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Original Research

Airflow Characteristics in Aeromedical Aircraft: Considerations During COVID-19

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A B S T R A C T

Objective: The aeromedical transport of coronavirus patients presents risks to clinicians and aircrew. Patient positioning and physical barriers may provide additional protection during flight. This paper describes airflow testing undertaken on fixed wing and rotary wing aeromedical aircraft.

Methods: Airflow testing was undertaken on a stationary Hawker Beechcraft B200C and Leonardo Augusta Westland 139. Airflow was simulated using a Trainer 101 (MSS Professional A/S, Odense Sø, Syddanmark, Denmark) Smoke machine. Different cabin configurations were used along with variations in heating, cooling, and ventilation systems.

Results: For the Hawker Beechcraft B200C, smoke generated within the forward section of the cabin was observed to fill the cabin to a fluid boundary located in-line with the forward edge of the cargo door. With the curtain closed, smoke was only observed to enter the cockpit in very small quantities. For the Leonardo AW139, smoke generated within the cabin was observed to expand to fill the cabin evenly before dissipating. With the curtain closed, smoke was observed to enter the cockpit only in small quantities

Conclusion: The use of physical barriers in fixed wing and rotary wing aeromedical aircraft provides some protection to aircrew. Optimal positioning of the patient is on the aft stretcher on the Beechcraft B200C and on a laterally orientated stretcher on the AW139. The results provide a baseline for further investigation into methods to protect aircrew during the coronavirus pandemic.

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Background

The coronavirus pandemic has had an unprecedented impact on service provision across many areas of health care. The learning curve related to the prehospital management of suspected and confirmed coronavirus disease 2019 (COVID-19) cases has been steep, with many aspects of clinical practice still being refined. The unique challenges of air medical transport[1,2] have been magnified in the current climate.[3,4]

The aeromedical transport of COVID-19 patients presents risks to clinicians and aircrew because of the proximity to patients and exposure to aerosolized particles. Not only do aeromedical providers need

to consider how to manage surge capacity[5] related to COVID-19, but they also need to determine how to safely transport patients in both pressurized and nonpressurized aircraft.

Key strategies for the safe and effective transport of COVID-19 patients include the selection of appropriate patients for transport,[6] minimizing the use of aerosol-generating procedures (AGPs), and ensuring the correct use of personal protective equipment (PPE).[3,7] Despite some consensus on PPE guidelines,[8-10] the use of these guidelines is challenging for clinicians and aircrew in both rotary and fixed wing aircraft. The COVID PPE and patient transfer guidelines used by Air Ambulance Victoria are summarized in Tables 1 and 2.[11]

The use of PPE must provide protection against contact, droplet, and airborne transmission.[12] The correct level of PPE is determined by the risk and type of exposure, and donning and doffing procedures

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Table 1
Air Ambulance Victoria Coronavirus Disease 2019 (COVID-19) Personal Protective Equipment (PPE) Requirements

PPE for every patient contact	Potential or confirmed COVID-19 case, aerosol-generating procedure (AGP) or aerosol-generating behavior	For staff assisting with patient loading, unloading, and aircraft decontamination	For nonclinical aircrew (fixed wing)	For nonclinical aircrew (rotary wing)
Nitrile gloves Protective eyewear P2/N95 face mask Face shield if splash risk from bodily fluids Surgical mask applied to patient and any patient escort	Addition of protective outer garment (long-sleeved disposable gown or Tyvek suit, DuPont, Macquarie Park, New South Wales, Australia)	Nitrile gloves Protective eyewear P2/N95 face mask Protective outer garment (long-sleeved disposable gown or Tyvek suit) Surgical mask applied to patient	BE200C: Standard COVID-19 PPE if assisting with loading or patient care Gloves worn exiting aircraft Cockpit curtain closed during flight P2 mask only to be worn in cockpit if AGP during flight	AW139: Standard COVID-19 PPE if assisting with loading or patient care Cockpit curtain closed during flight P2 mask only to be worn in cockpit if AGP during flight

need to be followed.[13] Additional strategies to minimize the exposure of pilots and aircrew must be considered to ensure that patient transfers can be performed safely.[3,14,15]

Patient isolation may be possible in different aircraft types[16]; however, portable isolation units are expensive, may require reconfiguration of existing aircraft layouts, and have limitations such as patient access and restraint.[17] Alternatively, the use of barriers such as screens or curtains may provide some level of protection for personnel positioned in the cockpit, and their effectiveness is reliant on airflow and the movement of airborne particles within the aircraft. Despite recommendations for patient positioning based on airflow[18] and previous reporting of airflow rates in fixed and rotary wing aircraft,[15] testing designed to observe air movement in aeromedical aircraft had not been published at the time of writing.

