took over 20 minutes for passengers coming from the back of the plane. This event may have indicated a lack of fresh air due to the throttling back of outside air being delivered to the cabin.

Figure 4.7   *Carbon Dioxide Measured on Two Flights*

Left panel BOS-ORD on 9/3/20 and right panel ORD-BOS on 9/8/20. Colors indicate different segments of the flight. Carbon dioxide was measured with a non-dispersive infrared carbon dioxide sensor, calibrated the same day of the measurements to outdoor air at approximately 400ppm (HOBO MX1102, Onset comp, USA). Ancillary temperature and relative humidity were collected with the same instrument at a logging rate of 10 seconds. Before deployment, CO2 was referenced to 400 ppm outdoor air to eliminate a drift error. CO2 drift and gain errors during deployment were estimated by collocating the IEQ monitors next to a recently calibrated instrument (Q-trak 7575; TSI Instruments, Shoreview, MN) inside a chamber, following 10 step-wise increments from 400 to 3,000 ppm.

The study by Cao et al. (2019), together with APHI's recent in-field measurements indicate that ventilation of aircraft while at the gate warrant attention. As noted in both National Research Council reports (NRC, 1986; NRC, 2002) on cabin air quality and health, it is these segments of travel that present higher risk for transmission of respiratory airborne infections.

Better ventilation during these segments is acutely relevant to issues surrounding the SARS-CoV-2 pandemic. The 2013 Transportation Research Board; National Academies of Sciences, Engineering, and Medicine report on *Infectious Disease Mitigation in Airports and on Aircraft*, anticipated the current situation when it recommended **"Airport operators and airlines should make preparations to provide gate-based ventilation to all parked aircraft in the event of an emergency or pandemic".** This recommendation is now echoed in the ICAO: Council Aviation Aircraft Module - Air System Operations Ground Operations (see Chapter 10). During this current CoV-2 pandemic, it is a prudent risk mitigation response to operate the APUs or the PCAs at ICAO recommended airflow settings. Higher flow rates of outside/HEPA filtered air (along with other measures discussed in the report) will also help reduce the risk of transmission.

4.5   VENTILATION OF AIRCRAFT COMPARED TO OTHER INDOOR SETTINGS

On commercial passenger aircraft, the recirculated air supplied to the cabin is HEPA-filtered where 99.97% of particles, including bacteria and viruses are removed. Occupied commercial and retail spaces with HVAC systems often supply a mixture of outdoor and recirculated air, while homes are typically naturally ventilated by infiltration of outdoor air through voids in the envelope.

In comparing the ventilation of an aircraft cabin to the mechanical ventilation systems of other indoor locations three factors are most relevant: the delivery rate of outdoor air per person (L/s/p or cfm/p), the amount of recirculation air, and efficiency of in-line filters to remove respirable-sized particles in the total supply air. The relative contribution of these three factors can be used to calculate the "clean air delivery rate" to occupants. In a typical 1,000 square foot (ft^2) home that is naturally ventilated and occupied by four persons, the annual average air exchange rate is approximately 0.25 ACH. In a home with no mechanical air circulation and filtration system, this equates to approximately 8 cfm (4L/s) of outdoor air per person. For mechanically ventilated homes, ASHRAE 62.2-2016 recommends 0.35 ACH.

The filters found in HVAC systems in commercial buildings are typically located after the outdoor air is mixed with return air. These filters were originally installed to minimize the fouling of the heat transfer surfaces in the equipment and were very inefficient at removing particles in the 1 μm size range. Increased awareness of indoor air quality in the last 20 years has resulted in better quality (i.e., more efficient) filters being installed in these systems. ANSI/ASHRAE Standard 52.2-1999 defined the Minimum Efficiency Reporting Value (MERV) for filters that specify removal efficiency based on particle size. The original filters installed to minimize equipment fouling

typically correspond to a MERV 6 rating that have no reliable efficacy for removing 1 um particles. The filtration of smaller particles increases as the MERV value increases.

Aircraft meeting current ventilation standards with 50% recirculation HEPA-filtered air will supply passengers with a clean air delivery rate of 19 cfm/person, which is essentially free of any virus particles. This far exceeds the ventilation rate in a typical naturally ventilated home of 1,000 ft^2 occupied by four persons without mechanical ventilation (8 cfm/person), where the only source of clean dilution air is the outdoor air. In the grocery store and office with no filtration, the only way to dilute virus concentrations in the space is to introduce outdoor air via mechanical systems. As the filtration efficiency increases the percentage of the smaller particles, including viruses, are removed by the systems' recirculated air increases. Another way to look at this is, as the filtration efficiency of recirculated air is increased, the clean air delivery rate will be increased proportionally. The amount of clean air per person is equivalent to the amount of outdoor air per person and the filtration efficiency times the flow of recirculated air per person. In equation form:

$$\text{Clean Air (cfm/person)} = \text{OA cfm/person} + \text{Filter Eff} * \text{Recirculated cfm/person}$$

For example, in an office, increasing the filtration from MERV 6A to MERV 11A will increase filtration efficiency from 0 to 62% for 1 μm particles. With a total supply airflow rate of 1 cfm/ft^2 in 1,000 ft^2 of space, with the ASHRAE design recommendations of 17 cfm of outdoor air per person, and an occupancy of five persons per 1,000 ft^2 of office space, 85 cfm of outdoor air is delivered, with the remaining 915 cfm of air recirculating through the system. Increasing the filtration efficiency of the recirculation air to 62% results in an additional 567 cfm of clean air for five persons (or 113 cfm/person) for a total of 130 cfm/person.

Table 4.3 shows the comparison of clean air delivery expressed in terms of rate of clean air delivery per person, air exchange rates for the volume of the occupied space (air changes per hour), as well as the average age of air for control of potentially infectious particles. It is presented for code compliant conditions and evaluates the effect of using enhanced particulate filtration in the different environments. Note that as filtration efficiency is increased in various environments, as is being currently recommended to reduce the impact of the pandemic, the Clean Air ACH increases and the Average Age of Air decreases.

These values permit comparison of ventilation rates of different environments in which people commonly find themselves. These environments are further compared by increasing the air exchange rates accomplished by improving the filtration efficiency. When the pollutant generation rate is relatively uniformly distributed among occupants over time, such as individually generated bio effluents (CO_2, body odors, etc.), they will be best controlled by increasing the outdoor air delivery rate per person. If the source were related to relatively rare, periodic/occasional emissions,

such as one or two individual passengers shedding viruses during a cough or sneeze, then the air exchange rate of total air and the age of air would be more relevant since these terms will better reflect the length of time other passengers could be potentially exposed to infectious aerosols.

The aircraft environment, when meeting current ventilation standards, with 50% recirculation of HEPA-filtered air, supplies a much higher delivery rate of clean air than any other commonly encountered environment. In fact, the aircraft air exchange rate significantly exceeds all normally encountered environments. When infectious particles are released in a typical, code compliant ventilated building and the aerosol has much more volume in which to disperse than that found on an aircraft, mitigating much of the exposure potential.

This analysis shows that aircraft will have a significantly lower age of air, resulting in a very short residence time for particles, and possibility of exposure to infectious particles than any other commonly encountered environment, which will help offset the counteracting effect of being in a smaller volume and in closer proximity to other passengers.

For episodic releases, such as from a cough or a sneeze, the very high air exchange rates in aircraft cabins assume that contaminants released in such events are fully flushed from the cabin in as little as two to five minutes, as opposed to some six hours in a commercial or retail space complying with current codes and standards where these particles will be mixed into the large volume of the space.

Table 4.3 Comparison of Clean Air Ventilation Rates for Various Space Types Expressed in Air Change Rates per Hour and Average Age of Air

Space Type	Available Volume ft³/person	OA cfm/person	ACH Total	OA ACH	% OA	Clean ACH	Ave Age of Clean Air (Min)	Filter Eff. @ 1.0 μm
Home (Natural Ventilation)	2,000	8	**0.25**	**0.25**	100%	0.25	240	0%
Commercial Aircraft #1(HEPA)	44.61	9.5	25.6	16.85	66%	25.6	2.3	**99.97%**
Commercial Aircraft #2 (HEPA)	33.95	9.5	33.6	16.85	50%	33.6	1.8	**99.97%**
Grocery Store (MERV 6A)	1,563	**15**	4.8	0.58	12%	0.6	104	0%
Grocery Store (MERV 11A)	1,563	**15**	4.8	0.58	12%	3.2	19	62%
Office (MERV 6A)	2,500	**17**	4.8	0.41	9%	0.4	147	0%
Office (MERV 11A)	2,500	**17**	4.8	0.41	9%	3.1	19	62%
Hospital Patient Room (MERV 14A)	2,250	75	**4**	**2**	50%	3.8	16	92%
Hospital Operating Room (MERV 14A)	1,188	59	**20**	**3**	15%	18.6	3.2	92%
Hospital Operating Room (MERV 14A)	1,188	59	**20**	**3**	15%	20.0	3.0	99.97%

ft³/person	cubic feet per person
OA	outdoor air
cfm/person	cubic feet per minute per person
ACH	air changes per hour
Ave	average
Min	minimum
Eff.	efficiency
μm	micrometer
HEPA	high efficiency particulate air
MERV	minimum efficiency reporting value

5.0 NON-PHARMACEUTICAL INTERVENTIONS (NPI) AND THE LAYERED APPROACH FOR RISK MITIGATION DURING AIR TRAVEL

Responding to the COVID-19 pandemic will rely ultimately on the development of herd immunity,[3] through infection and/or vaccine administration, and the application of effective medications and therapeutics to treat infected and ill persons. In addition, non-pharmaceutical interventions (NPI) are actions that can be implemented to slow and/or limit the spread of infections amongst a population. NPI can offer a level of protection for those at risk of illness upon infection by – in this case the SARS-CoV-2 virus. NPI measures fall into three general categories, namely:

1. **Personal:** These include routine personal hygiene measures, such as hand washing with soap. Also included are use of hand sanitizer, practicing cough/sneeze hygiene and wearing face-coverings such as masks.

2. **Community:** These include policies and strategies aimed at the community level to raise awareness about the disease and how it is spread. For example, educating people about steps that they can take to minimize the risk of transmission, such as not travelling when they feel unwell, adopting physical distancing in situations where they might normally be in close proximity to other people, and encouraging them to make efforts to minimize exposure to any known high risk populations.

3. **Environmental:** These include practices and procedures that seek to limit viral exposure, for example promoting cough/sneeze hygiene and the routine cleaning of surfaces to help reduce any viral contamination on surfaces and objects. Also included in this category are ways in which an environment might be manipulated, for example by increasing ventilation.

Combining elements of personal, community, environmental NPI provides a **layered approach** that seeks to capture the additive or synergistic risk mitigation effects of each intervention. **The layered NPI approach is highly relevant to efforts to minimize the risk of SARS-CoV-2 transmission during general operation of the aircraft and while travelling by air during pre-boarding, while on board and when deplaning.** The exposure risk mitigation system of NPIs is presented in Table 1.1 and Figure 5.1 gives examples of NPI for SARS-CoV-2 by each of the layers.

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[3]Herd immunity refers to a position when most of a population is immune to an infectious disease, this provides indirect protection—or herd immunity (also called herd protection)—to those who are not immune to the disease. There are two ways to achieve herd immunity: a large proportion of the population either is infected, or gets a protective vaccine.

The different layers of NPI are categorized as: Education and Awareness; Screening; Physical and Engineering Controls; Process Management, and PPE. Within these categories, various operational and programmatic controls have been identified that can be implemented. Figure 5.1 outlines various control measures for each category and how they might be integrated to provide the layered protection afforded by a systematic integration of NPIs.

Figure 5.1 The Layered Approach for Disease Mitigation Strategy using Non-Pharmaceutical Interventions

Modeling and measurement studies consistently support the assertion that applying multiple NPI across the different levels of control as shown in Figure 5.1 can be highly effective at reducing the spread of SARS-CoV-2 (Cowling et al., 2020). **Those seeking to reduce the spread of SARS-CoV-2 should consider the NPI proposed here as a system of interlinked risk mitigation interventions that when used together can effectively control the risk of exposure to the novel coronavirus during air travel.**

As more information becomes available with respect to the spread of SARS-CoV-2, the effectiveness of various control measures will continue to evolve and be quantified. As illustrated in Figure 5.1, NPI is a means to create layers of environmental risk management. For SARS-CoV-2, the layered NPI approach described here relates to:

- Testing for the virus and screening for COVID-19 and COVID-19-like symptoms
- Face-covering, including the wearing of face masks and/or face shields
- Process management via physical distancing and reduced density
- Cleaning and disinfection
- Physical engineering controls and ventilation

Each of these NPI layers are addressed in turn in sections 6.0-10.0, highlighting their use and relevance to deployment during air travel across the journey "Gate to Gate" as a means to reduce the risk of transmission of SARS-CoV-2.

6.0   NPI LAYERING: TESTING AND SCREENING

The CDC has identified a set of symptoms (see Section 2.3.3) that are consistently associated with a COVID-19 infection (Burke et al., 2020). Identifying symptomatic people with COVID-19 who are contagious and isolating them from uninfected people is the most effective means of controlling transmission of SARS-CoV-2. Screening for symptoms (for symptomatic people) and viral testing (for both asymptomatic and symptomatic people, see Section 2.3.3 for symptoms) can be helpful in identifying actual cases as well as PUI. With respect to air travel, this type of evaluation should start at home before a person leaves for the airport. Asking travelers to be aware of the symptoms of COVID-19 and self-screen before traveling are part of a control system.

Screening and testing form a key tenet of the triad "**Test-Trace-Isolate**" (CDC, 2020c) for the control of infectious diseases. Taken together they are a means of identifying and then allowing for the temporary removal from the community of contagious cases and those individuals suspected of being infected. The health of such persons can then be monitored and medical care provided as needed, with people released once they are well and/or no longer infectious. Testing, contact tracing to identify people potentially exposed to an infectious individual and isolation complement one another and taken together are a form of elimination in the context of the layering of control elements.

While several methods of symptom screening are included here, only self-screening for health symptoms of COVID-19 and health attestation to the airline concerned are in widespread use, with temperature checks used in specific settings. As rapid viral testing becomes more readily available, it is likely to be used widely. When implementing testing and screening plans a thorough evaluation of their feasibility, technical and economic, and their perceived effectiveness should be undertaken.

6.1.   HEALTH SELF-ASSESSMENT SYMPTOM SCREENING AND ITS EFFECTIVENESS

Health self-assessment symptom screening refers to the identification of people with health symptoms that are consistent with COVID-19. A survey tool may be employed asking people to attest to the presence/absence of certain symptoms – a so-called **health attestation**. A **temperature measurement** can be completed daily or more frequently, including while on board a plane. People with COVID-like symptoms may be considered suspect cases and are PUI who should be quarantined until their infection status is determined. Self-screening by passengers for health symptoms, followed by making a health attestation to the airline before travel is currently in widespread use. Temperature checks are being utilized in certain settings for the traveling public and consequently for crewmembers and staff.

Symptom screening can be effective in identifying COVID-19 cases in which the indicator symptoms manifest sufficiently to be noticed and reported truthfully by an affected individual. Aviation industry members should generally adopt guidance from CDC on COVID-19 symptoms, which to our knowledge is the most comprehensive and current assessment of COVID-19 symptomatology (see Section 2.3.3; Burke et al., 2020; CDC, 2020d). The aviation industry symptom list is consistent with clinical characteristics of COVID-19 patients reported in the scientific literature (Richardson et al., 2020; Wang et al., 2020b).

An analysis of over 2.6 million participants in the United States and United Kingdom, who reported symptoms via a smartphone App, showed that several symptoms and indicators together (i.e., loss of smell and taste, severe or significant persistent cough, severe fatigue, and skipped meals), reliably predicted the likelihood of testing positive for the virus and being a confirmed case (Hui et al., 2020). Screening for these symptoms in addition to gender and age correctly identified approximately 75% of the confirmed COVID-19 cases and 75% of the individuals demonstrated not to be carrying SARS-CoV-2 (Hui et al., 2020).

Screening by health self-assessment of symptoms will clearly not identify carriers of the virus who are asymptomatic, or who have yet to experience symptoms (i.e., pre-symptomatic). **However, screening for COVID-like symptoms is still a useful NPI.**

6.1.1 Body Temperature Screening before Boarding an Aircraft

Body temperature measurements have been used widely as a screening tool in airports and found to be useful in reducing the importation cases of infectious diseases, like Dengue Fever and Ebola (Guan et al., 2010; Thwaites & Day, 2017). For example, the effectiveness of temperature screening in detecting imported cases of Dengue Fever was 45% in Taiwanese airports between 1998 and 2007 (Guan et al., 2010; Thwaites & Day, 2017). Medical grade or industrial grade infrared thermometers can be used to measure the temperature at the temporal artery in the forehead. The instrument can be placed at a minimum distance of one foot (30.5 cm) away from a passenger's forehead and the body temperature measured easily. If readings are at or above 100.4°F (38°C), then the passenger is considered to have fever and should be prevented from boarding the airplane; those with an average body temperature (range 97-99°F; 36.1-37.2°C) may pass the health control and be allowed to board (CDC, 2020b).

Body temperature measurements can also be determined accurately by scanning the wrist of an individual (Chen , et al., 2020) using appropriate equipment. Infrared scanning cameras are preferred over handheld thermometers as they can be used without being close to a person who might be infected. When used properly, they are also faster than handheld devices, measure skin temperature accurately, and can be connected to a camera so that any suspected individuals might be flagged for secondary inspection (FDA, 2020a). Additionally, such a system can store

information for future use, which might enhance track and trace of individuals close to a confirmed COVID-19 case.

While body temperature screening in airports has been effective in detecting infected individuals for other infectious diseases, for COVID-19, it is unlikely that will be the case. The reasons for this include:

- Only some 24-31% of COVID-19 infected individuals develop a fever (Richardson et al., 2020; Mitra et al., 2020).

- Some passengers might be in the incubation phase of the disease and will not display any symptoms. The typical incubation period for COVID-19 is considered to be approximately five days (CDC, 2020e). Given individuals have been shown to be infectious up to 2.5 days *before* the onset of symptoms (Wolfel et al., 2020), it is likely that some will not be detected by thermal scanners prior to boarding, but might subsequently become infectious while onboard during the flight.

- Some travelers might choose to conceal their fever by taking anti-pyretic medications, such as acetaminophen or ibuprofen (Jamerson & Haryadi, 2020).

- The sensitivity of infrared thermometers and scanners is not 100%; it is close to 86% (Quilty et al., 2020).

- Factoring in a low rate of antipyretic medication usage (some 10 to 20% of travelers) and proper use of thermal scanning equipment that captures 100% of travelers prior to boarding, the effectiveness of body temperature screening would be between 16-24%. Thus, on average it would serve to detect only 20% of people infected with COVID-19.

6.2 VIRAL TESTING

Viral testing refers to diagnostic evaluations intended to identify people who are infected with the virus at the time of the test, i.e., confirmed cases. People who test positive can then be isolated to prevent transmission of the virus. Recent close contacts of the infected person are considered suspect cases and should be identified by contact tracing. Close contacts are generally quarantined until their infection status is determined. Some countries (DOS, 2020) require proof of a current negative viral test result to be presented by the traveler, prior to being allowed entry. Indeed this practice has been adopted by some airlines (Washington Post, 2020) and is being piloted in some airports. As rapid viral testing becomes more readily available and more affordable it will likely become more widely used by airlines and/or airport operators.

Viral testing for SARS-CoV-2 is diverse and evolving rapidly as numerous research laboratories and companies develop new measurement endpoints, methods, and devices. The U.S. Food and Drug Administration (FDA) authorizes test methods, as do international bodies. As of

September 23, 2020, the FDA had authorized over 120 different viral test methods that vary in many respects. For some tests, fluids are collected from several adjacent areas of the nasal region, while other tests rely upon saliva collected from the mouth. The methods also represent a variety of analytical techniques including, different types of polymerase chain reaction (PCR) assays, enzyme-linked immunoassays (ELISA), and others. In addition, the minimum amount of virus that can be detected varies by several orders of magnitude among the different test methods. The time it takes from when a sample is obtained to when the result is available also varies by the method adopted, ranging from 15 minutes to several days, dependent on the complexity of the testing protocol.