This report describes airflow testing that was undertaken on the Hawker Beechcraft B200C fixed wing aircraft and the Leonardo AW139 rotary wing aircraft. The intent of the testing was to determine the safest positioning of clinicians and actual or suspected COVID-19 patients during flight. The testing also aimed to assess the risk of exposure to aircrew seated in the cockpit of each aircraft type.

Methods

The methodology used to test and observe cabin airflow in the two aircraft types differed because of configuration and functionality. The methods for each aircraft will be outlined separately.

Table 2
The Procedure for Aircraft Retrieval at Air Ambulance Victoria of Suspected Coronavirus Disease 2019 Patients: Fixed Wing and Rotary Wing Aircraft

- A mobile intensive care ambulance flight paramedic or flight paramedic at Essendon must be appointed to assist the landing crew and coordinate all other personnel, ensuring appropriate PPE is worn.
- A trolley with PPE and cleaning equipment should be positioned in the respective hangar.
- The aircraft is to be towed into the hangar nose first, except for HEMS, which is positioned tail first.
- The road ambulance is to be positioned outside the hangar ensuring that beacons are on.
- The FCC is to announce via PA that we are currently unloading a patient in the hangar.
- Unload patient from aircraft using current procedures.
- Load road ambulance as per normal procedures.
- FCC to announce via PA that patient now departed from hangar.
- Aircraft to be cleaned as per respective procedures.
- PPE to be doffed within the hangar and placed into an infectious waste bag and then placed into infectious waste bin.
- Hand hygiene to be observed during the doffing procedure and before entry into main building.
- FCC to be advised as soon as possible that the aircraft is again operational.

FCC = flight coordination center; PPE = personal protective equipment.

Hawker Beechcraft B200C

Testing was completed in a stationary aircraft on the airfield apron at Essendon Airport, Melbourne, Victoria, Australia, on April 23, 2020. Testing of the Beechcraft was conducted over two sessions on April 23, 2020, between 12:11 PM and 3:16 PM. The outside temperature was recorded as 20°C, and the cabin temperature was recorded as 19°C.

One person was seated in the cockpit, and three people were positioned within the cabin for each test. Each person observed and reported on the flow and movement of smoke in the aircraft during the phases of testing.

The aeromedical fit out of the subject aircraft consisted of two stretchers (a forward left-hand and an aft right-hand stretcher), 3 medical seats, and associated medical supply systems and components. The aircraft is fitted with an optional Keith Dual Zone Air-Conditioning System (Air Comm Corporation, Westminster, Colorado, USA). This system distributes pressurised air from each engine to the fuselage through the wings via an air-to-air heat exchanger. The air is then directed to a mixing plenum for either distribution to the lower heating outlets or through the evaporators, to the cockpit or the cabin.

Testing included the simulation of phases of flight, the generation of smoke from different locations, and the manipulation of the cabin airflow variables to identify measures that may reduce the risk of transmission to the cockpit. Ground simulation of flight conditions included the following parameters: cabin pressurization, cabin heating, cabin cooling, and ambient environmental temperature. A Trainer 101 Smoke machine was used to simulate the flow of small-particle aerosols. The smoke generator properties are outlined in Table 3.

The aircraft engines and environmental control system were started to provide bleed air and power to the environmental control system. The cockpit and cabin temperature were set to approximately 21°C, being the default position for aeromedical operations in this aircraft.