The FDA issued an Emergency Use Authorization (EUA) for several new methods in late July and August 2020, including authorization of a device for on-site rapid testing of proteins attached to the coronavirus (see Figure 2.1; BD, 2020). Shortly thereafter, the FDA authorized testing of samples pooled from a small group of individuals (FDA, 2020b). In mid-August 2020, the FDA authorized a new, laboratory-based molecular test developed by researchers at Yale University that might offer shorter turn-around times and lower costs than the existing methods (FDA, 2020b). Other researchers are working on lateral flow assay techniques (Kotlikoff, 2020), akin to the at-home pregnancy testing kit, that could allow individuals to test themselves at home or while at the airport before boarding.

7.0   NPI LAYERING: FACE COVERINGS

Face coverings are an essential part of a comprehensive set of measures to reduce transmission of COVID-19 throughout air travel. As defined here, face coverings include surgical masks, cloth masks, respirators, and face shields. These devices can mitigate transmission of respiratory viruses such as SARS-CoV-2 by:

- Capturing respiratory droplets expelled when the person wearing the face covering breathes, talks, laughs, sings, sneezes, and/or coughs.
- Reducing inhalation of respiratory droplets expelled by others.
- Restricting a person from touching their face, mouth, and eyes.

Passengers and airport/airline employees should be required to wear face masks throughout their air travel journey – including time spent in the airport, boarding, in-flight, and deplaning. Since different coverings offer different protection and understanding of proper use may vary, it is of critical importance that consistent requirements of proper face covering selection and use be applied and clearly communicated for everyone throughout air travel.

7.1   THE ROLE OF FACE MASKS IN PREVENTING COVID-19 INFECTION DURING AIR TRAVEL

During air travel, passengers and crew on-board are typically in a very well ventilated space but in close proximity to one another for an extended period. As discussed earlier, SARS-CoV-2 infections can occur through the emission of virus-containing respiratory particles that are aerosols ($\leq$5 μm in diameter) and droplets (>5 μm in diameter) exhaled by infected people when coughing, sneezing, speaking, and during normal breathing (Asadi et al., 2020;Anderson et al. 2020; Leung et al., 2020a). While large particles fall to the ground quickly, smaller particles are lightweight and can remain suspended in the air (Prather et al., 2020). Face masks help block respiratory particles, yielding added protection in the aircraft environment.

Individuals who are infected but do not develop symptoms (asymptomatic) and those who are early in the disease course and yet to develop symptoms (pre-symptomatic) will likely be unaware they are infected and may be contagious but can still spread the virus through breathing and speaking (Prather et al., 2020). Therefore, the use of face masks is critically important throughout the air travel process, from entering the airport for departure to leaving the destination airport, because it will serve to diminish the release of infectious particles into the environment (Chen, 2020). Reducing the transmission from the source of infection, or "source control," provides an important layer of protection against COVID-19 for air travelers (Prather et al., 2020; Cotfas et al., 2020; Cheng et al., 2020). Higher amounts of transmitted virus result in both higher likelihood of infection and in more severe disease (Prather et al., 2020; Dalton, 2020).

When the use of masks is implemented in combination with other measures built into aircraft operations, such as increased ventilation with high efficiency particulate air (HEPA) filtration in the aircraft and disinfection of surfaces, these layered NPIs offer significant protection from acquiring COVID-19 through air travel (Cotfas et al. 2020; Chen, 2020; The Lancet Infectious Diseases, 2020).

7.2   TYPES OF FACE COVERINGS

A variety of face coverings are available for use in guarding against the transmission of the SARS-CoV-2 and serve to filter air breathed in and to block particles breathed out. The various types differ in many respects, including efficiency at capturing droplets, training required for proper use, availability, and cost, among other considerations such as comfort and durability. Detailed descriptions of criteria for selecting a face covering are available elsewhere (NIOSH, 1996). The CDC does not recommend using masks with exhalation valves for controlling infectious aerosols (CDC, 2020f). Here, four types of face coverings are described briefly and include respirators, face masks, cloth masks, and face shields. Their ability to capture respiratory droplets, and thus expected effectiveness at controlling transmission of SARS-CoV-2 within the context of the aviation industry COVID-19 management and risk program, have been highlighted.

Figure 7.1   Examples of Cloth face masks (top), Surgical Face Masks (middle) and an N95 Respirator (bottom)

7.2.1   Respirators

As defined by the CDC, a respirator is a personal protective device worn on the face covering at least the nose and mouth and is used to reduce the wearer's risk of inhaling hazardous airborne particles (including dust particles and infectious agents), gases, or vapors. One type of respirator, the N95 mask, is designed to have a minimum filtration efficiency of at least 95% for particles (Konda et al. 2020). The filtering material is fitted to form a tight seal around the nose and mouth and requires medical clearance and "fit testing" by a professional (Offeddu et al., 2017; Van der Sane et al., 2008). N95s are generally reserved for health care professionals who work in situations where there are high concentrations of infectious aerosols. They are not required to reduce community-based transmission of SARS-CoV-2 (CDC, 2020f; Howard et al., 2020).

As is appropriate, NLPI understands that N95s are being used in certain circumstances during air travel that require close contact with individuals for extended periods, such as dealing with an infected individual or one who has become symptomatic on a plane. Respirators might also be used by a passenger with medical clearance to wear one due to a preexisting condition (Sommerstein et al., 2020). Although respirators may seem desirable in some ways, they reduce the respiratory function slightly in pressurized air cabins and could become uncomfortable during long flights.

7.2.1.1   Expected Effectiveness

N95 respirators are highly effective at controlling exposure to airborne particles. When fit-tested and worn correctly, they can capture at least 95% of particles in the air. Previous scientific reports assessed the effectiveness of respirators in preventing transmission of known respiratory diseases like H1N1 Influenza, SARS-Cov-1, and tuberculosis. A meta-analysis of respiratory PPE, in which face covers acted as a barrier against inhalation of infectious aerosols, provided evidence of an 88% protective effect for N95 respirators (95%) against severe acute respiratory syndrome-SARS (Offeddu et al., 2017). Respirators are designed to be reused but may become contaminated during use and require cleaning or disposal.

7.2.2   Surgical Masks and Cloth Masks

In contrast to respirators, face masks (including both cloth and disposable surgical masks) are looser-fitting barriers, and their primary purpose is to block droplets emitted by the wearer from being emitted into the environment. They also block larger particles in the atmosphere from contacting the nose or mouth of the wearer (Prather et al., 2020; Howard et al., 2020). Masks are more comfortable than respirators, and cloth masks are user-friendly, reusable, and widely available. Surgical masks are currently needed for use in healthcare, so the CDC encourages the public to use cloth masks, which still serve this important barrier function (Van der Sande et al., 2008; Cheng et al., 2020; CDC, 2020f; Howard et al., 2020).

The face mask is worn as a public health infection control measure to reduce individuals exposing other people around them to aerosol. In the case of a potentially infected individual, who may or may not be exhibiting symptoms, a face mask worn by that person in public can reduce risk to the community from exposure to virus the person may be shedding. Wearing a face mask in this context functions as a "source" control measure (Verma et al., 2020), in contrast to a respirator, which is designed to protect the wearer from inhaling infectious aerosols. Still, a face mask should meet appropriate standards for construction and fit the individual for it to be effective.

Like surgical masks, cloth masks are loose fitting and may be washed and reused. They are available commercially or may be constructed from various cloth materials (CDC, 2020f). Research has found materials for cloth masks commonly available in a household (including silk,

cotton, tea towel, and linen) to be between 58-83% effective in filtering particles of 1 μm aerosolized bacteria and 49-72% effective in filtering out particles containing 0.2 μm aerosolized viruses Davies et al., 2013). Variation in barrier efficacy depends on several features of the mask: type of fabric; tightness of the weave; addition of a filter layer; number of layers of fabric, and fit. Researchers find that cotton fabrics with higher thread counts are more effective barriers, as are masks with more layers and those with filter material (for example, addition of cotton batting between layers).

Exhalation valves or vents allowing unfiltered breath containing respiratory droplets and aerosols to be released from the mask of the wearer, and masks with these devices should not be used to prevent the spread of SARS-CoV-2 (CDC, 2020h). Gaps around the top or sides of a mask diminish its efficacy (Konda et al. 2020). Emerging evidence suggests that improving fit of a cloth mask, for example by reducing gapping, might improve its filtration ability above that of surgical masks (Mueller et al., 2020). Some synthetic fabrics may add an electrostatic barrier, which filters smaller particles, in addition to the mechanical barrier of the cotton layers (Konda et al. 2020), but there is mixed data about whether inclusion of multiple materials improves the filtration of the mask (e.g., combining cotton layers with silk, chiffon, and flannel) (Zangmeister et al., 2020). Even with such variance in mask type, face masks are generally effective as a public health infection control measure in preventing individuals from exposing other people around them, and they also confer some protection to the wearer (Howard et al., 2020; Jayaweera et al., 2020).

According to various airline websites, all employees and passengers are required to wear facial coverings or masks (NPR, 2020). For the purposes of this Report, we anticipate that face masks will be required to be worn at all locations at the airport and aboard the aircraft, except while eating or drinking.

7.2.2.1   Expected Effectiveness

Scientific evidence has shown that NPIs such as face masks effectively decrease the risk of transmitting respiratory illness by blocking particles that contain the viruses or bacteria from being exhaled into the environment and inhaled in infectious doses by healthy

Individuals (Howard et al., 2020; Jayaweera et al., 2020; Prather et al., 2020). While face masks are imperfect barriers for droplets smaller than their filtration range, they can block larger droplets from entering the environment and evaporating into smaller, infectious particles that can be inhaled (Howard et al., 2020; Jayaweera et al., 2020; Nicas et al., 2005). In the absence of a vaccine or treatment, NPIs such as face masks are one of the most pragmatic and effective options for controlling the spread of SARS-CoV-2 (Li et al., 2020; Jayaweera et al., 2020). Universal use is key. A recent modeling study suggested that the universal use of surgical masks in the setting of ventilation rates of aircraft might reduce infection risk from respiratory particles to less than 1% (Dai and Zhao, 2020). Modeling studies cannot replicate real-life scenarios, but they

are useful for estimation. While cases of presumed in-flight transmission have been reported, scientists note that individuals may have contracted the disease before or after the flight, and that contagious individuals were not wearing masks (Hoehl et al., 2020; Yang et al., 2020). Researchers who calculated a 3.69% risk of SARS-CoV-2 transmission in aircraft prior to implementation of air travel NPI measures note that risk can be diminished by universal mask use (Yang et al., 2020).

Studies specifically focused on SARS-CoV-2 and the use of masks and assessing the impact of NPI implemented on aircraft are ongoing. However, prior scientific evidence has demonstrated the effectiveness of face masks in preventing infections from similarly transmitted respiratory pathogens and a growing number of case studies involving SARS-CoV-2 in settings similar to the on-board environment. With a variety of different research paradigms examining different respiratory infections with similar transmission routes, studies reflect that surgical masks confer protection for healthcare workers from respiratory illness in healthcare settings Offeddu et al., 2017) and as source control when worn by patients with known droplet- and airborne-transmittable infections by reducing emitted infectious particles (Dharmadhikari et al., 2012; Milton et al., 2013; Leung et al., 2020a).

Previous research highlights the low incidence of transmission of other respiratory pathogens on airplanes (Leder and Newman, 2005) and mask use could also help control the spread of respiratory infection on aircraft Zhang et al., 2013). On a population level, universal masking may be able to diminish the spread of respiratory viral pandemics (Brienen et al., 2010). Researchers consider that implementation of layered NPI, including mandatory mask use, helped decrease transmissibility of SARS-CoV-2 in China, leading to reduced case numbers after the initial outbreak (Leung et al., 2020b). As new data becomes available, how these variables interact and how existing knowledge generalizes to control of this novel virus will be determined. Future studies will also help quantify risk reduction.

Case studies demonstrating the utility of face masks in reducing SARS-CoV-2 transmission are continuing to emerge. For example, one such report describes that two symptomatic hair stylists with confirmed COVID-19 positivity who were in close contact with 139 clients. The stylists and the clients wore face masks, and no symptomatic secondary cases were reported following this potential exposure. Of the 67 clients subsequently tested for SARS-CoV-2, all test results were negative (Hendrix et al., 2020). Another report describes a symptomatic patient and his pre-symptomatic wife, both of whom tested positive for COVID-19, traveled on a 15-hour international flight with 350 passengers. Both cases wore masks, and no other passengers subsequently tested positive for COVID-19 (Schwartz et al., 2020). Finally, a systematic review and meta-analysis of results from 172 observational studies from 16 countries found that face masks were associated with an 85% reduction in risk of infection compared to no face covering (Chu et al., 2020).

Models of SARS-CoV-2 transmission indicate that widespread use of face masks can substantially reduce COVID-19 impacts on public health.

7.2.3 Face Shields

Face shields are transparent, plastic barriers that cover the face and are open along the sides and bottom. The top of the shield is typically attached to a lightweight frame that is worn around the wearer's head. A face shield is intended to decrease the likelihood that a droplet from another person will enter the wearer's eyes, nose and/or mouth. (CDC, 2020f). Currently, the only one international airline recommends the use of face shields.[4] Face shields are not an acceptable replacement for universal masking except when an individual is unable to wear a mask for medical or other reasons.

7.2.3.1 Expected Effectiveness

Face shields are worn routinely in clinical settings as an additional layer of protection against typical infections between caregivers and patients. In these settings, face shields can provide an outer layer of protection, compared to N95 respirators or surgical face masks that provide an inner layer of protection. Face shields are thought to be effective at minimizing ballistic transport of respiratory droplets that may otherwise deposit in the eyes of a healthcare worker. For example, laboratory-based studies with mannequins exposed to respiratory droplets generated with cough simulators indicated that face shields could reduce both inhalation of respirable-size particles by the wearer and emission of respiratory droplets from the wearer (Lindsley et al., 2014; Ronen et al., 2020). However, neither of these studies evaluated the effectiveness of face shields to mitigate exposure to aerosols transported passively (by diffusion) or mechanically (by turbulent indoor air) as may apply on aircraft.

According to the CDC, the potential benefit of face shields to control emission of respiratory droplets for another person's protection is not known (CDC, 2020f). Quoting directly from the same guidance, *"CDC does not recommend using face shields for everyday normal activities or as a substitute for cloth face coverings."* We are not aware of either observational studies or randomized clinical trials that have assessed the effectiveness of face shields for mitigating the transmission of SARS-CoV-2. Of note, a recent anecdotal report indicated that face shields were less effective than face masks at protecting servers in restaurants from the transmission of the coronavirus while working (Miller, 2020). In contrast, the effectiveness of face masks, especially when universal masking is practiced, is well documented in the scientific literature to contribute to controlling the transmission of various respiratory viruses, including SARS-CoV-2 (Brooks et al., 2020).

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[4] https://www.washingtonpost.com/travel/tips/qatar-airways-is-requiring-passengers-wear-face-shields-what-do-health-experts-recommend/

7.3   RECOMMENDATIONS FOR PROPER USE OF FACE MASKS DURING AIR TRAVEL

In summary, face masks offer an important line of protection against the spread of SARS-CoV-2 by reducing potentially infectious exhaled respiratory particles from the wearer as well as providing some barrier protection against inhaled particles. However, it is the proper use of a face mask that confers it effectiveness. The protective value of the face mask decreases significantly when the wearer's mouth or nose are not completely covered because it is no longer functioning as a barrier for respiratory particles (Van der Sande et al., 2008; Konda et al., 2020; Davies et al., 2013). For these reasons, **face mask compliance and correct use are critical while on board the aircraft.**

Additionally, passengers and crew should make every effort to ensure that their masks fit comfortably and without gaps in order to maximize their effectiveness as a barrier to viral spread (Konda et al., 2020; Mueller et al., 2020). Masks should be cleaned regularly in accord with the CDC recommendation (CDC, 2020f).

Taken together with the NPIs incorporated into the operation of the aircraft, such as high ventilation rate and high efficiency air filtration in the aircraft cabin, this NPI layered approach to infection control significantly reduces the concentration of infectious droplets in the air and greatly diminishes the risk of possible infection during air travel.

Masks reduce airborne transmission

Infectious aerosol particles can be released during breathing and speaking by asymptomatic infected individuals. No masking maximizes exposure, whereas universal masking results in the least exposure.

Particle size (μm)

100   10   1   0.1

Infected, asymptomatic   Healthy

Maximum exposure

Minimum exposure

Figure 7.2   Infographic of Reduction in the Potential Transmission of Respiratory Viruses Provided by Face Coverings. [Reproduced from Prather et al., 2020]

8.0   NPI LAYERING: PROCESS MANAGEMENT

Process management, in the context of airlines and the COVID-19 pandemic, refers to administrative policies, procedures, or orders designed to minimize the transmission of SARS-CoV-2 on aircraft. This approach provides tools and resources for analyzing, defining, and optimizing processes of interdependent operating procedures described in this report as well as those historically involved in air travel. The airline industry is based on a culture of safety and has well-trained, highly competent staffing able to provide the services needed during this pandemic. Passengers are conditioned to expect and adhere to established safety processes. A commitment to standardization and detailed implementation of procedures can help minimize the potential for transmission of infectious disease during travel. Administrative controls may be issued first as guidance but subsequently become legally enforceable orders.

Here, information on the expected effectiveness of two types of administrative controls is given. Firstly, reduction in cabin service to limit physical contact and, secondly, improvement to the boarding and deplaning processes to support physical distancing. Many of the processes outlined in Figure 5.2 have been adopted by many airlines. However, the nature of the pandemic requires that a periodic procedural review is undertaken to ensure that the most effective methods are implemented as knowledge about the risk of SARS-CoV-2 transmission evolves.

8.1   LIMITING CONTACTS BY REDUCING CABIN SERVICE

The risk of infection is linked directly to the frequency and duration and intensity of contacts between people, the distance maintained between people, and the length of time that people are in a confined space. Resolution of the latter two concerns is secured by using the highly effective ventilation provided onboard aircraft. This offers the equivalent desired spacing by delivering very high air exchange rates in the cabin (see Section 10).

Significant reductions in the number and intensity of contacts can be realized, thereby eliminating a potential route of transmission via exposure to droplets or fomites, by reducing or eliminating in-flight cabin service. If food and drink service cannot be eliminated completely due to considerations such as the length of the flight, airlines may choose to hand food packs out as people board (or have them on a cart as people board, for self-service). In this way, the frequency of direct face-to-face contact and conversation between cabin crew and passengers can be reduced. Associated trash can be collected as part of the regular clean up after passenger deplaning, assuming this is both safe and practicable. In addition to reducing the frequency of close physical contact with crewmembers and passengers, this approach also reduces movement and congestion in the aisle and the consequent disruption of cabin airflows. Further, it reduces the number of people handling potentially infectious materials and offers greater flexibility for passengers to eat and/or drink at their convenience. In this way, the removal of face masks will likely be more

staggered such that not all passengers at a given time will be without masks during a service period. In addition to reducing or eliminating beverage and food services, sales and promotional programs that bring cabin crew into routine contact with passengers should also be eliminated.

8.1.1   Expected Effectiveness

Eliminating or reducing in cabin service is intended to protect against transmission of the virus from inhalation of large respiratory aerosols, near-field small aerosol exposure and contact with potentially contaminated service materials. Face masks will be effective in controlling most of the potential exposure to the large droplets, but there can be some leakage of the smaller aerosol particles from around the mask. This can create a concentrated aerosol cloud close to the infected person (Liu, 2020) that will be rapidly diluted by the aircraft ventilation; however, minimizing the time that cabin crew members may be in the direct proximity of potentially infected individuals will certainly reduce their risk of infection.

8.2   BOARDING AND DEPLANING

Boarding and deplaning are routinized and proceed without incident under normal conditions. However, these segments of air travel could present increased risks of potential infection during COVID-19 times if specific procedures are not implemented to minimize risk of transmission of SARS-CoV-2. The goal is to reduce passenger density in the aisles and maintain appropriate physical distances during these segments of the trip. While boarding and deplaning, it is critical to ensure that aircraft ventilation systems are on and operating at their appropriate settings, as recommended by the manufacturers to minimize potential risk of infection (see Section 10).