Table 3
Smoke Specifications

(a) Item	(b) Parameter
(c) Smoke output	(d) Approximately 65 m³/min (e) 2,295 ft³/min
(f) Fluid consumption	(g) 10 mL/min
(h) Heat exchanger	(i) 400 W
(j) Fluid composition	(k) Monopropylene glycol (l) Triethylene glycol (m) Demineralized water (60+%)
(n) Fluid boiling point	(o) 101.6°C-201.6°C
(p) Fluid flash point	(q) > 78°C
(r) Vapor pressure	(s) 2.67 kPa (at 20°C)
(t) Vapor density	(u) 3.9
(v) Relative density	(w) 1.050 at (20°C)

Four states of pressurization were simulated during testing: unpressurized, increasing cabin pressure, steady cabin pressure, and decreasing cabin pressure. Manual override was used to achieve and maintain a maximum pressure differential of approximately 0.7 psi.

Two overhead cockpit cooling outlets and the cabin overhead outlets were adjusted during testing to determine their effects on airflow. Tested configurations consisted of the following: 1) all outlets open; 2) all cockpit outlets closed and all cabin outlets open; 3) all cockpit outlets open and all cabin outlets closed; 4) all cockpit outlets open, forward outlets open and facing aft, and aft outlets closed; and 5) all outlets closed.

When open, the overhead cooling outlets were set to a neutral downward-facing, fully open position. The position of the cockpit curtain was used to assess the effect on cabin airflow. The curtain material consisted of a perforated fabric with gaps of up to 10 mm above and around the perimeter of the opening. The curtain was either in a fully open or fully closed position.

Smoke generation was conducted from three locations: 1) at the approximate location of a patient's head while on the forward stretchers, 2) at the approximate location of a patient's head while on the aft stretcher, and 3) at a central location between the forward and aft locations. Smoke was generated from the backrest in the horizontal plane and at 48° from the vertical plane. Smoke was also generated in various orientations to simulate a patient facing forward, aft, and vertically.

Leonardo AW139

Ground testing was performed on the AW139 to simulate airflow and small-particle aerosol movement during flight. Two testing sessions were undertaken on May 4 and 5, 2020, from 11:39 AM to 12:13 PM and 8:50 AM to 9:18 AM, respectively. Testing was conducted in a stationary aircraft located in a hangar at Essendon Airport. Testing was undertaken with the hangar doors open and ground power supplied to the aircraft. The ambient temperature was recorded between 10°C and 13°C throughout testing. Four personnel were present during the first test and three during the second test. During each test, two people were situated in the cockpit, and the remainder were positioned in the cabin.

The aeromedical fit out of the helicopter consisted of a lateral stretcher positioned in the aft of the cabin, 2 aft-facing medical seats, a medical cabinet, medical stowage in the aft tunnel, and associated medical supply systems and components. A secondary configuration was tested with the 2 seats removed and a longitudinally orientated stretcher.

The aircraft used for testing was fitted with original equipment manufacturer air-conditioning and heating systems, as well as standard bleed air and ventilation systems. The cockpit featured four outlets located on the instrument panel (two on each side) supplied by the cockpit ventilation. The cabin featured twelve overhead outlets, with 4 located forward, four in the center, and four in an aft location. During testing, the cockpit and cabin ventilation fans were set in either the OFF, LOW or HIGH position. The air conditioning was set to OFF or to the RECYCLE function for tests with recirculation of air.

A cockpit bulkhead and enlarged night vision imaging system blackout curtain were fitted in the aircraft. The bulkhead featured a near airtight seal, with small air gaps between the bulkhead's edge and the cabin trim ranging from 3 to 10 mm.

The same Trainer 101 Smoke Machine was used in the AW139 trials. Smoke generation was conducted from two locations: 1) at the approximate location of a patient's head while on the aft stretcher and 2) at the approximate location of a patient's head while on the longitudinal stretcher.

Results

Hawker Beechcraft B200C

During testing, it was observed that smoke generated within the forward section of the cabin would first fill the cabin to a fluid boundary located in-line with the forward edge of the cargo door. The smoke would then proceed to flow forward into the cockpit and then be drawn toward the right-hand cockpit footwell and into the forward recirculation blower (Fig. 1). Smoke generated from the aft position would generally remain aft of the fluid boundary until it dissipated. With the curtain open, any smoke generated would equally fill the forward cabin and cockpit before being drawn to the right-hand cockpit footwell.

The most dramatic change to the cabin's mass airflow behavior was observed when the cockpit curtain was closed (Fig. 2). With the curtain closed, smoke was only observed to enter the cockpit in very small quantities, predominantly in the gap between the curtain and the headliner.

Immediately after the starting of the engine and activation of the environmental control system, a general flow of the smoke was observed to travel toward the rear of the aircraft. This was likely caused by the initial phase of heating the cabin air. By the third smoke test, completed 6 minutes after engine start-up, a clear trend of airflow toward the cockpit was observed.

No appreciable difference in the mass airflow behavior was observed between unpressurized and simulated cruise conditions. Smoke that passed through the air flow from the overhead outlets was observed to only be disturbed locally. No change was seen in the mass airflow behavior. When the aircraft engines and environmental system were shut down, smoke was observed to take longer to dissipate than in any other tests.

The orientation of the smoke generation from various backrest heights and positions resulted in initial local variations to the smoke propagations before conforming to the cabin's mass airflow. Smoke
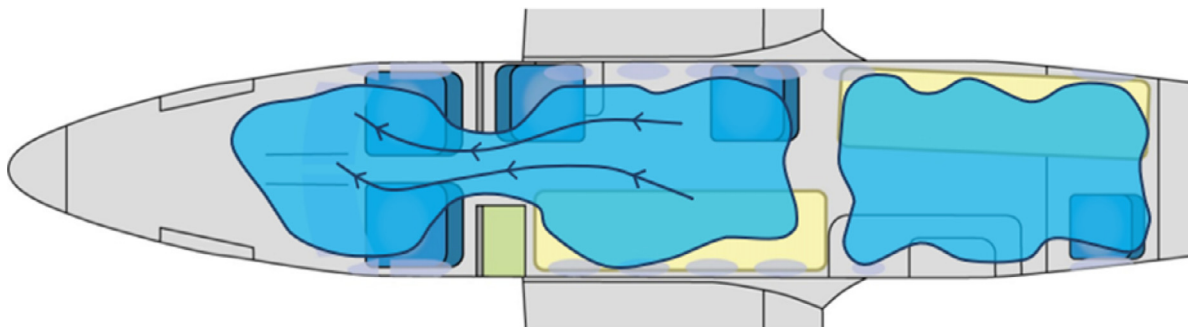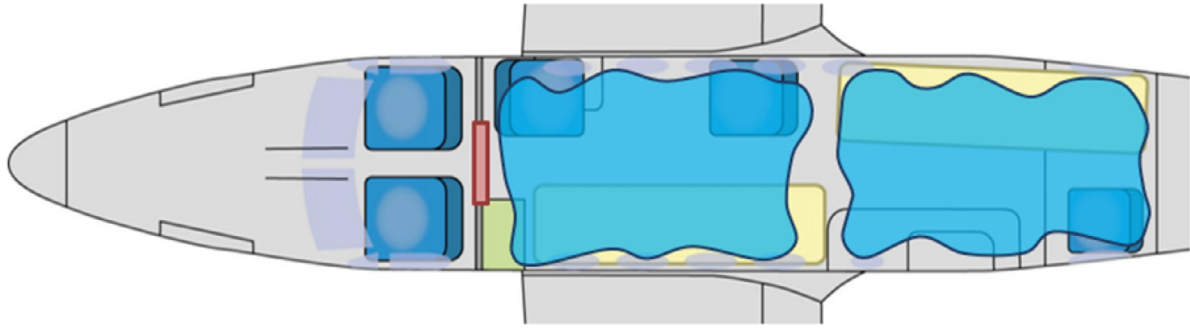

Figure 1. The flow of generated smoke with the curtain open in the Beechcraft B200C.

Figure 2. The flow of generated smoke with the curtain closed in the Beechcraft B200C.

generated from halfway between the forward and aft positions was observed to split into forward and aft main volumes across the fluid boundary and then continue to behave as smoke generated from either the forward or aft positions, respectively.