Developing ways of boarding aircraft efficiently and reduce queuing has been studied for years (Nyquist & MacFadden, 2008; Jaehn & Newman, 2015), with critical periods being those on the jetway, boarding the plane and deplaning. A challenging time to manage physical distancing is just after boarding when people are in close proximity while they locate their seats and place luggage in overhead bins/under seats. The quantity and type of hand luggage has a significant impact on the duration of queues and the number of close contacts made (Schultz, 2020). **Shultz (2020) found that by reducing hand luggage to only that which can be stored in an overhead bin, the number of close contacts encountered would be reduced by two-thirds during boarding.** This is important since, during that time, people are exerting themselves resulting in increased respiratory levels for a brief period, raising the potential for infectious aerosols to be exhaled into the cabin. Deplaning is generally a smoother and quicker process as people move through by rows in a more ordered fashion; however, it is not as controlled by crewmembers as the boarding process. The deplaning process can be enhanced by having passengers remain in their seats until directed to leave by a crewmember. Jetway management can be controlled by reducing the density of passengers embarking/disembarking at any one time and having them maintain appropriate physical distancing by observing markings on the floor and walls.

8.2.1 Expected Effectiveness

The aircraft ventilation systems can contribute to maintaining safe environments while operating during a flight and while the plane is at the gate, boarding or deplaning passengers. There are specific steps that can be taken that will help mitigate the impact that are straightforward and can be readily operationalized. These include 1) maintaining appropriate ventilation during all phases of travel; 2) Clearly marking required physical distancing on the jetway bridge; 3) Admitting limited numbers of passengers at one time; 4) Reducing the amount of carry-on to one item where possible; 5) Having crewmembers manage the disembarkation process. These simple process management measures combined with the use of face masks will minimize materially the risk of SARS-CoV-2 transmission during these critical segments of air travel.

9.0   NPI LAYERING: CLEANING AND DISINFECTION

Transmission of SARS-CoV-2 through close contact may occur via direct inhalation of the virus in respiratory droplets, or if deposited onto eyes, face and/or other parts of the body; it can also be transferred from inanimate surfaces to the mouth, nose, and/or eyes. Surface cleaning and disinfection can reduce virus on inanimate surfaces and thereby reduce the risk or transfer by contact. Importantly, the latest guidance from CDC and the World Health Organization (CDC, 2020h; WHO, 2020d) state that surfaces are not thought to be a significant route of SARS-CoV-2 transmission, indicating that direct inhalation and deposits onto the eyes, face, and/or body are more relevant to transmission when people are in close proximity.

9.1   COVID-19 INFECTION BY DIRECT CONTACT

Virus shed in respiratory droplets by infected individuals can become deposited onto surfaces, also referred to as "fomites." The virus will remain on these surfaces until neutralized by either disinfection or through natural degradation. A healthy individual could become infected with SARS-CoV-2when they touch a fomite with a sufficiently high concentration of an infectious virus and go on to touch their mouth, nose, and/or eyes. The surfaces in aircraft cabins however are cleaned frequently with effective disinfection agents approved by governmental agencies and reinforced by industry oversight bodies. Therefore, consistent with evidence from healthcare settings (Jones, 2020), there is likely to be a **very low probability of being infected with SARS-CoV-2 via fomites in the aircraft cabin.**

9.1.1   SARS-CoV-2 Survival Times on Different Materials

Surfaces are broadly classified as smooth or textured, porous or non-porous, with their cleanability and the products used to disinfect them a function of surface composition and texture (Table 9.1). The length of time a virus can survive on a surface depends on the type of material it is deposited on and the environmental conditions while on that surface, with transfer influenced by force of contact with the surface, surface texture etc. The survival time of SARS-CoV-2 on surfaces may be overestimated (Goldman, 2020), given the experimental conditions used in these early studies used very high concentrations of infectious viral particles applied to very small surface areas. While SARS-CoV-2 does degrade naturally on surfaces over time, disinfection with appropriate agents is recommended to minimize the risk from infectious viral particles in the environment (Cimolai, 2020; Kanamori, 2020; Sagripanti & Lytle, 2020).

Table 9.1	Survival Times for SARS-CoV-2 on Different Surfaces at 21 to 23 °C under Controlled Laboratory Conditions (van Doremalen et al., 2020; Chin et al., 2020)		
Surface	**Potential fomites inside the cabin**	**Half-life (~50% of the virus is still active, there is a medium risk)**	**Survival time (less than 0.1% of the virus is still active)**
Non-woven fabric	Pillows, blankets	3-6 hours	6-8 hours
Stainless steel	Lavatory, door handles, seats, seat buckles	6 hours	24 hours
Copper	Electrical system	1 hour	4 hours
Non-porous hard plastic	Tray tables, armrests, seats, cabin window, window shade, lavatory, air nozzles, lights, handsets	7 hours	48-72 hours
Paper or cardboard	Magazines, safety cards, paper bags, boarding passes, menu cards	5 hours	24 hours
Glass	Touchscreens, video monitors	24-48 hours	48 hours

9.2 CLEANING PRACTICES IN AIRPLANE CABINS AND THEIR EFFECTIVENESS IN REDUCING COVID-19 INFECTION VIA FOMITES

The basic and recommended way to disinfect remains 'spray and wipe', with cleaning undertaken before disinfecting. Aircraft manufacturers generally recommend disinfecting high touch surfaces in the cockpit and cabin with 70% isopropyl alcohol (IATA, 2020a). For other surfaces, the World Health Organization (WHO, 2020)d recommends disinfection products with at least 60% alcohol. In addition to routine cabin cleaning, high-frequency touch surfaces are also treated with disinfectants that are approved by the Environmental Protection Agency (EPA) and effectively kill 99.9% of SARS-CoV-2 in 10 minutes or less (see Table 9.2).

Table 9.2	EPA Approved Disinfectants to Kill SARS-CoV-2 (EPA, 2020)
Active Ingredient	**Average Time to Kill SARS-CoV-2**
Citric acid	5 to 10 minutes
Lactic acid	5 minutes
Isopropyl alcohol (> 70%)	5 minutes
Hydrogen peroxide (3%)	10 minutes
Quaternary ammonium	10 minutes

The EPA List N: Disinfectants for Use Against SARS-CoV-2 (COVID-19) (EPA, 2020), includes several active ingredients and more than 475 disinfectant products, but only a few are suitable for use on airplanes. Some disinfectants can oxidize and degrade susceptible materials found in the cabin and should not be utilized aboard aircraft (IATA, 2020a). If carpets, seat covers or the underlying upholstery is heavily contaminated with bodily fluids or vomit, they should be removed carefully, using appropriate PPE, sealed, and disinfected appropriately (EPA, 2020; IATA, 2020a; WHO, 2020d).

Disinfectants containing quaternary ammonium compounds (QACs) present a risk of occupational asthma, dermatitis, bronchial irritation, and allergic reactions among workers using these

compounds (Preller et al., 1996; Hecht et al., 1999). An indoor air study in hospital buildings checked for aerosolized QACs and found no detectable levels of these chemicals in indoor atmospheres when using regular manual surface cleaning, but found that contamination might occur if QACs were sprayed into the air and rooms are not adequately ventilated afterward (Vincent et al., 2007). This study indicates that occupational hazards might increase for cleaning workers if they are not using appropriate PPE when spraying QACs in the air or for frequent flyer customers if aircraft are not ventilated adequately.

The primary high-frequency touch surfaces on airplane seats are the 1) seat cushion; 2) seatbelt (buckle and latch and strap on both sides); 3) seatback cushion; 4) headrest; and 5) armrest (including seat recline button); see Figure 9.1.

Figure 9.1   High-frequency Touch Areas in an Airline Seat

High-frequency use surfaces in front of each passenger require special attention, as they pose a higher likelihood of particle deposits. These include 1) tray table latch; 2) tray table; 3) compartment and personal entertainment screen, and 4) the top edge of the pocket (see Figure 9.2). Lavatories on board aircraft are also high-frequency touch areas, and special cleaning practices are required to ensure that these areas are cleaned in-between flights (IATA, 2020a).

Figure 9.2 Extra-care High-Frequency Touch Areas Due to Repeated Use during a Flight (courtesy of Boeing Corporation)

9.2.1   Electrostatic Spraying of Active Ingredients

Portable electrostatic sprayers, or foggers, apply EPA-approved disinfectants to surfaces (including hard-to-reach surfaces). As they pass through the sprayer nozzle, positively charged disinfectant droplets are generated that can attach to negatively charged surfaces. Disinfecting agents are applied wet and left to dry, enabling the required contact time to disinfect surfaces (APHC, 2020). When using an electrostatic sprayer system, a cleaning agent with neutral or close to neutral pH needs to be used; products for safe use on electronics are approved by SAE International standards. Cleaning agents used in electrostatic sprayers include hydrogen peroxide, hypochlorous acid, and bleach-based cleaning products; QAC is sometimes recommended because it is naturally positively charged and more chemically stable for the process. Preferred products include those with "No Wipe" indications, which means that little or no residue remains after the manufacturer's recommended contact time (APHC, 2020).

Figure 9.3 Electrostatic Spraying in an Aircraft Cabin

The effectiveness of electrostatic spraying in inactivating the SARS-CoV-2 virus has not yet been determined. Some airlines check the effectiveness of cleaning practices by using ATP Testing, which detects residues containing ATP that is a biological indicator of cells (Sanna et al., 2018).

9.2.2 UV Disinfection

New methods are being developed that will further enhance the sanitization of surfaces. For example, ultraviolet (UV) disinfection is being tested by several airlines in the cabin, lavatories, and jetways. Germicidal UV (GUV) uses UV radiation to kill or inactivate bacteria, mold, spores, fungi, and viruses; it has a short-wavelength, known as UV-C 200-280 nanometers (nm), that effectively disinfects surfaces and aerosols (see Figure 9.4).

UV-C disinfection has been tested and proven to reduce bacterial and viral contamination in health care facilities and is used for surface and air disinfection (Duan et al., 2003; Andersen et al., 2006; Mphaphlele et al., 2015; Pavia et al., 2018; Dexter et al., 2020). UV-C inactivates a virus when high-energy photons interact photochemically with its RNA or Adenovirus molecules (or with the DNA of bacteria), damaging these nucleic acids (genetic material), making them non-infectious. When applied at 254 nm wavelength and intensity 10-14 J/m2, UV-C had at least a 95% effectiveness in inactivating viruses and killing bacteria (McDevitt et al., 2012). In aircraft cabins, low relative humidity levels improve the effectiveness of UV-C and can inactivate viruses like

SARS-CoV-2 and MERS (Figure 9.4). A new UV-C system with a 222 nm wavelength is considered safe due to minimal tissue penetration (IES, 2020), providing air and surface disinfection throughout irradiated spaces. This system might also be suitable in coffee bars, restaurants, store counters, and other surfaces typically found in airports (IES, 2020).

Improved cleaning regimen should include surface disinfection and UV-C approaches as UV disinfection alone may be limited by shadowing in some areas of the room (Andersen et al., 2006). Deep surface disinfection may also benefit from UV-C or equivalent technology because human factors can result in cleaning failure.

Figure 9.4   Ultraviolet-C (UV-C) Portion of the Electromagnetic Spectrum (Source: IES, 2020)

9.2.3   Antimicrobial Coatings and Materials

Aircraft manufacturers, airlines and OEMs are exploring the use of antimicrobial materials in lavatories and on other high touch surfaces. These materials have active ingredients that can inactivate viruses (Beythet al., 2015). There are two main groups of antimicrobial coatings:

1. Inorganic antimicrobial materials, such as metals and metal oxides e.g., silver (Ag), iron oxide (Fe_3O_4), titanium oxide (TiO_2), copper oxide (CuO), and zinc oxide (ZnO) and their properties are described in Table 9.3. These materials interact electrostatically with bacterial and virus membranes by releasing free radicals that hinder protein function and cause nucleic acid destruction. Most metal oxide nanoparticles exhibit antimicrobial properties through reactive oxygen species (ROS) generation, although some are effective due to their physical structure and metal ion release.

2. Polymeric (organic) antimicrobial materials can kill microorganisms by releasing antibiotics, antimicrobial peptides, or act as contact-killing surfaces; others are quaternary ammonium compounds, alkyl pyridiniums, triclosan, chitosan, organometallic polymers, or quaternary phosphonium (see Table 9.3).

Table 9.3 List of Common Organic and Inorganic Antimicrobials

Antimicrobial Material	Main Features	Applications
Silver (Ag)	Non-toxic, good electrical conductivity, expensive material	Used as a colloidal silver suspension or applied as a silver nanoparticle in clothing, textiles, consumer electronics, and appliances.
Iron Oxide (Fe_3O_4)	Inert material, anti-adherent properties, inexpensive	Applied as nanoparticles, it is a microbial inhibitor. Vehicle for other antimicrobials, helps in drug delivery and bacterial detection.
Titanium Oxide (TiO_2)	Has a photocatalytic activity, inexpensive material	Kills all types of bacteria and inactivates viruses. Used for UV protection and self-cleaning surfaces
Copper Oxide (CuO)	Non-toxic, good electrical conductivity, relatively inexpensive material	Applied as a nanoparticle, it has the strongest bonding capacity to bacteria and the highest bactericidal effect. Used as a direct coating for commercial surfaces or mixed with polymers to give consumer products and textiles long-lasting antimicrobial properties.
Zinc Oxide (ZnO)	Has a photocatalytic activity	Applied as a nanoparticle, it is an antimicrobial used in textiles
Quaternary Ammonium	Strong lipophilicity, cationic surfactant	Mixed with polymers to act as an antiviral, antibacterial, and antifungal material for consumer products, building components, and biomedical products.
Triclosan	Non-ionic broad-spectrum agent, non-toxic	Usually mixed with a solvent like water, gel, or organic compound. Used in personal care products like deodorants, oral care, shower gels, and handwashes.
Chitosan	Good biocompatibility, non-toxic, low immunogenicity	Biocompatible antimicrobial agent, it is a hydrophilic biopolymer used in the food and biomedical applications.

Source: Beyth et al., 2015; Dastjerdi & Montazer, 2010

9.3 RECOMMENDATIONS FOR PREVENTING SARS-COV-2 INFECTION THROUGH CONTACT WITH FOMITES WHILE TRAVELING

It is possible to become infected when mucous membranes (mouth, nose, and/or eyes) are exposed to the virus by, for example, touching them with contaminated fingers. Travelers can protect themselves against contacting potentially contaminated fomites using appropriate hand hygiene and by not touching potentially contaminated surfaces (WHO, 2020d). The steps to prevent SARS-CoV-2 infection through the fomite pathway include:

- Wash or sanitize hands regularly and adequately. During handwashing, soap should cover all the surfaces of both hands (including the back of the hand and under the nails) for 20 seconds or more (Rutala et al., 2008; Freeman et al., 2014; Wölfel et al., 2020). Hand sanitizers that contain at least 60% alcohol can be used if hand-washing facilities are not readily available.

Soap and the active ingredients in disinfectants destroy the protein protective layer of the SARS-CoV-2 virus with an effectiveness of more than 99.9% in less than 1 minute (Van Doremalen et al., 2020).

- Minimize contact with frequently touched surfaces and objects in public spaces. It is not possible to clean and disinfect all available surfaces; therefore, a traveler should minimize direct contact with surfaces using a tissue or other methods to reduce direct contact. Because it is difficult to avoid touching surfaces directly, travelers may consider carrying and using their own disinfectant wipes. However, passengers should only use wipes approved for aircraft usage or ones provided by the air carrier, to avoid damage to onboard materials and equipment by non-approved chemicals. Further, some non-approved disinfectants have the potential to introduce irritating chemicals and odors into the cabin environment.

- Avoid touching eyes, nose, and mouth as much as possible. After touching a contaminated surface, the virus might survive for two to four hours on people's hands. Therefore, travelers should avoid touching their eyes, nose, and mouth as much as possible when proper hand hygiene is not available.

In summary, when travelers are mindfully following guidance on minimizing exposures and airplane cabins are cleaned, sanitized, and environments are maintained, it is possible to achieve near elimination of transmission by infectious doses of SARS-CoV-2 that had been deposited on surfaces.

10.0   NPI LAYERING: PHYSICAL ENGINEERING CONTROLS AND VENTILATION

Ventilation is an essential component of a layered approach to reduce the risk of SARS-CoV-2 transmission in air travel. By necessity, for the convenience of flying, passengers share the confined space in an aircraft cabin. The ECS is designed to satisfy the physiological needs of passengers while maintaining their comfort and health. The ECS is relied upon to deliver high volumes of clean air to rapidly disperse, dilute and remove contaminants including potentially infectious particles. Ventilation, as a control strategy, must be applied consistently for all segments of air travel.

However, ventilation alone is not sufficient for risk reduction of SARS-CoV-2 transmission and must be applied in conjunction with other layered protective strategies, including wearing a face mask and hand hygiene to deal effectively with reducing exposure to infectious particles. As discussed in a preceding chapter (Chapter 7.0), face masks can reduce substantially virus shedding from infectious people by removing a large fraction of potentially infectious mass discharges produced by sneezing, coughing, talking and breathing. The types of face masks commonly worn do not make a tight seal around the wearer's face so the remaining smaller fraction of exhaled mass will leak out around the edges of the mask in one or more low velocity discharges. These low velocity exhaled airflows enter the turbulent directional (top to bottom) air stream of the cabin. This chapter evaluates the evidence developed that addresses the ability of aircraft mechanical air systems to safeguard effectively all passengers occupying a crowded plane.

The evaluation undertaken by the Harvard APHI Science and Technical (S&T) Team included a review of the computational fluid dynamics (CFD) models of Airbus and Boeing. Independent of Airbus and Boeing, the S&T Team developed a multi-compartment simulation-infectious disease model to evaluate various scenarios including the boarding and deplaning segments. The TRANSCOM/ AMC report, *Commercial Aircraft Cabin Aerosol Dispersion Tests* (TRANSCOM, 2020), became available as Phase 1 was being finalized. This important document described simulation studies, performed in operational commercial aircraft that utilized aerosol tracers to assess airborne dispersion, deposition and removal in the cabin under cruise and ground conditions. These experiments were conducted on two aircraft models in current use under maximal settings of ECS and APU to demonstrate the capabilities of the mechanical ventilation systems. These experimental studies were authorized and supported by the United States Transportation Command (USTRANSCOM) and Air Mobility Command (AMC) and made available publicly on October 15, 2020. The S&T Team benefited from a pre-release discussion with investigators of the experimental design and testing procedures, although the team did not have early access to the results.

10.1   SIMULATING AIRFLOW AND TRANSMISSION RISK IN CABIN ENVIRONMENT USING CFD

A CFD model is used to produce high-resolution (e.g., 10 cm in space and 1 second in time) simulations of airflow and other variables, such as temperature and pollutant concentration in outside or inside environments. The model solves the basic equations (e.g., Navier-Stokes and mass-conservation) in time on a 3-D grid. The total domain size can extend from 10 m (in a study of the plume in a building) to several km (in a study of pollutants' transport and dispersion in and around buildings in an urban area). CFD models are classed as Large Eddy Simulation (LES) or Reynolds Averaged Navier-Stokes (RANS), with LES models taking much more data storage space and time because they produce time-variable 3D fields. In contrast, RANS CFD models by definition produce time-averaged output fields.

A great benefit of CFD models is that they can produce high-resolution space and time variable wind fields in the airplane cabin that automatically satisfy mass continuity constraints for the air. For example, for a typical CFD model grid volume that is a cube 10 cm on a side, for any second of the calculation, the CFD model-simulated flow velocities on all six faces of the cube will satisfy air mass continuity. This is important in an airline cabin because there are found to be two large counter-rotating eddies (due to the vent placements) on a cross-section of the cabin, with smaller eddies around seats, passengers, and other obstacles. In contrast, the multizone model or a Gaussian puff model will not be able to produce high-resolution time and space variations in flow that satisfy these conditions. Instead, those simpler models must assume flows that are significantly averaged in time and space (a constant wind velocity will automatically satisfy mass continuity everywhere).

Many versions of CFD model software are available with some publicly available for free, such as OpenFOAM. Fluent is an example of a widely used CFD model software that can be obtained only via a paid license. Many CFD models are developed by universities and research laboratories for special purposes and are shared among a few investigators. Sometimes, an industry will develop its own CFD model to fit its specific needs. While the CFD model is able to simulate directly flows and dispersion at scales greater than the model's grid size, there is still a need to parameterize sub-grid-scale turbulence. These parameterizations have been found to be very important for simulating accurately small-scale flows and pollutant gradients, especially in confined areas such as the corners of rooms and aircraft cabin environments.

A comparison of six CFD models' predictions of flow and dispersion in the street canyons around Madison Square Garden was described by Hanna et al. (2006). All the models examined were able to predict the general patterns but there were individual differences. Zhang et al. (2009) described the application of a CFD model to calculate flow and dispersion in an airplane cabin. Although CFD models output flow vectors and pollutant concentrations with great precision, there is actually significant uncertainty. The multi-CFD model comparison undertaken by Hanna et al. (2006)

demonstrated the variability in several model predictions and the quantitative performance of models regarding simulating observed winds behind buildings and in street canyons.

A CFD model can be of great value when used together with a few observations to "fill in" the flow vectors or concentration fields between the observations. Boeing and Airbus have applied CFD models in this way to produce three-dimensional details of flows in airplane cabins. The CFD model is also good for understanding "What if?" scenarios. As in any CFD model application inside a room, it is essential to provide the model with accurate inputs of flows into and out of vents and the characteristics of the HVAC systems.

10.1.1   Boeing Simulations of Dispersion and Removal of Infectious Particles

Boeing researchers used a CFD model to assess the ability of the ECS to disperse and remove simulated cough particles from the cabin of single aisle and twin-aisle aircraft. Cough scenarios without masks represent a "worse case" challenge for CFD simulations. Their analysis also evaluated the effect of people wearing face masks, where emissions from an infectious source would be reduced. Various scenarios included "movement" of the infectious passenger to various seats, including the middle seat of a row. As shown in Figure 10.1 (courtesy Boeing Corp.), the CFD simulations applied to a five-row 30-seat economy section with the boundary conditions assuming conservation of mass with no longitudinal flow to forward or aft sections. Since passengers often modify their thermal comfort by adjusting gaspers, CFD simulations included different variations of individual overhead air vents.

Figure 10.1 Results of CFD modeling estimating equivalent "physical" distance between passengers for respirable particles entering the breathing zone. (Note: although shown in the legend, there were no cases that were less than 6 feet social distance) (Courtesy of Boeing Corp.)

Particles from coughing rapidly evaporate as exhaled plume mixes rapidly with the dry turbulent cabin air. Boeing's model accounted for mass loss and particle size reduction due to evaporation. This is relevant because with the wearing of face masks, small droplets and aerosol particles that escape capture will continue to desiccate and become even smaller particles and less likely to deposit on interior surfaces and instead, be readily removed by effective ventilation systems. Figure 10.2 (courtesy Boeing Corp.) gives a general representation of air velocities and direction for a cross section of a single aisle aircraft. Air is delivered to the cabin from ducts in the ceiling along its center axis and removed at floor level along the fuselage creating a well-mixed interior environment.

Cough in the Airplane

Measured particles from a cougher to surrounding breathers using standard airflow settings in the single-aisle and twin-aisle airplane

Figure 10.2   Airflow Patterns Showing the Directional Flow and Entrainment of Emissions from a Coughing Passenger (courtesy of Boeing Corp.)

Boeing researchers tracked how particles from coughing and breathing moved around the airplane cabin. The CFD findings showed that significantly fewer particles reached the breathing zone of neighboring passengers on an airplane. Models calculated that particle mass emitted by the infected passenger would be reduced by greater than 50% by the time the air reached the breathing zone of a passenger in an adjacent seat, and even lower for those people sitting in front or behind the infected person. The S&T Team were briefed by Boeing researchers on its CFD findings. Technical reports/articles are now undergoing independent peer review.

The S&T Team concurs with the general findings derived from Boeing CFD simulations as summarized in Boeing's *Briefing Document: Probabilistic Analytics Findings* (10/8/20) noted:

"*The combination of high air exchange rate (every 2-3 minutes), air flowing from ceiling to floor in a circular pattern, high efficiency particulate air (HEPA) filters that trap 99.9%+ of*

particulates and the airplane seat configurations (forward facing, high-back seating) contribute to a reduction in passenger exposure to particles compared to other indoor environments."

The sophisticated CFD analysis of the ability of airflow to protect fellow passengers from simulated SARS-CoV-2 transmission is but one piece of supporting evidence. Models alone cannot capture fully the many variations of passenger behavior, e.g., movement in the aisles, blockage of airflow with open luggage bins and bags placed under seats.

10.1.2 Airbus Simulations of Dispersion and Removal of Infectious Particles

Airbus used a CFD model to simulate airflow in a five-row section of an A320 cabin. Their simulation mathematically represented droplets emanating from a cough as a burst release of particles. The model then traced the dispersion and removal of these particles following their movement within the cabin airflow. Similar to Boeing's effort, the source term was moved among seats in the middle (i.e., third) row of a series of five contiguous rows. The effect of masks was approximated by reducing the source term (i.e., fewer particles being emitted into the aircraft cabin environment), by a factor consistent with separate face mask reduction studies while keeping other conditions constant. Figure 10.3 displays the color-coded airflow velocities, with arrows indicating direction for the A320 aircraft modeled. Airbus also assessed the influence of gaspers on internal circulation patterns to determine how directing their flow in different directions would alter the particle concentrations in an adjacent passenger's breathing zone.

Airbus engineers and modeling experts shared the details of their CFD simulations and results with the S&T Team in several video conferences. Like Boeing, Airbus applied CFD simulations to hypothetical indoor settings to illustrate the comparable performance of aircraft ventilation to conventional mechanical systems found in buildings. While Airbus' CFD model, as well as some scenarios they investigated, was different from those of Boeing, their findings were similar. Each CFD modeled scenario quantified the number of particles (Airbus) or mass (Boeing) in the breathing zones of each of the 30 passengers, including the source passenger. Figure 10.4 presents a stylized summary of Airbus' findings that was presented at the IATA News Briefing on October 8, 2020 (IATA, 2020b). Quantitative findings for the multiple scenarios analyzed were used to assess dilution of source material and compare the relative risks among scenarios. Airbus and Boeing then used these reductions in exposure to convert their CFD-derived finding as "equivalent physical distance" asserting that due to the features of their aircraft ECS design, potentially infectious particles released under realistic scenarios will be rapidly diluted and removed from the proximity of passengers to provide the equivalent distance of being >6 feet (1.83 m) away from an adjacent passenger.

The S&T Team concurs with the general findings derived from Airbus CFD simulations.

High quality full **3D Computational Fluid Dynamic models** of cabin air flow, **correlated with aircraft test-data** and physical ground tests

Figure 10.3   High-quality Full 3D CFD Models of Cabin Air Flow (Courtesy of Airbus Corp.) (IATA, 2020b)

Protective barrier layers

The study demonstrates **very low risk** of particle exposure for passengers

Figure 10.4   Protective Barrier Layers (Courtesy of Airbus Corp.)

10.1.3   Critical Analysis of CFD Modelling of Aircraft Cabins

As with all mathematic simulations, even within the highly precise constructs of CFD simulations, there are limitations, not least of which are the scenarios selected to represent "reality". While the CFD model is able to simulate directly flows and dispersion at scales greater than the model's grid size, there is still a need to parameterize sub-grid-scale turbulence. These parameterizations have

been found to be very important for accurately simulating small-scale flows and pollutant gradients (Gupta et al, 2012; Chen et al., 2015), especially in confined areas such as the aircraft environment. Passengers and their exhaled breath create thermal plumes: people move around the cabin, their carry-ons may obstruct/disrupt airflow patterns and the ECS, APU and PCA may be operating at settings not considered in the modeled scenarios.

Results from Airbus and Boeing CFD modeling carried out independently are important contributions to understanding the effectiveness of ventilation on aircraft. Engineers from these companies have unique information on ECS design and performance. Before the COVID-19 pandemic, they have used their engineering and modeling expertise to evaluate and improve the design of cabin ventilation systems (B787, A350 XWB). **The S&T Team considers the results presented by Airbus and Boeing as important evidence that optimally operated ECS under the quasi-static conditions during cruise conditions and assuming passengers are complying with airline policies to wear appropriate face masks, would provide a very low risk cabin environment.**

The following section summarizes the findings derived from independent modeling performed by the S&T Team and described below. Section 10.2 provides a more detailed description of the multi-compartment approach that used the Wells-Riley construct for probability of infection of quanta (i.e., unit dose to cause infections in ~67% of people exposed). A more detailed description of Wells-Riley can be found in Section 3.1.6. Given the importance of the public health message concerning the safety of air travel in our time of COVID-19, the S&T Team decided to perform an independent assessment of ventilation strategies across all segments of flying.

10.2   S&T TEAM CABIN CONTAMINANT TRANSPORT MODEL

To understand the risk of airborne transmission of SARS-CoV-2 in the airplane, the cabin was modeled using a three-dimensional multi-zone approach and simulated the contaminant transport (i.e., infectious aerosol) by a Markov model. This model structure was chosen as a preliminary assessment of cabin conditions during cruise, as well as other scenarios, when aircraft systems and behaviors associated with exposure risks are different from cruise conditions (e.g., boarding, deplaning, taxiing, descent). The multi-zone Markov approach has been documented in the occupational hygiene literature (Nicas, 2000; Jones, 2009; Chen, 2015) and has been used extensively given its flexibility in modeling near- and far-zone contaminants, allowing a more refined account of the variability in concentrations at a certain position and time within an enclosed space.

In summary, this method divides the cabin space in N exclusive volumes (also referred to as zones or states). In a discrete time-step delta T, the probability that a particle stays in the same volume or transitions to a physically contiguous zone is determined by the magnitude of each of the mass transport mechanisms present in the cabin, such as exhaust ventilation, advective velocity and

turbulent diffusion. Gravitational and virus inactivation first-order constants were not considered due to the predominance of the aforementioned removal mechanisms. These probabilities are arranged in a matrix of NxN dimensions, known as the one-step transition probability matrix P. This matrix contains all the information about the probabilities of particles released at any zone to enter an adjacent zone. By recursively multiplying P by itself n times, an estimate of the probability that a particle is still in the cabin at the nth step is determined. For example, the expected concentration at time t at a zone corresponding to the *ith* row and *jth* column of P is:

$$E[C_{(i,j)}(t)] = (N\_0 \times P\_{(i,j)}^t)/V \qquad \text{Eq.1}$$

where No/V is the initial particle concentration at time zero. The model consists of a subsection of the economy cabin in a Boeing 737-900 with 36 seats, six rows of six seats each. Each seat, as well as the aisle space between the seats in each row, were represented as three vertically stacked volumes (for dimensions see Table 10.1). A total of 144 zones were included in the model, of which 12 are described as absorbing zones or states, corresponding to the exhaust located in the lower zone of each window seat. The magnitude of the first-order constants used in the simulation is also included in Table 10.1

Table 10.1	Input Variables for the Multi-zonal Model of SARS-CoV-2 Transmission on Airplanes		
Parameter	**Distribution Type**	**Parameters**	**Reference**
Air exchange rate (1/h)	Normal	HIGH: mean=25, sd=2, min=20, max=30	Discussions with manufacturer, 2020
		LOW: mean=12.5, sd=2, min=2, max=20	
Advective flow (m/s)	Gamma	mean=0.1m/s; 72% of values <0.1m/s	Jones, 2009; Liu, 2012
Turbulent intensity (%)	Uniform	Range=30-50%	Jones, 2009; Liu, 2012
Quanta rate (q/h)	Log-normal	Breathing: mean=log10(-4.4e-1), sd=log10(7.1e^1)	Buonanno, 2020
		Speaking (low-vol): mean=log10(0.69), sd=log10(7.1e^1)	
		Speaking (high-vol): mean=log10(1.5), sd=log10(7.1e^1)	
Mask efficiency	Normal	Emitter: mean=50%, sd=10%	Howard et al, 2020
		Receptor: mean=30%, sd=10%	
Breathing rate	Truncated Log-normal	Low: mean=log(1.2e-2), sd-log(0.2), min=0, max=1.2e-1	Allan, 2008; EPA, 2011
		Mid: mean=log(2.6e-2), sd-log(0.2), min=0, max=1.2e-1	
Zone dimensions		Height=0.6m; width=0.45m; depth=0.9m	
Air exchange rate (1/h)	Normal	HIGH: mean=35, sd=2, min=30, max=40	Discussions with manufacturer, 2020

Quantitative Risk Assessment

A risk assessment was performed using the probabilistic Wells-Riley (WR) model (see Appendix G). In this model, the probability of infection follows an exponential behavior described by the equation:

$$p = 1 - e^{-d} \qquad \text{Eq.2}$$

where d is the inhalation dose. In this model, the infectious emission rate is expressed in "quanta per hour"; quanta represent the minimum dose of a given inoculum leading to infection. WR assumes that the infectious release is instantaneously and uniformly mixed in the emission zone. The transmission risk in each compartment was estimated using Eq.2 by calculating the inhalation dose as the mean expected concentration over a period of time T, multiplied by the exposure time and the hourly breathing rate:

$$E[D(T)] = \frac{b \times f_D}{T} \sum_{t=0}^{T-1} E[C_2(t)]$$

Results

The model results are in general agreement with the modeling results from aircraft manufacturers and with the empirical evidence from the US TRANSCOM study. When the aircraft ECS 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.

Three constant quanta emission rates, reflecting the uncertainty in the infectious dose needed for transmission, were modeled. From generation rates estimated by Buonanno et al (2020), a low quanta emission rate of 14 q/hr corresponds to breathing and speaking at low volume; a medium emission rate of 48 q/hr corresponds to speaking at higher volume. This analysis used a high emission quanta rate of 100 q/hr that we obtained from the Vietnam Airlines flight VN54. This emission rate, while high, might be appropriate for a scenario where screening controls could fail to detect a potential highly infectious individual ("superspreader"). Moreover, a similar quanta emission rate (100.8 q/hr) was found in the study of an aircraft outbreak of SARS-Cov-1 (You et al., 2012).

The results from the maximum exposure that took place in the cabin are presented, one seat apart from the emission zone. Exposure was evaluated for a 1 hr period at the breathing zone, assuming a breathing rate of 0.5 m³/hr. For cruise ventilation conditions ranging from 20-30 ACH (mean=25 ACH) without considering the use of masks, the estimated time to infection ranges from 7.5 to 55.7 hours for cruise conditions (Table 10.2). The time to infection increases approximately five-

fold when considering the use of masks with a combined efficiency of 80% (60% emitter, 50% receiver). **This finding is considered to be of special importance and highlights the need for strict adherence to a universal policy to wear a face mask during air travel in order to mitigate the risk of SARS-CoV-2 transmission during travel.**

Table 10.2	Estimated Minimum Time to Infection Derived from the Multi-zone Markov Model during Cruise Conditions (mean=25 ACH; range=20-30 ACH). Estimates correspond to airborne exposures at the breathing zone from the seat adjacent to the emission seat.		
		No Masks	**Masks**
Scenario	**Quanta emission rate [q/h]**	**Flight time to infection [h]**	**Flight time to infection [h]**
Low emission rate	14	47.1 (41.0-55.7)	238.4 (202.3-275.9)
Medium emission rate	48	14.6 (12.5-16.8)	70.0 (59.6-81.0)
High emission rate	100	7.5 (6.5-8.5)	34.0 (29.0-39.3)

ACH   air changes per hour
q/h   quanta per hour
h   hour

For the boarding/deplaning scenario, three ventilation scenarios were considered: 1) a nominal ventilation rate of 25 ACH with the APU on; 2) a ground PCA unit providing 19 ACH with no recirculation; and 3) a low flow scenario with 50% the nominal ventilation rate of scenario a (12.5 ACH). On average, nominal ventilation rates during boarding/deplaning offer a 2.4 to 4.4 protection factor over the ground PCA scenarios 2 and 3 considered here (see Table 10.3). Once more, the use of masks will convey an additional protection factor that increases the minimum time to infection well above the usual boarding/deplaning times, or any other period of transitory reduced ventilation.

Table 10.3 Estimated Minimum Time to Infection Derived from the Multi-zone Markov Model during Boarding/Deplaning under three different Ventilation Scenarios. Estimates correspond to airborne exposures at the breathing zone from the seat adjacent to the emission seat.

Scenario	Quanta emission rate [q/h]	No Masks Time onboard to infection [h]	Masks Flight time to infection [h]
APU on [25 ACH]			
Low quanta	14	39.6	195.6
Mid quanta	48	12.1	57.5
High quanta	100	6.2	27.9
Ground PCA [19 ACH – no recirc]			
Low quanta	14	15.6	75.29
Mid quanta	48	5.1	22.50
High quanta	100	2.9	11.18
Ground PCA [12 ACH]			
Low quanta	14	8.2	37.9
Mid quanta	48	2.9	11.6
High quanta	100	1.9	6.0

q/h	quanta per hour
h	hour
APU	auxiliary power unit
ACH	air changes per hour
PCA	pre-conditioned air
recirc	recirculating

10.3   STUDY SUMMARY US TRANSCOM COMMERCIAL AIRCRAFT CABIN AEROSOL DISPERSION TESTS

The United States Transportation Command (USTRANSCOM), in conjunction with The Defense Advanced Research Project (DARPA) and Air Mobility Command, conducted a study to characterize aerosol particle distribution from an infected person within the passenger compartment of a commercial aircraft. The study was designed to measure the relative particle transport and dilution from a simulated infected case (source) into breathing zones of assumed passengers in adjacent seats and surrounding rows. Particle concentrations were measured in different sections of the aircraft and with the source seated at different locations within the aircraft.

Boeing 777-200 and Boeing 767-300 were used as representative aircrafts. Multiple tests were conducted with the aircraft both flying and on the ground with either the ECS or APU on maximum settings and achieving effective air exchange rates of approximately 30/hour to 35/hour. Other than for investigators, the cabin was not occupied during tests. However, thermal blankets were used to represent the thermal buoyancy associated with passengers. Some tests were conducted with gaspers operating. Test scenarios included simulations of emissions from normal breathing and coughing along with the influence of mask-wearing by the simulated index case.

The tracer particles were 1 µm fluorescent microspheres and 3 µm DNA-tagged microspheres based on a study by Liu et al. (2020). Fluorescent-tagged microspheres were generated through a tripod-mounted mannequin head for one minute in a breathing pattern with two seconds on and two seconds off. Velocity of output air was maintained at approximately 1.43 m/s (at the mannequin's lips) for breathing scenarios; coughs were simulated by increasing the exit velocity of the aerosol to 12.84 m/s. DNA-tagged beads were generated for five minutes to examine deposition on nearby surfaces, with surface coupons dispersed near the release seats on common touch surfaces such as arm rests, tables, and seatbacks. A group of 42 Instantaneous Biological Analyzer and Collector (IBAC) discrete particle detectors (simulating passengers) were placed within the breathing zones of individual seats around the simulated index case. Overall, 300 discrete release tests were performed with more than 11,500 breathing zone seat measurements in 46 seats of the airframe. Testing was conducted in triplicate. Results were averaged and presented as a fraction of particle microspheres captured at each location relative to the total number released by the simulated source.

Results indicate that the particle concentrations (and therefore the risk of secondary infection) in the breathing zone of passengers around the source are driven primarily by the high AERs, rapid dispersion, downward flow ventilation design and HEPA-filtered recirculation in an airframe. It appears that the released particles are rapidly diluted, mixed, and purged from the cabin by filtration and exhaust through the outflow valve. On average, there was a 99.99% reduction in the number of aerosolized particles from the source to the 40+ breathing zones tested around it. Importantly, average time to purge the test particles from the aircraft was approximately five minutes. Additionally, in-flight, ground, and boarding conditions offered similar protection provided the APU maintained effective air exchange rates as during the in-flight tests.