Leonardo AW139

Smoke generated from various locations within the cabin, including a forward position on the longitudinal stretcher and from the lateral stretcher, was observed to expand to fill the cabin evenly before dissipating. Smoke was observed to remain within the cabin over 3.5 minutes with the cabin ventilation off and the cockpit curtain raised.

As with the Beechcraft B200C, a dramatic change to the cabin's mass airflow behavior was observed when the cockpit curtain was opened. With the curtain open, smoke would equalize between the cockpit and cabin (Fig. 3).

With the curtain closed, smoke generated in otherwise identical conditions was observed to enter the cockpit only in small quantities. This occurred predominantly through the largest gap in between the bulkhead and the left-hand trim. With positive pressure in the cockpit from the ventilation system, no smoke was observed to enter the cockpit past the bulkhead and curtain (Fig. 4). With lower ventilation settings, it was observed that airflow was less turbulent and resulted in the smoke spread being slower than with higher settings.

The overhead cabin outlets were observed to move smoke from the upper cabin downward and accelerate the spreading smoke throughout the cabin. Smoke generated from the forward position was observed to spread to the aft section and filled the cabin volume quicker than when smoke was generated in the aft position.

Discussion

COVID-19 can be spread via direct droplet and airborne transmission.[12] It has been reported that droplet spread of the disease can occur when fluid particles greater than 5 μm directly contact a person but that microscopic aerosol particles can also be inhaled when droplets < 5 μm remain airborne for longer durations.[19] COVID-19 may be detected in aerosols for up to three hours,[10] and a high percentage of aerosols have been reported to be deposited on surfaces close to the expiratory source in aircraft cabins.[20] These points reinforce the risks to aircrew[21,22] working in the confines of aeromedical aircraft.

There are limitations of the testing that must be considered. All testing was conducted while the aircraft were stationary on the ground, and the nature of airflow while at altitude would need to be studied further to definitively report on dynamics during flight. The use of smoke as a medium for testing, the environmental control systems on both aircraft types, and varying aircraft configurations warrant discussion.

The characteristics of the smoke generated during testing are important because a direct comparison with the characteristics of COVID-19 movement and transmission is difficult.[23] The use and type of smoke as a medium for testing has limitations[24-26] but has been used to simulate airflow around oxygen masks[27] and air escape in hospital isolation rooms[28] and to estimate the pattern of movement of aerosolized particles.[26] Computational fluid dynamics modeling has been used to simulate aircraft cabin airflow,[29] but such a method was beyond the scope of this testing. Smoke was selected for this testing for several reasons. A primary aim of the testing was to assess the movement of small-particle aerosols entering the cockpit and exposing flight crew who are unable to wear full PPE. Using smoke to demonstrate small-particle movement was deemed more appropriate for this reason. Also, smoke is highly visible, easily
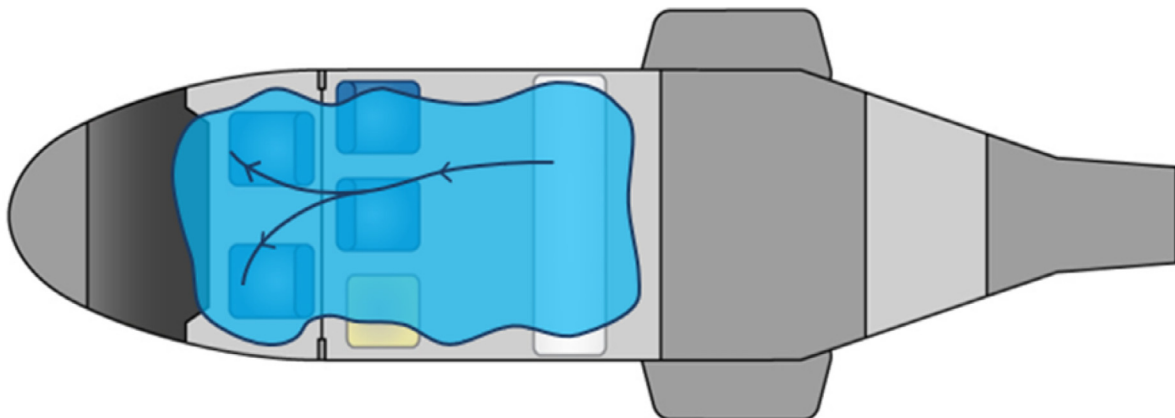
Figure 3. The flow of generated smoke with the curtain open in the AW139.
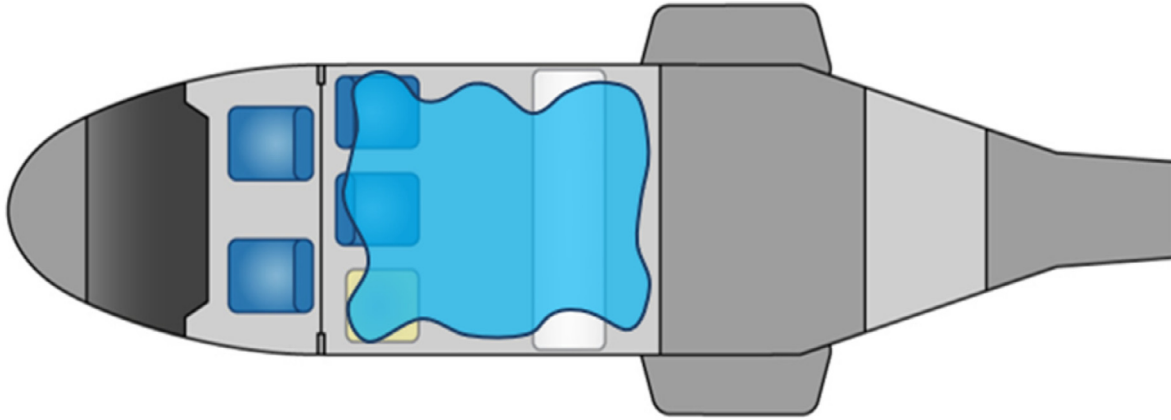
Figure 4. The flow of generated smoke with the curtain closed in the AW139.

generated, and able to visually demonstrate air movement throughout the cabin and cockpit. The smoke medium used for testing had a relative density of 1.050, being slightly denser than the surrounding air and is designed for longevity of visibility. This density resulted in the smoke gradually sinking to the cabin floor before dissipating.

The outside temperature was relatively constant during testing, and greater variations would be expected during flight in both aircraft types. There may be variation in the extent of heating and cooling regulated by the automated systems during flight. During flight, cabin temperatures are more stable, and the effect of the air circulation will be greatest because the cabin environmental control systems will be operational. Testing was completed within closed-cabin environments such that no wind would affect results, and external air-conditioning would have a negligible effect. In addition, a maximum pressure differential of 0.7 psi was achieved during Beechcraft testing compared with a pressure differential of 6.5 ± 0.1 psi, which can be encountered during flight. This pressure differential was deemed to be sufficient to measure the effects on the airflow characteristics during pressurization and depressurization cycles.

The Keith Dual Zone Air-Conditioning system differs between Beechcraft Kingair 200 and Beechcraft Kingair 300 aircraft models. The main difference between models is the method of temperature control. The more recent systems incorporate a computer to control the cockpit and cabin separately via sensors in the ceiling and ducts and servo valves in the mixing plenums and by directly controlling bleed air pass valves in the wings and the vapor cycle compressor/condenser blower. The older system manages temperature with thermistors, bridge balance circuits, valve position switches, and a temperature selector rheostat. Both models generate similar mass airflow in the cabin and cockpit. On all models, pressurized warm air is distributed at floor-level outlets, and cool air is distributed below the glare shield in the cockpit and at the ceiling level in the cabin. On all models, air exits the cabin via the same outflow locations at various phases of flight and ground testing undertaken in this study aimed to replicate these phases of flight.

In rotary wing aircraft, or any unpressurized aircraft, the ambient air temperature and cabin pressure at normal cruise altitudes are typically less than at the surface level, and these conditions were not able to be replicated during the ground testing of the AW139. Cabin temperatures will be subject to variation (cold winter vs. hot summer), but this variation will be greatest when on ground during patient loading and unloading. During flight, cabin temperatures in rotary wing aircraft are more stable, and this is where the effect of the air circulation will be greatest because the cabin environmental control systems will be operational.