The general results are summarized here. For the breathing scenario without mask (BNM), the maximum fraction of released particles detected in the breathing zone of the passengers (per section of the airframe) ranged from 0.010% to 0.082% for the boarding scenario and from 0.016% to 0.215% in the ground and in-flight scenarios. With mask applied for the breathing scenario (BM), maximum fractions of detected particles in the breathing zone ranged from 0.008% to 0.050% for the boarding scenario and from 0.012% to 0.074% for the ground and in-flight scenarios. There was an approximately 10% to 75% reduction in particles with the mask applied in the breathing scenario relative to no mask. In the coughing scenario without mask (CNM), tested only for Boeing 767-300 in-flight scenario, maximum breathing zone impact ranged from 0.024% to 0.065%. This suggests that even for this worse case CNM scenario, passengers exposed the most would still experience a >99% reduction in aerosol particles in their breathing zones relative to the source. In the coughing with mask (CM) scenario, maximum penetration was approximately 0.002%, indicating that a mask provides greater than 90% reduction in particle penetration in a coughing scenario.

As for studies with DNA-tagged beads, the highest concentrations were always located closest to the release point with lower risk towards the forward than the aft of the plane. Less than 0.06% of the tracer particles settled during testing, with the highest concentration on the surfaces closest to each release location. It is difficult to apply these findings for situations where an unmasked passenger could be releasing droplets considerably larger than the 3 μm spheres used as tracers in these tests. From the data collected, worst-case exposure under the BNM conditions was predicted to be in the mid-aft section of the Boeing 777-200, where a passenger may inhale 18.43 virions (at a breathing rate of 7.5 LPM) during a 12-hour flight.

These tests provide experimental evidence consistent with the modeling results of Airbus and Boeing. Interpretation requires consideration of the context of the experimental design. Except for the researchers, the test was conducted on an empty aircraft with ECS or APU set to OEM recommended air exchange rates. These results demonstrate that rapid dispersion, dilution and removal of viral particles can be achieved for all flight segments, under these operating conditions.

While these results are encouraging, the dose of SARS CoV-2 to cause infection is unknown and likely to depend on host susceptibility, transmission routes, and viral strain. Given this concern, it would be more appropriate to express an infectious dose as a range or distribution. Since there might be many viral copies per inhalable particle, simply looking at the number of particles detected does not provide a complete picture of possible risk. A more conservative approach would be to conduct a sensitivity analysis that would propagate parameter uncertainties giving a range of possible estimates. For example, consider a lower infectious dose of 500 virions (i.e., 50% reduction), an air exchange rate of 20/h during cruise (33% reduction), and intermittent unmasking during the flight (50% reduction) – to calculate a range of possible exposures.

10.4   EXPECTED EFFECTIVENESS

This chapter examined current quantitative evidence regarding commercial aircraft's ECS and their effectiveness in disrupting the airborne transmission of SARS-CoV-2 virus. **The aircraft ventilation systems can contribute to maintaining safe environments while operating during a flight and while the plane is at the gate, boarding or deplaning passengers.**

The S&T Team evaluated the findings of recent CFD modeling efforts undertaken by Boeing and Airbus for aircraft during cruise conditions. As an independent check, the S&T Team constructed its own advection-diffusion multi-compartment model to assess the potential for transmission of SARS-CoV-2 in the cabin environment across various flight segments including ground/gate activities as well as cruise conditions. The S&T Team also reviewed the USTRANSCOM experiments where the reduction of a potential secondary infection was estimated from detailed particle measurements that were sampled in aircraft cabins that had air exchange rates in excess of 30 ACH both on the ground and during cruise conditions. These particle releases were designed to

simulate both normal breathing and coughing conditions and while wearing a surgical mask as well as being unmasked.

The modeling exercises of Airbus, Boeing and the S&T Team showed consistent findings in estimating significant reductions of particles, mass and quanta in the breathing zones of passengers adjacent to a simulated index case. The findings held for cruise settings for the ECS even as the index case was relocated to different seats in a row. The S&T Team did not have access to CFD modeling results for boarding and deplaning situations for Airbus and Boeing. **The Harvard APHI S&T Team's model showed that appropriate levels of safety were maintained during these shorter periods as long as congestion in the jet bridge and aisles was avoided, and sufficient airflow was provided via ground based systems or the aircraft's APU.**

Guidance from the ICAO and aircraft manufacturers recommends operating APUs and PCAs to provide a high volume of clean air flow when a plane is on the ground as clearly stated on ICAO's website. To underscore the importance, recommended operating procedures are given in the side bar.

Ventilation systems on aircraft deliver high amounts of pathogen-free air to the cabin that rapidly disperses exhaled air with displacement in the downward direction, reducing the risk of passenger-to-passenger spread of respiratory pathogens. Aircraft ventilation offers enhanced protection for diluting and removing airborne contagions in comparison to other indoor spaces with conventional mechanical ventilation and is substantially better than residential situations. 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.

11.0   CONCLUDING REMARKS

The Harvard T.H. Chan School of Public Health Aviation Public Health Initiative (APHI) developed this Phase 1 report. The multi-disciplinary academic scientific and technical team were informed by regular dialogue with a consortium of airline operators, aviation industry manufacturers, airport operators, and independent experts at universities and private research organizations. The report is an independent research-led account of the COVID-19 crisis as it affects operations across the aviation industry. It presents the scientific evidence in support of adopting a non-pharmaceutical interventions (NPI) strategy using a layered approach to control the transmission of the novel coronavirus SAR-CoV-2 on board aircraft. The report provides a series of recommendations for risk mitigation that can be adopted readily by airlines, airline passengers and crewmembers. **This layered NPI approach, of wearing face masks, disinfection of surfaces and maintenance of appropriate ventilation gate-to-gate, will ensure the risk of SARS-CoV-2 transmission onboard aircraft will be below that found in other routine activities during the pandemic, such as grocery shopping or eating out.**

The pandemic is a health crisis with profound economic impact, with efforts to control its spread exerting a devastating impact on business in general and, relevant here, to the aviation sector in particular. In the United States alone, airline capacity declined seven to 17 times more than during the 2008 global financial crisis (Boin et al. 2020). Many airports closed entirely, others shut one or more terminals and airlines suspended operations or cancelled a significant proportion of flights, with seat miles for US airlines down by 71% in April 2020 (Curley et al. 2020; Dalrymple et al. 2020). To adapt to the COVID-19 crisis, airlines have closed and/or altered routes and frequency, with the number of seats offered by airlines in 2020 some 42-52% less than originally planned (ICAO, 2020). Most airlines furloughed or laid off staff. Recognizing the economic impact of the sector, governments were quick to announce bailout and stimulus packages, with US passenger airlines calling for US$50 billion to survive the crisis (Financial Times, 2020). Reopening and recovery will focus on 'building back better', using science and the best evidence available currently to design and implement risk mitigation strategies that reduce the risk of disease transmission. Adopted widely, the recommendations in this report build upon aviation's central premise of safety.

The charge to APHI was to capture the science of SARS-CoV-2, in a field that is fast moving with new information emerging globally every day. The team then considered this information in light of the unique defined indoor environment presented by an aircraft to understand how the virus and its transmission will be affected by the conditions experienced across the passenger journey. They went on to develop strategies to mitigate transmission in the confined space of an aircraft, taking due account of behavioral change needed by crewmembers and passengers to protect themselves and others nearby them.

This Phase 1 report address the Gate-to-Gate portion, with air travel segmented into the pre-boarding, boarding, cruise and deplaning. The team's balanced view took into account the rigor of scientific studies, published and in pre-print format, and informed original investigation undertaken by the team. The recommendations also thought through the suitability of the NPI measures to routine and widespread adoption by the airlines and those traveling, including passengers and crewmembers. The layered approach proposed is thus a unique combination of engineering and physical controls as well as hygiene and physical distancing as applied to air travel.

Key findings from the report highlight the interactions of the different NPI layers to risk mitigation and include:

- Compliance with face mask-wearing and the aircraft's environmental control systems effectively diluting and removing pathogens significantly reduce the risk of passengers and crewmembers from acquiring COVID-19 during the cruise segment of their journey.

- Mask compliance reduces the dispersion of larger droplets that may deposit on surfaces, while general airline cleaning practices and passengers sanitizing hard surfaces around their seats lowers the probability of contacting SARS-CoV-2 infected surfaces (which is already low to begin with).

- Taken together, mask compliance, managed physical distancing and improved ventilation during boarding and deplaning, can effectively reduce the risk of potential transmission to the very low levels encountered during cruise conditions.

- Requiring passengers to attest to the absence of COVID-19 symptomatology, mandating they comply with all the airline's COVID-related procedures including physical distancing during boarding and deplaning provides some degree of protection (yet to be determined). The role of gate and flight crewmembers in assuring compliance will be essential and supported by airlines' policies to hold passengers accountable.

Implementing the layered risk mitigation strategies described in this report will help to ensure that air travel, with respect to SARS-CoV-2 transmission, is as safe as or substantially safer than the routine activities people undertake during these times. The potential effectiveness of any one NPI remains uncertain given that estimates of their effectiveness are based upon models. Thus, assessing the individual effects of any one intervention relative to the cumulative effect of concurrent use of multiple NPI must rely on application of the best available science at the time. Hence, the report recommends a layered NPI strategy so that additive and synergistic benefits can be harnessed to reduce the risk of disease transmission. As more information becomes available with respect to the spread of SARS-CoV-2, various control measures will continue to evolve and their effectiveness will be quantified.

The findings and recommendations in this report offer the public the opportunity to reach informed decisions about air travel. It is possible to implement strategies that mitigate spread of the COVID-19 while allowing people to use the airline sector. Following the science and acting upon it can achieve both public health safety and economic opportunity.

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APPENDIX A

SUMMARY OF EPIDEMIOLOGY STUDIES

POTENTIAL TRANSMISSION OF SARS-COV-2 ON A FLIGHT FROM SINGAPORE TO HANGZHOU, CHINA: AN EPIDEMIOLOGICAL INVESTIGATION

- **Subject matter**: Describe COVID-19 outbreak among 335 passengers
- **Geography**: Changi Airport, Singapore to Hangzhou, China
- **Date**: 24 January 2020
- **Objectives**: Investigate the source of COVID-19 exposure among 335 passengers; assess risk of transmission during the flight
- **Methods**:
- Masks required? No mask requirement, but all 16 cases wore masks beside mealtime. One reported that he did not wear mask "tightly" and nose was exposed. Other passenger's use of masks not reported.
  - Other personal protective equipment? No
  - Isolation before/after flight?
    - After: all passengers considered close contact, so were required to follow medical isolation and observation protocols for at least 14 days after January 24
      - Group A isolated at Hotel A near Hangzhou airport
      - Group B isolated at Hotel B in Hangzhou city center
      - Passengers (of either group) who were symptomatic after preliminary investigation were sent to hospital in Hangzhou (except children w/parents)
  - Require negative COVID-19 test? No
  - Temperature screening prior to flight?
    - No, all passengers were required to take their temperature before deplaning (when they arrived at Hangzhou)
  - Social distance requirements prior/post flight? Not specified
  - Infection period consistent with time course of travel?
    - Varied. Only those testing positive 0-14 days after flight included in definition. All passengers tested Jan 26 (2 days later), but some before and after that
  - Barriers? No
  - Middle seats blocked or available?
    - No, plane was 89% full
  - Flight class: Not specified
  - Number of travelers
    - 335 of 375 seats (89%)
      - 324 passengers
      - 11 crew (all Singaporean)
    - 2 groups
      - Group A: departed from Wuhan to Singapore on a previous January 19 flight
      - Group B: no history of travel to Wuhan, including crew
  - Specified ventilation requirements?
    - None, but "flight was equipped with air handling system"

- - Decontamination procedures? Not specified
  - Cases diagnosed with PCR or symptoms?
    - Symptomatic = PCR+ and symptoms
    - Asymptomatic = PCR+ but no symptoms
  - Did the study account for travel partners? Yes
- Summary
  - Info collected before, during, and after flight
    - Interviews (face-to-face or by phone) before, during and after flight
      - Demographics
      - Health conditions
      - Symptoms
      - Mask-wearing status
      - Seat location
      - In-flight activities
    - Temperature before deplaning
  - After flight all were to follow medical isolation and observation protocols for at least 14 days after January 24
    - Group A (Wuhan) isolated at Hotel A near Hangzhou airport
    - Group B (all others, including crew) isolated at Hotel B in Hangzhou city center
    - Passengers (of either group) who were symptomatic after preliminary investigation were sent to hospital in Hangzhou (except children w/parents)
  - All passengers were required to take temperature twice daily and report symptoms
    - If symptoms reported, sent immediately to hospital
  - All crew (Singaporean) returned to Singapore on quarantine day 2
  - Statistical analysis
    - Crew members excluded
- Findings
  - 335 total passengers and crew. (January 24, 2020 flight)
    - 11 crew
    - 324 passengers
      - 16 tested positive for SARS-CoV-2 by RT-PCR between January 24 and February 15, 2020
        - 10 symptomatic
        - 6 asymptomatic
  - Timeline
    - January 19 - Case passengers flew to Singapore (one from Hangzhou; 15 from, Wuhan)
    - January 23 - 2 symptomatic cases have symptoms before flight (still boarded plane)
    - January 24 – flight that is focus of this study flew from Singapore to Hangzhou, China
    - January 24 – passengers placed in medical isolation in Hangzhou

- January 24 – 1 passenger develops symptoms after flight
- January 26 – all passengers tested for SARS-CoV-2 by RT-PCR
  - 2 more symptomatic cases confirmed
  - 6 asymptomatic cases detected
- January 31 – 1 more asymptomatic case
- February 2 – 2 more cases develop fever
- February 6 - all passengers again tested for SARS-CoV-2 by RT-PCR
  - No additional cases
- February 8 – passengers who did not depart from Wuhan released from medical isolation
- February 15 – passengers who departed from Wuhan released
- Seating
  - Two seating areas had relatively high concentration of cases
    - 6 in Row 11 and 12
    - 5 in Row 29 to 31
    - Remaining were scattered in Row 6, 16, 18, and 44
- Characteristics of cases
  - 12 cases belong to one of four tour groups (Group A)
  - One in Group B
  - Two in Group C
  - One in Group D
- Overall attack rate 4.8 (16/335)
- Geographic attack rate
  - Passengers departing from Wuhan (on January 19) = 13.8% attack rate
  - Passengers not departing from Wuhan = 0.4% attack rate
- Sex: no difference
- Attack rate higher among passengers age 20-29 and 40-59
- Highlights
  - Of all cases:
    - Three meet reasonable timeline of potentially acquiring infection on the plane
    - 7 days later - one likely to have contracted COVID-19 from the flight because it had no relatives on the flight with COVID-19, did not originate from Wuhan, and were not part of Tour Group A (most affected)
    - Married couple did not originate from Wuhan and did sit near three cases, but were part of Tour Group A so it is unclear. Study does not believe these to be cases originating from the flight, but it is possible.
      - Wife spouse presented symptoms 5 days later
      - Husband spouse presented symptoms 7 days later

ASYMPTOMATIC TRANSMISSION OF SARS-COV-2 ON EVACUATION FLIGHT

- **Subject matter**: Cohort study in controlled environment to investigate asymptomatic transmission
- **Geography**: Milan, Italy to South Korea
- **Date**: Milan to South Korea: 31 March 2020
- **Objectives**: Investigate transmission from 6 asymptomatic individuals on flight.
- **Methods**:
  - Masks required/provided? Yes, provided N95. Most wore them except during meals/restroom.
  - Other personal protective equipment? Not specified
  - Isolation before/after flight?
    - 1 passenger who likely contracted COVID-19 from flight reported to have quarantined for 3 weeks prior to flight.
    - All passengers isolated and quarantined in government facility after flight for 2 weeks
  - Require negative COVID-19 test? No
  - Temperature screening prior to flight? Yes - Physical examination, interview, temperature check
    - Social distance requirements prior/post flight? 2 meters apart during pre-boarding and isolated from each other during 2-week quarantine
  - Infection period consistent with time course of travel? Yes
  - Barriers? No
  - Middle seats blocked or available? Not specified
  - Flight class: Evacuation flight (not a commercial flight)
  - Number of travelers: 299
  - Specified ventilation requirements? Not specified
  - Decontamination procedures? Not specified
  - Cases diagnosed with PCR or symptoms?
    - Symptoms/physical examination and interviews prior to flight
    - PCR on 299 quarantined and isolated passengers following flight
  - Did the study account for travel partners?
    - Yes, study accounted for two business partners from the same company who traveled together and both experienced COVID symptoms.
- Summary
  - Primary Study
  - 310 passengers boarded
    - Physical examination, interview, temperature check
    - 11 Symptomatic passengers removed from flight
  - 299 passengers who landed isolated from each other and quarantined for 14 days in government facility

- Quarantine day 1: 6 asymptomatic patients tested positive by PCR and transferred to the hospital. After 14 days, no symptoms.
  - Quarantine day 14: 1 woman (28 years) tested positive by PCR and transferred to hospital. Reported coughing, rhinorrhea, and myalgia on quarantine day 8. On the flight, she wore N95 except when using toilet, which was shared by passengers sitting nearby including one positive, asymptomatic case and seated 3 rows away from that case.
  − Crewmembers (n = 10) and KCDC medical staff (n = 8) also quarantined for 2 weeks at government facility and tested on day 1 and 14. All 18 were negative on both tests.

- <u>Examination of a different dataset for validation:</u> Another evacuation flight from Milan to SK on April 3. Not much detail on this data.
  − 205 passengers who landed isolated from each other and quarantined for 14 days in government facility
    - Quarantine day 1: 3 asymptomatic patients tested positive
    - Quarantine day 14: 1 patient tested positive who had tested negative on day 1
- Findings
  − Among 299 passengers:
    - 6 had a confirmed positive result for SARS-CoV-2 on quarantine day 1
    - 1 case became symptomatic on day 8 and tested positive on quarantine day 14
- Highlights:
  − Being seated next to asymptomatic cases is a major risk factor for transmission.
  − Patient who contracted COVID-19 likely did so while using toilet which was near asymptomatic cases
  − Contact with contaminated surfaces may play role
  − Masks should be work and proper hand hygiene should be practiced
  − Physical distancing should be practiced before and after flight

Figure

A

Flight from Milan, Italy

Arrived in South Korea

All passengers were tested for SARS-CoV-2

All passengers were tested once again for SARS-CoV-2

31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

March   April

Airplane | Government quarantine facility

299 asymptomatic passengers

293 asymptomatic passengers with negative results for SARS-CoV-2 → 292 passengers / 1 patient with COVID-19

6 asymptomatic patients with positive results for SARS-CoV-2

B

A B C D E F G H I J
36
37
EXIT
38
39
40
58
59
60
61

1st floor

A B C D
1
2
EXIT   EXIT

2nd floor

○ Asymptomatic passengers with negative results for SARS-CoV-2

● Asymptomatic patients with positive results for SARS-CoV-2 on April 2, 2020

● Patient with a positive result for SARS-CoV-2 on April 15, 2020

Toilet

C

● Patient (28/F) with a positive result for SARS-CoV-2 on April 15, 2020

Airplane | Government quarantine facility

Body temperature, °C

37.0
36.5
36.0

31 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16

March   April

She shared the inflight toilet with an asymptomatic patient with SARS-CoV-2

The patient tested negative for SARS-CoV-2

The patient reported a cough, rhinorrhea, and myalgia

The patient tested positive for SARS-CoV-2

SARS-COV-2 INFECTION AMONG TRAVELERS RETURNING FROM WUHAN, CHINA

- **Subject matter**: Assessment of patients' symptoms pre- and post-flight.
- **Geography**: Wuhan, China to Singapore
- **Date**: 30 January 2020
- **Objectives**: Follow up on 92 passengers exposed to 2 SARS-CoV-2 positive passengers
- **Methods**:
  - Masks required? Yes, surgical masks provided on board the plane
  - Other personal protective equipment? Not specified
  - Isolation before/after flight? All passengers quarantined after
  - Require negative COVID-19 test? No
  - Temperature screening prior to flight? Yes, before and after travel
    - Body temperature screening conducted at check-in and before boarding
    - Body temperature screening upon arrival in Singapore
  - Social distance requirements prior/post flight? Not specified
  - Infection period consistent with time course of travel? Possible
  - Barriers? No
  - Middle seats blocked or available? Not specified
  - Flight class: Not specified
  - Number of travelers:
    - 94
  - Specified ventilation requirements? Not specified
  - Decontamination procedures? Not specified
  - Cases diagnosed with PCR or symptoms? PCR
  - Did the study account for travel partners?
    - Yes, study accounted for mother-son relationship for two infected travelers.
- Summary:
  - 97 tickets purchased
    - 3 positive cases for fever barred from flight
      - No additional information on these 3 passengers available
  - 94 passengers
    - 2 positive cases [Patient 1 and Patient 2] for fever upon arrival, tested positive for SARS-CoV-2 and hospitalized
  - 92 afebrile passengers quarantined for 14 days at government facility
    - Checked for symptoms and fever three times per day
    - 6 reported symptoms (4 reported symptoms on quarantine day 2; 2 reported symptoms on quarantine day 3) and were hospitalized
    - All 6 PCR-tested negative for SARS-CoV-2
  - Day 3 (February 2) of quarantine:
    - 76 of 86 asymptomatic passengers were nasal swabbed and PCR-tested:

- 1 positive for SARS-CoV-2; son of other passenger who tested positive upon arrival [Patient 1]. Was last exposed to Patient 1 on January 30. New case remained PCR-positive for 14 days.
  - 1 inconclusive PCR case (multiple tests)
- Day 6 (February 5) of quarantine:
  - 87 asymptomatic passengers tested negative for SARS-CoV-2
- Findings:
  - <u>Results of infection rate</u>: Of 92 passengers exposed to 2 SARS-CoV-2 positive passengers [Patient 1 and Patient 2], 1 was likely infected by relative and 1 was inconclusive.
    - Between 0-2 passengers out of 92 passengers were infected by 2 positive cases from their flight.
- **Highlights**: See figure below.
- **Comments**:
  - Surgical masks were provided on board the plane. The report did not specific whether surgical masks were required prior to boarding the plane.
  - Did not specify whether proper social distancing was implemented prior to, during, or after travel.

Figure 1. Follow-up of 94 Persons who Boarded an Evacuation Flight from Wuhan, China, to Singapore on January 30, 2020.

Of the 6 persons who had been transferred to a hospital before February 2, 2020, 3 returned to the government quarantine facility and are included with the 87 persons who underwent testing at the facility on quarantine day 6 (February 5, 2020). SARS-CoV-2 denotes severe acute respiratory syndrome coronavirus 2.

IN-FLIGHT TRANSMISSION CLUSTER OF COVID-19: A RETROSPECTIVE CASE SERIES

- **Subject matter**: Potential for COVID-19 transmission by airplane
- **Geography**: Singapore to China
- **Date**: January 2020
- **Objectives**: To find data for in-flight transmission of COVID-19
- **Methods**:
  - Masks required? Flight attendants wore masks; most passengers had taken no precautionary measures against possible exposure to SARS-CoV-2
  - Other personal protective equipment? Not specified
  - Isolation before/after flight? After a passenger tested positive, crew and passengers were placed under isolation and routine medical checks for 14 days to observe whether illness onset will happen
  - Require negative COVID-19 test? No
  - Temperature screening prior to flight? Yes – at airport in Singapore – strict preflight screening to find fever and respiratory symptoms
  - Social distance requirements prior/post flight? No
  - Infection period consistent with time course of travel? Yes
  - Barriers? No
  - Middle seats blocked or available? Not specified
  - Flight class: Not specified
  - Number of travelers 325 passengers and crew
  - Specified ventilation requirements? Not specified
  - Decontamination procedures? Not specified
  - Cases diagnosed with PCR or symptoms? PCR and chest CT scan
  - Did the study account for travel partners? No
- Summary
  - In a retrospective study, a symptomatic Passenger 1 tested positive for COVID-19 post a flight from Singapore to China where he was not wearing a mask. Post flight, 11 other passengers tested positive. Not a single passenger has been exposed to a confirmed or suspected COVID-19 positive person 14 days prior to the flight. While it is possible that the passengers were infected before the flight due to a 24-day long incubation period, the study believes that the most likely time for transmission of COVID-19 in the 10 passengers was during or immediately before the flight.
- Findings
  - This study reports for the first time small volumes of pleural effusion in both lungs in a non-severe patient of COVID-19.
  - 9 patients were tested RT-PCR positive at admission while only 5 patients were chest CT scan positive at admission, indicating that RT-PCR has a higher sensitivity than chest CT scans in diagnosing COVID-19 (see Figure below).

- Highlights
  - To estimate the risk of aircraft transmission, the study calculated the numbers of persons diagnosed with COVID-19 divided by the total number of persons on this flight, the result is 3.69% (12/325).
  - The risk of in-flight transmission for influenza appears to be far higher that SARS, with 72% of all passengers developed a clinical syndrome of influenza during the next 3 days after a 3-hour flight
  - Study suspects the real risk of SARS-CoV-2 transmission within aircraft cabins in our investigation could be much higher than 3.69% because there might be asymptomatic COVID-19 patients among the other 313 passengers and crew member
  - A period of 5 hours together in aircraft cabin with index patient is long enough to facilitate the transmission of SARS-CoV-2.

PROBABLE AIRCRAFT TRANSMISSION OF COVID-19 IN-FLIGHT FROM THE CENTRAL AFRICAN REPUBLIC TO FRANCE

- **Subject matter**: Timeline of passenger and who travelled by plane from Paris, France to Bangui, Central African Republic and back
- **Geography**: Bangui, Central African Republic (CAR) to Paris, France
- **Date**:
  - Paris to Bangui: 13 February 2020
  - Bangui to Paris: 25 February 2020
- **Objectives**: Determine likely source of infection for infected passenger.
- **Methods**:
  - Masks required? Not specified
  - Other personal protective equipment? Not specified
  - Isolation before/after flight? Not specified
  - Require negative COVID-19 test? No
  - Temperature screening prior to flight? Not specified
  - Social distance requirements prior/post flight? Not specified
  - Infection period consistent with time course of travel? Yes
  - Barriers? No
  - Middle seats blocked or available? Not specified
  - Flight class:
    - Patient 1 and Patient 2 flew economic class
  - Number of travelers Not specified
  - Specified ventilation requirements? Not specified
  - Decontamination procedures? Not specified
  - Cases diagnosed with PCR or symptoms? PCR
  - Did the study account for travel partners?
    - Yes, study accounted for two business partners from the same company who traveled together and both experienced COVID symptoms. They also accounted for a third employee who was on the same flight, but was seated in a different section.
- Summary
  - One passenger [Patient 1]
    - Travelled to CAR on February 13th and returned to France February 25th
    - During time in CAR, engaged in presentations with approximately 30 people for 6 days
    - Symptoms developed on February 29th
    - Visited general practitioner on March 6
    - Sent to ER on March 9th, tested positive for SARS-CoV-2 by PCR
  - Another passenger [Patient 2]
    - Identified as partner of Patient 1 who works at the same company as Patient 1

- During time in CAR, engaged in presentations with approximately 30 people for 6 days
- Exhibited symptoms February 25th to February 29th
- Tested negative by PCR on March 3rd

- Findings
  - Researchers ruled out Patient 1 to have contracted SARS-CoV-2 in France before travelling to CAR due to the incubation time range and the fact that there were only 15 documented cases in France at the time before travelling
  - Researchers determined that Patient 1 was unlikely to have contracted SARS-CoV-2 in Central African Republic since all known business contacts were screened and ruled out
  - Researchers ruled out Patient 1 to have acquired the infection in France after return between February 25th and 27th since there was no local circulation documented during that time
  - Researchers determined that Patient 1 likely contracted SARS-CoV-2 on plane, while traveling with patient diagnosed 11 days later in Cameroun (see schematic below)
    - The first SARS-CoV-2 case diagnosed in Cameroun was a French national [Patient 0] who entered country after flying Air France who flew from Paris to Yaoundé, Cameroun, with a stop in Bangui
      - Did not indicate method of diagnosis (i.e., symptoms or test)
    - Patient 1 and Patient 2 used same flight from Bangui to Yaoundé, Cameroun and then continued to Paris and Marseille in economic class
    - Another French employee [Employee 3] from the same company as Patient 1 and Patient 2 flew back on same flight but in business class

- Highlights:
  - Researchers determined the patient to have contracted SARS-CoV-2 while on plane with a traveler who was later diagnosed with SARS-CoV-2

MASS AIR MEDICAL REPATRIATION OF CORONAVIRUS DISEASE 2019 PATIENTS

- **Subject matter**: Repatriation evacuation procedures during COVID-19
- **Geography**: Wuhan, China
- **Date**: 29 January 2020; February 2020; March 2020
- **Objectives**: Review evacuation procedures from transporting 2,000 US citizens and diplomats via aircraft (primarily fixed wing) who were COVID positive, PUI, or asymptomatic from COVID hot spot areas (Wuhan, China & cruise ships)
- **Methods**: Described contamination control measures
  - Masks required? Surgical masks for PUIs and N95 for known positives
  - Other personal protective equipment? Crews used Tyvek suits with booties and a hood, double layer gloves, and either powered air-purifying respirator (PAPR) or N95 mask with a face shield
  - Isolation before/after flight? Isolated evacuees at federal quarantine centers or sent home to quarantine
  - Require negative COVID-19 test? No
  - Temperature screening prior to flight? Not specified, but screened individuals to determined positive cases and PUIs
  - Social distance requirements prior/post flight? Not specified
  - Infection period consistent with time course of travel? Not applicable
  - Barriers? Plastic sheeting to segregate and treat patients
  - Middle seats blocked or available? Not specified. Tried to maintain 6 feet distance.
  - Flight class Not applicable
  - Number of travelers Multiple flights, over 2,000 individuals transported
  - Specified ventilation requirements?
    - Kept cabin ventilation on at all times, including ground delays
    - Airflow exchanges between flights
  - Decontamination procedures? Mandatory aircraft surface decontamination
  - Cases diagnosed with PCR or symptoms? Not specified
  - Did the study account for travel partners? Yes, transported people and their families
- Summary
  - Evacuation from China:
    - 1/29/2020: transported the first American citizens and family from Wuhan, China to CA via Boeing 747
    - Early February: 4 additional flights transported remainder of American citizens
    - Total of ~800 passengers repatriated via charter flights from Wuhan to U.S.
    - Provided in-flight medical monitoring and screening upon arrival to U.S.
  - Evacuation from Cruise Ships
    - Diamond Princess and Grand Princess cruise ships

- Early February: evacuation 338 US citizens from Diamond Princess off coast of Japan via 2 Boeing 747s
- 3/9/2020: Grand Princess made early return to CA with 3,533 persons, including 21 known to be COVID positive
  - Most Americans were transferred to federal quarantine centers via Boeing 737s
  - After disbursement to federal centers, the patients were decompressed by a Boeing 737, Learjet 35, regional jet or charter bus to their state of residence for screening and home quarantine
  - During these flights, 2 patients became symptomatic, requiring hospitalization upon arrival at destination

- Air transport considerations relied upon:
  - CDC's Guidance for Air Medical Transport of Severe Acute Respiratory Syndrome Patients
  - Guidance on Air Medical Transport for Middle East Respiratory Syndrome Patients
- Isolation precautions:
  - Efforts were made to transport known positives only with known positives and cohort PUIs with PUIs
  - HHS AET crew limited to minimum necessary staff in accordance with Federal Aviation Administration regulations and National Disaster Medical System care standards
- Infection control precautions:
  - Source & engineering controls, PPE, safe work practices limited to contamination, containment of potential contamination
  - PPE:
    - Positive patients wore N95 masks and PUIS were at least standard surgical masks
    - Crew wore Tyvek suits with booties and a hood, double layer of gloves, PAPR or N95 with a face shield when in close proximity to patients (< 6 ft.)
    - Crew outside of 6-ft range (pilots and flight attendants) wore N95 and gloves at a minimum, usually also wore gown and face shield
- Engineering controls:
  - Used plastic sheeting to isolate area to segregate and treat patients who developed symptoms while airborne
    - Placed symptomatic individuals in back section of plane to allow separate egress
- Safe work practices limited to contamination
  - Passengers work diapers to avoid potential fecal exposure during transport
  - Mandatory aircraft surface decontamination
  - Airflow exchanges between flights
  - Lavatories inside protected area for crew use only
  - Frequent hand hygiene with alcohol-based solution
- Airframe evaluation

- There are specific considerations when evaluating airframe for transport of potentially infectious patient
- Considerations: airflow, HEPA filters, air outlet locations, directional airflow capabilities, and abilities to isolate air mixing between cockpit and patient care cabin
- Poorly controlled interior airflow: rotor wing aircraft, non-pressurized fixed wing aircraft
  - Implement physical barriers & N95 masks or higher respiratory protection when interior airflow poor
- Recommendations:
  - Ideally, patient should be positioned as far downwind as possible
    - Not possible in most civilian aircraft
  - Separate lavatory facilities for patients and crew, with patient location contained inside their area of occupancy
  - Ambulatory patients should be seated against cabin sidewall and wear surgical mask to reduce droplet contamination
- Decontamination
  - After transport, exit doors should be closed and aircraft air conditioning turned on at maximum capacity for several minutes to allow at least 1 complete air exchange
  - Non-pressurized aircraft should be aired out, with doors open long enough to ensure a completed air exchange
  - Blower and high-powered fans should not be used because they could re-aerosolize infectious material
  - Cleaning personnel should wear gloves, eye protection, and isolation gowns/coveralls at a minimum; an N95 should be worn if concern for re-aerosolization
- Findings
  - Described various contamination control measures implemented while transporting over 2,000 Americans (many of work were COVID positive, PUIs, or asymptomatic) from COVID hotspot areas flown on 39 missions from primarily fixed wing aircraft transport
  - There was no infection of any transporting HHS air medical evacuation crews
  - There may be different control measures required for rotor wing or ground transport
- Highlights
  - Studied largest repatriation (over 2,000 individuals) of potentially contagious patients in history without infection of any transporting US Department of Health and Human Services air medical evacuation crews.

COMMERCIAL AIRLINE PROTOCOL DURING COVID-19 PANDEMIC: AN EXPERIENCE OF THAI AIRWAYS INTERNATIONAL

- **Subject matter**: Airline protocol during the COVID-19 pandemic.
- **Geography**: Sydney, Australia, Auckland, New Zealand, Bangkok, Thailand
- **Date**: 26-27 April 2020
- **Objectives**: Explore the implementation feasibility of Thai Airways International protocol from the perspectives of passengers and aircrews.
- **Methods**: Review and summarize information gathered via an online questionnaire survey of 377 Thai passengers and in-depth interviews with 35 aircrews to determine perspectives of Thai Airways International protocols during the COVID-19 pandemic. Respondents were randomly selected from 2 repatriation flights operated by Thai Airways International using Boeing 777 aircraft (equipped with 18 business class seats and 306 economy class seats).
  - TG476 from Sydney to Bangkok, 209 passengers
  - TG492 from Auckland to Bangkok, 168 passengers
  - Masks required? Passengers received surgical mask
  - Other personal protective equipment? Face shield, cleaned hands with alcohol gel prior to boarding
  - Isolation before/after flight? Quarantine at government-provided hotel in Bangkok for 14 days after flight
  - Require negative COVID-19 test? No
  - Temperature screening prior to flight? Yes prior to flight and 1-2 times during flight
  - Social distance requirements prior/post flight? 4-5 feet physical distancing at check-in, boarding, and in-flight
  - Infection period consistent with time course of travel? Not applicable
  - Barriers? Yes, cabin areas divided by disposable curtains into 5 designated areas:
    - Clean area: only for crews with PP
    - Buffer zone: assigned as dressing area for crew
    - Passenger sitting area: seating for passengers
    - Quarantine area: last 3 rows for passengers or crews with unanticipated symptoms identified onboard
    - Lavatories: front end of the plane allowed only for crews
  - Middle seats blocked or available?
    - Sometimes, adjacent seat was empty except for the declared family members.
  - Flight class:
    - Flight equipped with 18 business class seats and 306 economy class seats
  - Number of travelers
    - TG476 from Sydney to Bangkok, 209 passengers
    - TG492 from Auckland to Bangkok, 168 passengers
  - Specified ventilation requirements? Not specified
  - Decontamination procedures?

- Lavatory disinfected after each use
- Alcohol gel provided to passengers
- Cleaning staff disinfected aircraft after flights
  - Cases diagnosed with PCR or symptoms?
    - All passengers tested for COVID via PCR
  - Did the study account for travel partners?
    - Yes, accounted for declared family members
- Summary
  - Study evaluated current protocols and surveyed passengers and crews on their perspective of current COVID-19 procedures
  - The Civil Aviation Authority of Thailand (CAAT) developed a COVID-19 risk score, based on number of COVID-19 cases from country of departure, proportion of seats to be occupied by passengers, and flight duration, to determine eligibility and requirements to fly to Thailand (Table 1).

Table 1. COVID-19 risk score, The Civil Aviation Authority of Thailand (CAAT).

Score	1	2	3	4	5
Number of Covid-19 Cases in Country of Departure	< 50	50–100	101–500	501–1,000	>1,000
Proportion of Seats Occupied with Passengers (%)	< 40	40–80	> 80	-	-
Flight Duration (hours)	<4	4–8	> 8	-	-
Risk-based Interventions:					
Low Risk (score 3–4)	Passengers: Body temperature check by using a non-contact infrared thermometer before boarding. Passengers with body temperature higher than 37.3 degree Celsius or upper respiratory tract symptoms (cough, sore throat, running nose, and shortness of breath) will be reassessed by Port Health Officer if a boarding pass could be given.				
	Crews: Disposable medical or surgical masks.				
	Pilots: Disposable medical or surgical masks.				
Moderate Risk (score 5–7)	Passengers: Body temperature check by using a non-contact infrared thermometer before boarding and in-flight for long-haul (>4 hours) flights.				
	Crews: Disposable medical or surgical masks.				
	Pilots: Disposable medical or surgical masks.				
High Risk (score 8–11 or no HEPA[a] filtering system)	Passengers: Body temperature check by using a non-contact infrared thermometer before boarding and in-flight for long-haul (>4 hours) flights.				
	Crew: N95 or surgical masks, goggles, and disposable rubber gloves.				
	Pilots: Surgical masks and goggles.				

[a]High-Efficiency Particulate Air

  - https://doi.org/10.1371/journal.pone.0237299.t001
  - Thai Airways International implemented various preventative measures:
    - Passengers estimated 4-5 feet physical distancing prior to flight
    - Passengers received surgical face mask, face shield, and gel alcohol
    - Passengers' temperature was taken before flights and 1-2 times during flights
    - Cabin areas were divided by disposable curtains into 5 designated areas Removed magazines, newspapers, and unnecessary documents from seating areas

- Adjacent seats were empty except for the declared family members
- Staggered times to eat by passenger section to minimize the chance of simultaneous mask removal by nearby passengers
- Passengers were asked to use alcohol gel provided before and after the meal.
- Passengers asked to drop their garbage in the cart themselves or on service trays to minimize physical contact with cabin crew.
- The lavatory was disinfected after every use.
- During landing, passengers instructed to remain seated and maintain physical distancing while disembarkation.
  - Crew noticed several passengers attempted to move out too early which might fail physical distancing principle.
  - Crew allowed passengers to stand and disembark on a row-by-row basis
- All passengers in both flights tested for COVID-19 via PCR and were quarantined at government-provided hotel in Bangkok for 14 days
- Limitation to study:
  - Response rate (22.5%) low; however, responses were from an unbiased seat selection and could be representative of flights
  - Self-reported data relied on passengers' perception and might not be accurate
  - Nature of Thai passengers might not reflect other ethnic origins
- Findings
  - Total of 78 passenger respondents
    - 63 respondents at least 18 years old
  - Mean age of passengers: 28 years old
  - Average body temperature: 36.5°C (97.7°F) [prior to flight]
  - Passengers estimated average physical distance of 1.59, 1.41, and 1.26 meters (5.2, 4.6, and 4.1 feet) at check-in, boarding, and in-flight, respectively
  - Passengers' temperature taken 1-2 times during flight
    - As described in Table 1, in-flight body temperature check was required for long-haul moderate- and high-risk flights, but no frequency was specified.
  - Passengers moved around approximately 2 times during the flight
  - Passengers when to the bathroom approximately 2 times during the flight
  - Passengers' confidence in the airline company was statistically significantly increased from 7.64 ± 2.47 before the trip to 8.10 ± 2.49 after the trip (p=0.0001).
  - Aircrews were satisfied with the protocol and provided suggestions
    - Expressed some concerns regarding occupational exposure to themselves and their family members
      - Concerns seemed to be alleviated after experience of repatriation flights
    - Physical distancing at ~1.5 to 2.0 meters (3.3 – 6.6 ft) more practical at check-in counter, pre-boarding area, and boarding line than during the flight.
  - Crews critiqued `Buffer zone' where crew would change; crews with higher PPE would cross paths with less protected crews.