Droplet movement, as well as virus survival in aerosols,[30] may be affected by changes in pressure, altitude, temperature, and humidity.

Testing did not replicate the lower outside air pressure and temperatures from increased altitude where these variations may influence airflow because of saturation and convection. Typically, in Victoria, Australia, the cruising altitudes of rotary wing aircraft would not be expected to have a significant impact on the test results.

During testing of the AW139, the aircraft engines were not operated, and heating system and air-conditioning functionality was not included. The effect on cabin airflow caused by heated air being supplied to the cabin and cockpit floor-level outlets was not tested nor was the effect of supplying the cockpit outlets and cabin overhead outlets with cooled air. AW139 testing was conducted using fan-forced air at different settings in the cockpit and cabin outlets.

The AW139 ventilation, heating, and air-conditioning systems can be operated with either ram air or fan-forced air. Stationary testing excluded the use of ram air, but ram air characteristics would be similar to fan-forced characteristics in flight. Differences in fan-forced airflow when the aircraft is stationary or in flight would not be significant unless a cockpit window or cabin door is open. For normal interhospital transport operations, the cockpit window and cabin door would be closed. The testing conducted on the AW139 was intended to reflect air circulation during a typical flight environment, and the results obtained are reflective of this.

Based on the results of this testing, ventilation system settings in the AW139 can be used to generate airflow from the cockpit into the cabin to reduce cabin air entering the cockpit. Positive cockpit pressure can be generated using one of the following ventilation system configurations: 1) cockpit ventilation low and cabin ventilation off and 2) cockpit ventilation high and cabin ventilation low. The air-conditioning recirculation setting should be avoided because smoke was observed to linger for extended periods in the cabin when this setting was used.

Stretcher configurations of both aircraft types used in testing were not reflective of all stretcher configurations available to other aeromedical operations; however, they are reflective of the normal operations of Air Ambulance Victoria aircraft and the transport of actual or suspected COVID-19 cases. The results of this testing are specific to the configurations as described and may vary depending on the number and orientation of stretchers in other aircraft types.

Because of the tendency for airflow generated from the forward stretcher in the Beechcraft B200C to flow toward the cockpit, it is recommended that patients requiring AGPs or demonstrating aerosol-generating behaviors be transported on the aft stretcher. In the AW139, it is suggested that patients requiring AGPs should be transported on the stretcher in the lateral orientation rather than north-south orientations relative to the aircraft.

Importantly, the tests conducted and observations made cannot be used as definitive evidence that the cockpit curtain in the

Beechcraft and night vision imaging system screen in the AW139 provide high levels of protection against COVID-19. Awareness of the limitations of protection provided by the cabin curtain in the Beechcraft is important, and further investigation into alternative barrier material may be useful. Consideration should be given to removing or minimizing the gaps between the bulkhead and the surrounding trim of the cabin curtain in the AW139 to reduce the potential for aerosol movement into the cockpit.

The observations made during airflow testing on both the Beechcraft 200C and Leonardo AW139 aircraft provide insight into the effectiveness of physical barriers in protecting nonclinical aircrew. The results may assist clinicians with the positioning of patients in flight to minimize the risk of COVID-19 exposure. The safe and wise approach to the aeromedical transfer of confirmed or suspected COVID-19 patients in our current climate is to strictly adhere to accepted safety guidelines and infection control procedures.[7,13,31]

Conclusion

The safe management and transport of COVID-19 patients requires the use of appropriate PPE in combination with practical distancing measures applicable to various transport platforms. This report describes airflow testing procedures undertaken in fixed wing and rotary wing aircraft designed to assess the efficacy of physical barriers and patient positioning during flight.

Observations from the airflow testing undertaken reinforce that physical barriers between the cockpit and the cabin of both the Beechcraft B200C and Leonardo AW139 provide a degree of protection for nonclinical aircrew. The diligent use of these measures, in addition to the stringent and disciplined use of PPE, provide a degree of safety for staff engaged in the aeromedical transport of COVID-19 patients. The results of this airflow testing provide a baseline for further investigation into practical measures that can be adopted to enhance the safety of aircrew against infective aerosolized particles.

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