- Crew determined approach of providing passengers with surgical mask, face-shield, and cleaning hands with alcohol gel prior to boarding impractical because several passengers had many carry-ons
- Highlights:
  - Study suggests that the passengers reported varying degrees of physical distancing at check-in, boarding and in-flight and that the in-flight body temperature check was possible.
  - The Thai Airways protocol was well received by passengers and aircrews.

LACK OF COVID-19 TRANSMISSION ON AN INTERNATIONAL FLIGHT

- **Subject matter**: First Canadian cases of COVID-19 by plane from China
- **Geography**: Traveled from Wuhan to Guangzhou to Toronto, Canada
- **Date**: Arrived in Toronto 22 January 2020
- **Objectives**: Public health response to the first Canadian cases of COVID-19
- **Methods**:
  - Masks required? Not specified
  - Other personal protective equipment? Not specified
  - Isolation before/after flight? Not specified before flight. After flight, passengers were monitored but isolation was not specified
  - Require negative COVID-19 test? No
  - Temperature screening prior to flight? Not specified
  - Social distance requirements prior/post flight? Not specified
  - Infection period consistent with time course of travel? Yes
  - Barriers? No
  - Middle seats blocked or available? Not specified
  - Flight class? Not specified
  - Number of travelers ~350
  - Specified ventilation requirements? Not specified
  - Decontamination procedures? Not specified
  - Cases diagnosed with PCR or symptoms? Throat and nasopharyngeal swabs via PCR
  - Did the study account for travel partners? Yes
- Summary
  - One man traveled from Wuhan to Toronto was symptomatic during 15-hour flight, his wife was symptomatic one day after the flight, both tested positive for COVID-19.
  - Of the identified 25 close contacts on the flight, none tested for COVID-19 even 14 days after the flight.
  - 5 non-close-contact passengers became symptomatic, but tested negative for COVID-19 by nasopharyngeal and throat swabs
- Findings
  - There were 2 out of 350 passengers that tested positive for COVID-19 traveling from Wuhan to Guangzhou to Canada.
  - The 2 COVID-19 positive cases were spouses and became symptomatic on the day after the flight, indicating that they potentially acquire infection prior to the flight.
  - The remainder of the passengers who were close contacts and non-close-contacts did not report to be COVID-19 positive.
- Highlights
  - Lack of secondary cases after prolonged air travel exposure supports droplet transmission, not airborne, as the likely route of spread of the COVID-19.
  - Exposure may have been mitigated by mild symptoms and masking during the flight

FIRST IMPORTED CASE OF 2019 NOVEL CORONAVIRUS IN CANADA, PRESENTING AS MILD PNEUMONIA

- **Subject matter**: First believed case of COVID-19 in Canada
- **Geography**: Traveled from Wuhan to Guangzhou to Toronto, Canada
- **Date**: Arrived in Toronto 22 January 2020
- **Objectives**: Patient appeared to have pneumonia but tested positive for COVID-19
- **Methods**:
  - Masks required? Not specified
  - Other personal protective equipment? Not specified
  - Isolation before/after flight? Not specified
  - Require negative COVID-19 test? No
  - Temperature screening prior to flight? Not specified
  - Social distance requirements prior/post flight? Not specified
  - Infection period consistent with time course of travel? Not specified
  - Barriers? No
  - Middle seats blocked or available? Not specified
  - Flight class Not specified
  - Number of travelers Not specified
  - Specified ventilation requirements? Not specified
  - Decontamination procedures? Not specified
  - Cases diagnosed with PCR or symptoms? Throat and nasopharyngeal swabs via PCR
  - Did the study account for travel partners? Not specified
- Summary
  - A 56-year-old man returned from a 3-month trip from Wuhan, China and was hospitalized in Toronto with symptoms of pneumonia. He tested positive for COVID-19 but did not need a ventilator. He returned home after five days once his fever went away. The virus could be contained if individuals that do not need ventilators recovered while in isolation at home rather than occupying hospital beds.
- Findings
  - If COVID-19 positive individuals such as this patient could be identified and isolated at home instead of at a hospital, an outbreak could be minimized
- Highlights
  - Only a minority of previously reported cases had thrombocytopenia, but the patient did not require intubation or supplemental oxygen.

ABSENCE OF IN-FLIGHT TRANSMISSION OF SARS-COV-2 LIKELY DUE TO USE OF FACE MASKS ON BOARD

- **Subject matter**: Lack of COVID-19 viral transmission during flights
- **Geography**: Japan to Israel (passengers repatriated from Diamond Princess cruise ship)
- **Date**: 20 February 2020
- **Objectives**: Show no evidence of viral transmission during flights
- **Methods**:
  - Masks required? Yes
  - Other personal protective equipment? Not specified
  - Isolation before/after flight?
    - Passengers were isolated on the cruise ship before flight and transferred in a bus directly from the ship to plane/isolated for 14 days once in Israel
  - Require negative COVID-19 test? Yes
  - Temperature screening prior to flight? Not specified
  - Social distance requirements prior/post flight? Not specified
  - Infection period consistent with time course of travel?
    - Potentially, one case developed symptoms during the flight.
  - Barriers? No
  - Middle seats blocked or available? Not specified
  - Flight class Not specified; Flew Charter Bombardier Galaxy 6000 commercial aircraft
  - Number of travelers 11 passengers plus 4 staff
  - Specified ventilation requirements? Aircraft had 2 outflow valves that alternate between, and one air mixture unit
  - Decontamination procedures? Not specified
  - Cases diagnosed with PCR or symptoms? PCR
  - Did the study account for travel partners? Not specified
- Summary
  - 11 Israeli citizens who were passengers of the Diamond Princesses cruise ship were transported by aircraft back to Israel from Japan. Only two passengers of 11 close contact passengers tested positive for COVID-19 after the flight but they also both had spouses that were hospitalized for COVID-19 in Japan, so it is likely that they contracted the virus before getting on the flight.
- Findings
  - There may be a low risk of SARS transmission on aircrafts, especially when passengers use higher standard masks.
  - The 2 of 11 COVID-19 positive cases post flight may have contracted the virus from their spouses who were hospitalized in Japan.
- Highlights
  - Even after being in close contact on the flight with the two positive cases, 13 remaining passengers and crew tested negative during the 14-day quarantine

ASSESSMENT OF SARS-COV-2 TRANSMISSION ON AN INTERNATIONAL FLIGHT AND AMONG A TOURIST GROUP

- **Subject matter**: COVID-19 transmission of a tourist group on an international flight
- **Geography**: Tel Aviv, Israel to Frankfurt, Germany
- **Date**: 9 March 2020
- **Objectives**: Trace possible transmission on flight between tourists
- **Methods**:
  - Masks required? No
  - Other personal protective equipment? No
  - Isolation before/after flight? Not specified
  - Require negative COVID-19 test? No
  - Temperature screening prior to flight? Not specified
  - Social distance requirements prior/post flight? Not specified
  - Infection period consistent with time course of travel? Yes
  - Barriers? Not specified
  - Middle seats blocked or available? Not specified
  - Flight class: Not specified; flew Boeing 737-900
  - Number of travelers 102
  - Specified ventilation requirements? Not specified
  - Decontamination procedures? Not specified
  - Cases diagnosed with PCR or symptoms?
    - Plaque reduction neutralization test (PRNT)
  - Did the study account for travel partners? Yes
- Summary
  - On a commercial flight, 24 tourists had contact with a COVID-19 positive person before boarding. The group had contact with a hotel manager who was later diagnosed with COVID-19
  - There 2 likely COVID-19 transmissions on the flight and 7 index cases. Both individuals were seated with two rows of an index case.
- Findings
  - Airflow in the cabin (ceiling to floor and front to rear) may have help reduced the transmission rate.
- Highlights
  - There were likely 2 COVID-19 transmissions on the flight and 7 index cases
  - Findings did not rule out airborne transmissions in an airplane cabin.

Figure 1. Seating of the Index Cases and Other Passengers on the Aircraft (Boeing 737-900)

Legend:
- ☐ Empty seat or seat not accounted for
- ☒ Person not interviewed
- ⊞ Index case with no symptoms
- ⊞ (red) Index case with symptoms
- ☐ Tested negative at the airport
- ☐ (light blue) Transmission excluded by appropriate testing
- ☐ (dark blue) Transmission not excluded; passenger asymptomatic but not tested
- ☐ (red) Likely transmission; tested positive
- ☐ (yellow) Transmission not excluded; passenger symptomatic with previous contact to COVID-19

Figure 2. Flowchart of the Tests for Severe Acute Respiratory Syndrome Coronavirus (SARS-CoV-2) and of Symptoms of the 71 Passengers Who Were Interviewed

71 Passengers — Exposed to 7 index cases on the flight

63 Passengers — No symptoms of COVID-19 after the flight

8 Passengers — Symptomatic after the flight

- **1 Passenger** — Tested positive by PCR and also by SARS-CoV-2 IgG after 7 weeks → Likely transmission
- **46 Passengers** — Not tested by PCR or antibody test → Asymptomatic but not tested
- **1 Passenger** — Borderline test result for SARS-CoV-2 IgG after 7 weeks, neutralization assay negative → Transmission excluded
- **11 Passengers** — Tested negative by PCR → Transmission excluded
- **4 Passengers** — No SARS-CoV-2 IgG detected after 6-9 weeks → Transmission excluded
- **5 Passengers** — No SARS-CoV-2 IgG detected after 7 weeks → Transmission excluded
- **1 Passenger** — Tested negative by PCR and no SARS-CoV-2-IgG detected after 7 weeks → Transmission excluded
- **1 Passenger** — Tested positive for SARS-CoV-2-IgG after 9 weeks → Likely transmission
- **1 Passenger** — Previous contact with COVID-19, not tested by PCR or antibody test → Symptomatic but not tested

COVID-19 indicates coronavirus disease 2019; PCR, polymerase chain reaction.

CHOI, E. M., CHU, D. K., CHENG, P. K., TSANG, D. N., PEIRIS, M., BAUSCH, D. G., & WATSON-JONES, D. IN-FLIGHT TRANSMISSION OF SEVERE ACUTE RESPIRATORY SYNDROME CORONAVIRUS 2. EMERGING INFECTIOUS DISEASES, 26(11).

- **Subject matter**: Evaluate transmission of SARS-CoV-2 among four passengers.
- **Geography**: Boston, Massachusetts to Hong Kong, China
- **Date**: 9-10 March 2020
- **Objectives**: Review viral genetic sequencing from respiratory samples from 4 patients who were SAR-CoV-2 positive and flew on the same flight for an extended period
- **Methods**:
  - <u>Masks required</u>? Not specified
  - Other personal protective equipment? Not specified
    - <u>Isolation before/after flight</u>? Before: not specified; After: Yes, for the 4 cases identified.
  - Require negative COVID-19 test? Not specified
  - Temperature screening prior to flight? Not specified
  - Social distance requirements prior/post flight? Not specified
  - Infection period consistent with time course of travel? Yes, cases defined at 1-11 days after the flight.
  - Barriers? Not specified
  - Middle seats blocked or available? Not specified
  - Flight class:
    - Yes, study tracked seat classifications of patients who were passengers
    - Patients A & B both sat in window seats of business class.
  - Number of travelers 294
  - Specified ventilation requirements? Not specified
  - Decontamination procedures? Not specified
  - Cases diagnosed with PCR or symptoms? PCR
  - Did the study account for travel partners? Yes, patients A & B were married.
- Summary
  - Examined public records from for 1,110 persons with laboratory-confirmed COVID-19 in Hong Kong, China recorded from January 23, through June 13, 2020
  - Identified cluster of four people with COVID-19 (patients A-D) associated with a commercial flight that departed from Boston, MA on March 9 and arrived in Hong Kong, China on March 10, 2020.
    - Airplane: Boeing 777-300ER
    - Flight duration: 15 hours
    - Passengers: 294
  - Cluster comprised of 2 passengers and 2 crew members
    - Were PCR tested and determined positive within 5-11 days of arrival

- Patients A & B were married
  - Patient A:
    - 58-year-old man with underlying disease
    - Sat in window seat in business class
    - Developed fever and cough March 10
    - March 13 - mild abdominal discomfort, followed by diarrhea 2 days later
  - Patient B:
    - 61-year-old woman, wife of patient B, with underlying disease
    - Sat directly in front of husband in business class window seat
    - Developed sore throat March 10
    - March 11 – fever and cough
  - Both hospitalized on March 14
  - Respiratory samples collected on March 14 and 15 were positive for SARS-CoV-2
  - No indication of whether or not the patients were symptomatic during the flight
  - Prior to flight and within 14-day incubation period, visited: Toronto, Ontario, Canada (February 15 – March 2); New York, New York (March 2-5); and Boston (March 5-9)
  - Centre for Health Protection (CHP) of China classified couple as imported cases into Hong Kong
- Patient C:
  - Asymptomatic 25-year-old man identified through contact tracing by Hong Kong government and airline as close contact of patients A & B
  - Hong Kong-based business class flight attendant who served patients A and B during the flight
  - Tested on March 16 and determined positive for SARS-CoV-2 on March 17
  - Stayed in Boston March 5-9
- Patient D:
  - 51-year-old female Hong-Kong-based flight attendant on same flight
  - March 18 – developed fever and cough
  - March 21 – tested positive for SARS-CoV-2 and hospitalized
  - No information on travel prior to flight or contact to other patients during or after flight
  - CHP categorized as close contact to patients A & B
- Patients A & B most likely contracted virus in North America and transmitted to flight attendants/patients C & D during flight
- The only location where all 4 persons were in close proximity for extended period of time was inside the airplane
- Cannot rule out possibility that patients C and D were infected before boarding [from other index case(s)], though the unique virus sequencing and 100% identity across the whole virus genome across the 4 patients makes scenario unlikely

- Patient D may have acquired infection from patient C since their test result was positive within 1 incubation period, but it is more likely patient D was infected by patient A or B
- Not able to quantify virus attack rate because not all passengers were tested
- Findings
  - Sequenced the viruses from the patients' upper respiratory samples
    - Near full-length viral genomes for all 4 patients were 100% identical and phylogenetically grouped to clade G
    - None of the other 189 viral sequences deduced from samples collected in Hong Kong (January 21 – May 12, 2020) belonged to clade G
  - In March 2020, virus sequences related to patients A-D with only 2 nt differences were isolated to Toronto, New York City, and Massachusetts, making it plausible that patients A & B acquired a similar virus during visit
- Highlights
  - 4 people with SARS-CoV-2 infection had traveled from same flight from Boston, MA to Hong Kong, China
  - Determined the virus genetic sequences from 4 patients to be identical, unique, and belong to a clade not previously identified in Hong Kong, suggesting the virus can be transmitted during air travel
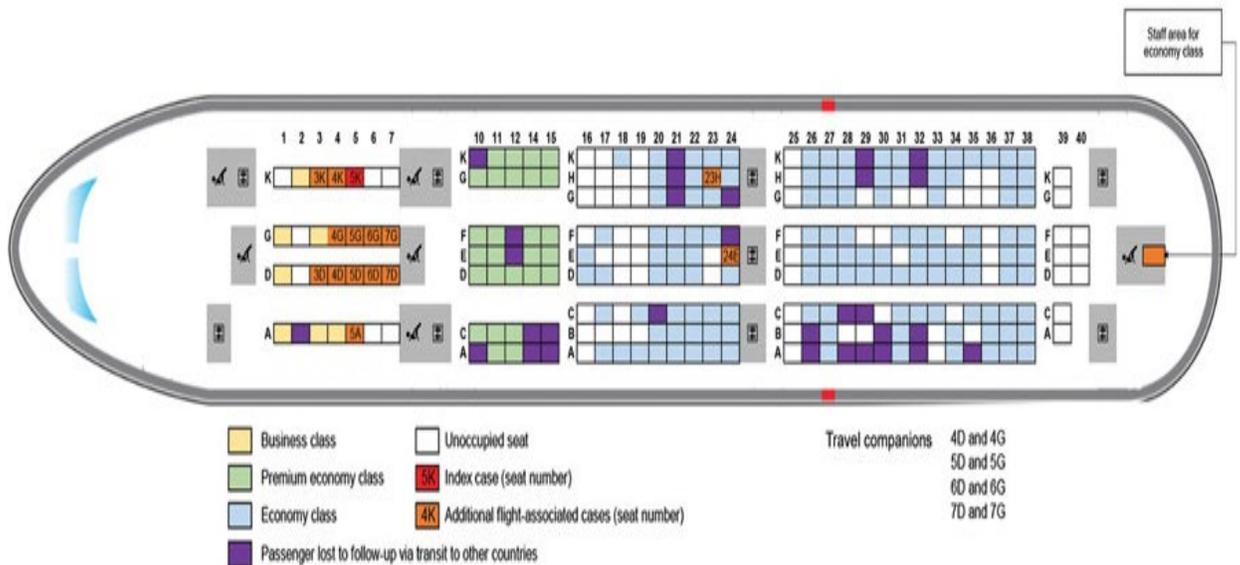
TRANSMISSION OF SEVERE ACUTE RESPIRATORY SYNDROME CORONAVIRUS 2 DURING LONG FLIGHT

- **Subject matter**: Cohort study in long commercial flight
- **Geography**: London, UK to Hanoi, Vietnam
- **Date**: 1-2 March 2020
- **Objectives**: Investigate transmission from six asymptomatic individuals on flight.
- **Methods**:
  - Masks required/provided? Use of face masks was not mandatory on airplanes or at airports
  - Other personal protective equipment? Not specified
  - Isolation before/after flight? Before: Not specified; After: Yes, passengers who were successfully traced were told to quarantine.
  - Require negative COVID-19 test? Not specified
  - Temperature screening prior to flight? Not specified
  - Social distance requirements prior/post flight? Not specified
  - Infection period consistent with time course of travel? Yes, cases defined at 2-14 days after flight
  - Barriers? Yes, between business class and economy and premium economy
  - Middle seats blocked or available? Not specified
  - Flight class: 274 seats total
    - 28 business class seats (21 occupied, 75%)
    - 35 premium economy seats (35 occupied, 100%)
    - 211 economy seats (145 occupied, 67%)
    - Index case: Business class
  - Number of travelers
    - 201 passengers
    - 16 crew
  - Specified ventilation requirements? Not specified
  - Decontamination procedures? Not specified
  - Cases diagnosed with PCR or symptoms? PCR
  - Did the study account for travel partners? Yes
- Summary
  - 2 March 2020: Flight from London to Hanoi (10-hr) with 217 travelers
  - 274 seats total split into three seating categories: business class, premium economy, and economy
  - 4 toilets for business class and premium economy; and 5 toilets for economy
  - Two meals were served, flight attendants worked in 2 teams, 1 for business and premium economy sections and 1 for the economy section.
  - Upon arrival in Hanoi:

- All passengers from COVID-infected areas, including UK had their body temperature measured by thermal imaging
- All passengers required to declare any COVID-19 symptoms
- Only passengers from China, SK, Iran, and Italy were required to undergo SARS-CoV-2 testing and 14-day quarantine
    - Probable index case (case 1):
        - 27-year-old Vietnamese businesswoman based in London since February
        - February 18: Case 1 travelled to Italy with sister; sister was later confirmed SARS-CoV-2 positive in London
        - February 20: Case 1 returned to London to stay with sister for another 2 nights
        - February 22: Case 1 and sister return to Milan, Italy and then to Paris, France
        - February 25-29: Case 1 return to London and reside in London
        - February 29: While in London, began experiencing symptoms; sore throat and cough
        - March 1: Case 1 boarded flight to Hanoi seated in business class, continued to experience symptoms. Case 1 symptoms progressed further after arrival; fever, sore throat, fatigue, and shortness of breath
        - March 5: Case 1 sought care at hospital in Hanoi
        - March 6: Swab + PCR confirmed SARS-CoV-2 positive
        - March 7: 3 household personnel in Hanoi received positive SARS-CoV-2 results and one friend in London received a positive SARS-CoV-2 result from Case 1's visit February 29
    - March 10:
        - All 16 (100%) flight crew traced, quarantined, interviewed, PCR-tested
        - 168 (84%) of passengers traced, quarantined, interviewed, PCR-tested
        - 33 (16%) passengers transited to other countries
    - Flight-associated case criteria:
        - They experienced signs/symptoms 2–14 days after arrival or if they were SARS-CoV-2 positive by PCR 2–14 days after arrival in the absence of signs/symptoms
        - In-depth investigation did not reveal any potential exposure to SARS-CoV-2 before or after the flight during their incubation period
        - They had shared cabin space with the probable index case during the flight
    - All 16 crew and 168 (84%) passengers who remained in Vietnam were traced
        - Quarantined, interviewed, and swabbed
- Findings
    - Of the 16 (100%) crew and 168 (84%) passengers:
        - 15 additional COVID-19 cases identified (met all inclusion criteria)
            - 14 passengers
            - 1 crew member
            - Ages 30-74 (median = 63.5)
            - 9 males
            - 12 British nationality

- 12 (80%) passengers were in business class, 1 crew member in economy, and 2 passengers in economy class
- Attack rate:
  - Business class: 13 cases /21 passengers = 62%
    - 11 of 12 (92%) passengers ≤2 m away from case 1 (or ≤2 seats away) were positive
    - 1 of 8 (13%) passengers >2 m away (or >2 seats away) were positive
  - Risk ratio: 7.3 (95% CI 1.2–46.2)
  - Overall estimated (minimum) attack rate: 15 cases/ 216 passengers = ~7%
- Of the 12 additional cases in business class, 8 (67%) developed symptoms
  - Median symptom onset 8.8 days after arrival
  - None of the additional cases showed symptoms during the flight
- Investigation did not reveal evidence supporting SARS-CoV-2 exposure before or after flight, all cases were attributable to the flight
- Accounted for travel companions
  - 4 traveling companion couples
  - Couples sat next to each other in business class
  - 3 pairs (6 people) were positive for SAR-CoV-2 on the same date: 6 days after arrival (March 8)
- None of the couples/individual cases traveled or stayed with another couple or individual case prior to the flight or after arrival
- Of the >1,300 close contacts of passengers after the flight, 5 confirmed cases were identified, 3 linked to index case.
- Interviews with probable secondary cases did not reveal exposure to other sources.
  - At the time, the case count was low in the UK, though testing was not that prevelant. Determined multiple people coming aboard incubating the illness to be unlikely.
  - Considered transmission after the flight, but as of March 1, only 16 cases had been reported in Vietnam and 17 days had past since the last reported case. Determined no evident of community transmission of SARS-CoV-2 in Vietnam when the flight arrived.
  - There were 2 cases: case 3 and case 14 experienced symptoms 17 days after the flight
  - Indicates unusually long incubation or symptoms caused by conditions other than COVID-19
- Acknowledge aerosol or droplet transmission from case 1 might have occurred outside the airplane at the airport
  - Business class passengers have access to pre-departure lounge area or during boarding process
  - Other points of contact between business and economy class: immigration, baggage claim
- Limitations:
  - Did not have genomic sequencing data to support hypothesis of in-flight transmission

- Lack detailed information on activity of passengers while on board (movements, seat changes, use of toilets, sharing meals, etc.)
- Passengers' preflight exposure to other confirmed cases relied upon interviews only
- No data available on individual mask use while on board
- Masks were not mandatory during this time
- No environmental samples collected

- Highlights:
  - 1 symptomatic passenger (case 1) likely transmitted virus during a 10-hour flight to at least 12 other passengers in business class (probable secondary cases).
  - Seating proximity was strongly associated with increased infection risk (risk ratio 7.3, 95% CI 1.2–46.2).

- Discussion:
  - Attack rates are not adjusted to account for loss-to-follow-up potential cases (33 passengers who had moved onto other countries)
  - Biggest factor was sitting in business class. This is likely due to business class being isolated from the rest of the plane. This likely protected non-business class passengers and increased the risk in business
  - Better screening of passengers would have eliminated exposures
  - Thermal imaging and self-declaration of symptoms are limited

APPENDIX B

GLOSSARY OF TERMS   (in relation to infectious disease)

Airborne   When a virus can be transmitted from person to person by the tiny particles of moisture released from the mouth or nose when speaking, breathing or singing.

Asymptomatic   Not showing any signs of illness. A person can be contagious without showing any symptoms.

Cluster   Two or more people who shared the same space at the same time when they developed symptoms and who subsequently tested positive for COVID-19.

Communicable   Similar in meaning as "contagious". Used to describe diseases that can be spread or transmitted from one person to another.

Community spread   Used when the source of someone's coronavirus infection is unknown.

Confirmed case   Someone tested and confirmed to have COVID-19.

Contact Tracing   An attempt by public health officials to identify persons who may have been in contact with an infected person.

Contagious   Communicable, or able to be passed from one person to another. COVID-19 is thought to be spread primarily through direct contact with an infected individual, by inhaling the microscopic droplets sprayed into the air during a cough or sneeze, or by touching a contaminated surface and then touching one's eyes, nose or mouth.

Coronavirus   A type of microscopic organism that causes illness in humans. "Corona" alludes to the tiny spikes found on the surface of the virus, which scientists thought resembled a crown, when seen through a microscope.

COVID-19   A shorthand way of referring to the novel **CO**rona **VI**rus **D**isease, an upper respiratory infection that was first identified in 2019. The germ that causes it is formally known as SARS-CoV-2.

Droplet Transmission   A form of direct transmission, this is a spray containing large, short-range aerosols (tiny particles suspended in air) produced by sneezing, coughing and/or talking. Droplet transmission occurs – in general and for COVID-19 – when a person is in close contact with someone who has respiratory symptoms. People all spray droplets when they talk or breath, a person does not necessarily have to cough or sneeze, these just propel the droplets further.

Epidemic	A cluster of outbreaks that have spread from one geographical area to others; also see related terms, "pandemic" and "outbreak".
Exposure	Describes the period of time and/or conditions where a person is in contact with an infected person who may or may not display symptoms.
Fomite	An inanimate object that can be the vehicle for transmission of an infectious agent (e.g., bedding, towels, or surgical instruments). There is evidence that the coronavirus spreads via fomites, although, this is a less common route of transmission. (Source: CDC)
Hand hygiene	A key strategy for slowing the spread for COVID-19. Washing hands with soap and water for at least 20 seconds is one of the most important steps to take to protect against COVID-19 and many other diseases.
Herd immunity	When enough people have developed immunity to a particular infectious disease that the risk of further community transmission is either eliminated or significantly reduced.
Immunity	The body's ability to resist or fight off an infection. The immune system is a network of cells and molecules that help avoid and tackle infections and toxic assault.
Immunocompromised	Also called immune-compromised or immuno-deficient describes someone who has an immune system that cannot resist or fight off infections like most people. Can be caused by several illnesses. Some treatments can also cause someone to be immunocompromised.
Incubation period	The amount of time it takes for an infected person to start showing symptoms of illness after exposure. In the case of coronavirus, the incubation period is thought to be between two days and two weeks, with the average being five days before symptoms start to appear.
N95 respirator (facemask)	Personal protective equipment used to protect the wearer from airborne particles and/or liquid contaminating the face.
Pandemic	The worldwide spread of a new contagious disease that has infected a large number of people. WHO declared COVID-19 a pandemic on 11 March 2020. Also, see related terms, "epidemic" and "outbreak".
Personal Protective Equipment (PPE)	Equipment worn to minimize exposure to hazards that could cause illness or injury.
Quarantine	The practice of isolating people who appear healthy, but may have been exposed to a contagious disease, such as COVID-19. Quarantines can be self-imposed or government mandated.

R0/reproductive rate	An epidemiologic metric used to describe the contagiousness or transmissibility of infectious agents, usually estimated with complex mathematical models developed using various sets of assumptions. It is an estimate of the average number of new cases of a disease that each case generates, at a given point in time. R_0 estimates for the virus that causes COVID-19 are around 2 to 3, which is slightly higher than that for seasonal influenza (R_0 ~1.2-1.3), but far lower than more contagious diseases such as measles (R_0 ~12 - 18). (Source: <u>The basic reproduction number (R0) of measles: a systematic review</u>, The Lancet, July 27, 2017.)
Screening	A basic series of questions posed by medical personnel to determine if someone should be tested for a particular disease or condition. In the case of SARS-CoV-2, screening may include taking a temperature, and questions about possible exposure to someone with confirmed or suspected COVID-19.
Self-isolation	The practice of separating someone who is sick from healthy individuals to prevent the spread of disease. Strategies include confining oneself to a single room/bathroom during the recovery period and not going out in public until the risk of transmission has passed.
Self-quarantine	The practice of isolating oneself from others until it is considered safe. In the case of COVID-19, people who suspect they might have been exposed to the virus are advised to self-quarantine for 14-days.
Social distancing	The practice of staying at least six feet (two meters) away from another person, avoiding crowds and gatherings, to reduce the spread of disease.
Super-spreader	A person who, for unknown reasons, can infect an unusually large number of people. Infectious disease specialists say it is common for super-spreaders to play a large role in the transmission of viruses. In what is typically known as the 80/20 rule, 20% of infected patients may drive 80% of transmissions.
Suspected COVID-19	Refers to a patient who is exhibiting COVID-19 symptoms and is currently awaiting test results.
Symptom	Any visible sign of illness that can indicate someone has been infected by a particular pathogen. Typical COVID-19 symptoms are fever, cough and shortness of breath.

TCID50	The concentration at which 50% of the cells are infected when a test tube or well plate upon which cells have been cultured is inoculated with a diluted solution of viral fluid.
Testing	The practice of using blood, urine, saliva, mucus or some other bodily fluid to determine if someone either has a specific condition or has been exposed to a particular infectious disease. In the case of COVID-19, patients typically undergo screening to determine if they need to be tested.
Centers for Disease Control (CDC)	The United States federal health protection organization.
Viral shedding	The period after the virus has replicated in the host and is being emitted.
World Health Organization (WHO)	United Nations organization that monitors and seeks to protect public health around the world.

QUESTION GUIDE FOR SECTION 2.5 INTERVIEWS WITH THE AIRLINE MEMBERS FROM THE HARVARD AVIATION PUBLIC HEALTH INITIATIVE SCIENCE TEAM

We offer these questions to guide our conversations with Airlines. We understand that aggressive efforts are being made to reduce the risk of COVID transmission in air travel. For us to offer opinions on the overall effectiveness of multi-faceted efforts to reduce risk we need to more about both the technical aspects of such things as ventilation and the management aspects passenger and crew compliance.

It would be of immense help to our efforts on behalf of A4A to know more details. We appreciate that procedures may vary by aircraft type, airport and other factors. There may well be a need for follow up discussions and documentation of some of the issues raised in our discussions.

We have organized our questions in the following categories:

1. What efforts are being made to screen passengers and crew members to reduce the probability of having an infectious person on board
   a. COVID testing for crew
   b. Use of health attestations/checklists before reporting for service
   c. Screening of passengers

2. Protocols to reduce transmission by fomite contact including
   a. crew trainings,
   b. Cleaning protocols between flights, overnight
   c. Passenger briefings and monitoring of products they bring to sanitize their areas.
   d. We are interested in know of efficacy testing of these cleaning strategies, if they exit.

3. Policies on wearing masks and protocols to ensure compliance.
   a. Are crew required to wear a mask?
   b. Do you specify the type of mask that crew must wear?
   c. Are passengers required to wear masks?
   d. Do you specify the type of mask that passengers must wear?
   e. Do you restrict masks with exhalation valves?
   f. Is mask wearing included in the preflight safety briefings?
   g. Do you provide masks to passengers that either do not have them or their personal masks are unacceptable?
   h. How is the mask policy monitored and enforced?

4. Boarding and deplaning
   a. Have you modified procedures at the gate area to maintain physical distancing?
   b. How is that working?
   c. Have you modified boarding and deplaning procedures to reduce congestion on Jet Bridge and in the aisle?
   d. What are those procedures and the observations on how well this is working?

e. Do passengers comply?
f. Do you transport passengers from gate to planes parked on the tarmac?
g. Have you modified the occupancy of buses?
h. Do you have transmission risk models for buses?

5. Ventilation of planes on the ground is of critical importance for passengers during boarding, deplaning and for cleaning/service personnel at other times.
    a. What are the current procedures for using ECS while the plan in on the ground?
    b. Do the ECSs on your fleet of aircraft have variable airflow settings? How to your pilots operate the ECSs while in the ground?
    c. We would like to know the performance of APU in terms of 'clean air delivery rates' -- cfm or L/s
    d. Do APUs recirculate air through filters? What is the percent of the supply air is recirculated and what are the filter ratings?
    e. Describe ground air supply systems. What are their capacity to deliver conditioned air? Do they have variable settings? What are your SOPs and have they been modified to increase airflow? Does this air supply bypass the ECS filters?
    f. Are airlines responsible for their jet bridges? Do jet bridges have dedicated supply air?
    g. Has your company measured ventilation rates in jet bridges, buses, on board with APUs, on board with ground air supplies?

6. Protocols for on board incidents
    a. Passengers refusing to wear masks
    b. Passengers (or crew) using unauthorized cleaning agents
    c. Passengers expressing COVID symptoms during travel

SUMMARY OF AIRLINE PRACTICES AT THE TIME OF DATA COLLECTION: INTERVIEWS WITH AIRLINES

[Table to be uploaded later]

APPENDIX E

INFECTIOUS PARTICLES VS. QUANTIA OF INFECTION – THE CASE FOR USING QUANTA

Derivation of Well-Riley Equation from Basic Principles (from Riley & Nardell, 1989)

This definition of infectious dose, being circular, is dissatisfying to those investigators who want a definite number, or even an average number, to apply to human infection, which is certain to be quite variable. However, as has been demonstrated in various models of infection associated with airborne transmission of other diseases (Nardell, 2016), from the host perspective, not all inhaled infectious particles are virulent or settle into alveoli, and not all virulent *M. tuberculosis* reaching the alveoli of the lungs overcome local innate or adaptive immune responses to initiate or sustain infection. While not well-studied, it is believed that only a fraction of airborne (preferentially intercellular) organisms remains viable during the stress of aerosolization, dehydration, and airborne transport, and an even smaller fraction is both viable and remains virulent enough to initiate sustained infection in an immunocompetent host.

If infectious droplet nuclei suspended in the air were evenly distributed, the number of quanta inhaled by susceptibles, N, would be equal to the concentration of quanta in the air times the volume of air breathed by susceptibles. In the steady state, the concentration of quanta would equal Iq/Q: the number of infectors, I, times the rate of production of quanta per infector, q, divided by the volume of fresh or disinfected air into which the quanta are distributed, Q. The volume of air breathed by susceptibles would equal Spt: the number of susceptibles, S, times the pulmonary ventilation per susceptible, Q, times the duration of exposure, t. In the special case where Iqpt/Q = 1, N would equal S, and each susceptible would inhale one quantum of infection. All susceptibles would be infected.

$$N = \text{concentration x volume} = Iq/Q \text{ x } Spt = S(Iqpt/Q) \text{ (1)}$$

In the real world, infectious droplet nuclei are separated by large volumes of uninfected air, often amounting to thousands of cubic feet, and the distribution of infectious particles is more nearly random than even. If Iqpt/Q = 1 and the number of airborne quanta inhaled by susceptibles equaled the number of susceptibles, some susceptibles would escape infection and others would inhale more than one quantum. According to Poisson's law of small chances, the probability of escaping infection in this special case would be approximately e-1 or 0.37, where e is the base of natural logarithms with a value of approximately 2.7. The probability of acquiring infection would be (l-e^{-1}) or 0.63, and the total number of infections would be S(I- e^{-1}). Thus, in this

special case where $Iqpt/Q = 1$, 63% of susceptibles would be infected with random distribution as opposed to 100% with an even distribution.

The general expression, based on these physical relationships, is:

$$C = S(1 - e^{-Iqpt/Q}) \quad (2)$$

where C = number of new infections or cases. In this expression, the exponent, $Iqpt/Q$, represents the degree or intensity of exposure to infection and $(1 - e^{-Iqpt/Q})$ represents the probability of infection.

The ability to estimate q has been a useful addition to the understanding of airborne infection and the role of air disinfection. To determine q, one must first estimate Q, the amount of ventilation with fresh (non-recirculated) air. Even in buildings with central air conditioning, fresh air ventilation may be difficult to ascertain. Accurate measurement of carbon dioxide (CO_2) concentration obviates this difficulty because Q is the amount of fresh air required to dilute the CO_2 added by room occupants to the measured concentration. A correlation for CO_2 from nonhuman sources is made by turning the meter to zero at the level of CO_2 in outdoor air. The amount added indoors is then:

$$nV_{CO_2}/Q = F_{CO_2} \quad (3)$$

$$Q = nV_{CO_2}/F_{CO_2} \quad (4)$$

where n = number of room occupants; V_{CO_2} = estimated CO_2 output per occupant per unit time (about 0.4 L/min for office workers); Q = fresh air ventilation in volume per unit time per occupant (1 cubic foot per minute [cfm] = 28.3 liter per minute [l pm]); F_{CO_2} = fractional concentration of CO_2 in indoor air as measured.

Equation (4) is comparable in principle to the alveolar ventilation equation, where alveolar ventilation, VA (analogous to Q), equals CO_2 production, V_{CO_2}, divided by the fractional concentration of CO_2 in alveolar gas, FA_{CO_2}.

Adequate ventilation (minimum for comfort purposes) is 15 cfm per occupant and corresponds approximately to a fractional concentration of CO_2 of 0.001 or 1,000 ppm: $(1 \times 0.4)/(15 \times 28.3) = 0.00094$. Results should be interpreted with care because of possible errors in the estimate of CO_2 output per occupant and CO_2 from nonhuman sources; the latter can be an important source of error if there are nonhuman sources of CO_2 indoors.

When Q is known (equation (4), q can be calculated from the basic equation of airborne infection (equation (2). Equation (2) was first used in analyzing successive generations of a measles epidemic. Day-to-day variations in school ventilation were taken into account as well as

infectious exposures out of school. In the simple form presented above, there is the implicit assumption that all variables in the exponent (I, q, p, t, and Q) remain constant during the period of exposure. This is not true for Q because in air-conditioned buildings, the amount of air recirculated is related to changing outdoor temperatures and it is not true for q, which depends on the frequency of coughing and the concentration of infectious organisms in respiratory secretions. Calculations based on the assumption of constant conditions, including those that follow, are no more than approximations.

The few values of q reported in the literature range from 1.25 quanta per hour (qph) in tuberculosis patients receiving chemotherapy (Riley and Mills, 1962) to 13 qph in a tuberculosis case who infected 27 of 67 co-workers in an office building (Nardell et al., 1991) to 60 qph in a case of laryngeal tuberculosis to 249 qph during intubation and bronchoscopy of a tuberculosis patient (Cantazaro, 1982). For comparison, the measles case that started an epidemic in a school produced an estimated 5,480qph (Riley and Murphy, 1978). These values reflect the enormous range of q observed in different patients and different diseases.