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Review Article

Safety and Flight Considerations for Mechanical Circulatory Support Devices During Air Medical Transport and Evacuation: A Systematic Narrative Review of the Literature

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A B S T R A C T

Objective: The air medical transportation industry has seen a steady rise in the use of mechanical circulatory support devices (eg, intra-aortic balloon pumps, ventricular assist devices, and extracorporeal membrane oxygenation) during transport missions, either for definitive management or repatriation. As these complex devices become more common, the industry will have to adapt to support their use in their clientele. The goal of this narrative review was to assess our current experiences regarding mechanical circulatory support devices in air medical transportation and to identify important factors to ensure successful transport.
Methods: We conducted a systematic search on MEDLINE and Embase using the following search terms: aeromedical transportation, air transportation, intra-aortic balloon pump, ventricular assist device, and extracorporeal membrane oxygenation. Results were cross-referenced to identify articles addressing both air medical transport and mechanical circulatory support devices.
Results: After a systematic review of the available literature, 49 articles addressing mechanical support devices transported by rotary wing and fixed wing aircraft were reviewed. In summary, our review encompassed 811 total aerial transports (152 by balloon pumps, 12 by ventricular assist devices, and 647 by extracorporeal membrane oxygenation). We found air medical transportation with these devices carried out in the public, private, or military sectors, to be safe, with low rates of serious adverse events. Dedicated training sessions focused on device troubleshooting and problem-solving during transport, optimal medical crew composition, predeparture logistical preparations, and on-demand specialist consultation can improve mission success.
Conclusion: We report that air medical transportation of patients supported by mechanical circulatory support devices is safe. Complications can be mitigated by training and addressed either during the predeparture or in-transportation phase.

The air medical transport world has seen a steady rise in the use of mechanical circulatory support devices (MCSDs) as a treatment modality for refractory circulatory collapse and/or respiratory failure. MCSDsrange from an intra-aortic balloon pump (IABP) and extracorporeal membrane oxygenation (ECMO) to paracorporeal and microaxial ventricular assist devices (VADs).[1] The choice of MCSDs depends not only on the patient's pathophysiologic derangements but also on several technical factors such as maintenance complexity, circulatory support and oxygenation capabilities. With increasing experience and high-quality evidence of efficacy, such as peritransplantation support, their use has increased in many clinical settings.[1] Technological advances have led to a decrease in size and an increase in the portability of these MCSDs, facilitating interfacility transport over long distances.

Global travel for tourism or business has become more common as air travel has become more affordable and accessible to the general population. The average age and medical comorbidities of current travelers have been steadily increasing.[2] Most people are able to

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complete their travels without complications; it was estimated that only less than 0.5% of travelers require air medical evacuation.[3] Nevertheless, with the increase in global movement, more patients are hospitalized in countries distant from their country of origin. Medical hospitalization and necessity for air medical evacuation during a trip have led to a growing industry in medical evacuation.[4]

The combination of global population movement and the increasing use of MCSDs in critical illness has led to an increasing number of patients who potentially require repatriation to their home country while being supported with an MCSD. In addition, the complexity of MCSD operation has led to the creation of tertiary care hubs where MCSD-supported patients are being concentrated, additionally increasing the need for transport to those hubs. In this narrative review of the literature, we focus on pretransport considerations, safety, and potential complications of MCSDs during air medical transportation.

Methods

We conducted a systematic search in MEDLINE and Embase using the following search terms: aeromedical transportation, air transportation, intra-aortic balloon pump, ventricular assist device, and extracorporeal membrane oxygenation. The results were cross-referenced to identify articles addressing both air medical transport and MCSDs (Fig. 1).

A total of 388 articles were identified in MEDLINE: 60 articles on IABPs, 73 articles on VADs, and 255 articles on ECMO and air transport. In Embase, a total of 675 articles were identified: 40 articles on IABPs, 231 articles on VADs, and 404 articles on ECMO and air transport. A total of 1,063 articles were found; 241 duplicate articles were removed.

The abstracts of the articles were reviewed for relevance to air transport, rotary wing (helicopter) or fixed wing aircraft. Articles were included in this review if the topic focused on long-distance medical air transport with patients on MCSDs. Seven hundred seventy-three articles were excluded. Articles were excluded if they did not have a focus on transport experience in mechanical support, if the full-text article was not available in the English or French language, or if the full text was not available or the articles were conference abstracts.

Forty-nine articles addressing case reports or case series on air medical transport experience were kept for review. Twenty-five articles involved ECMO. Twenty articles described transport using VADs. Four articles described transport using IABPs. Articles reporting larger numbers of patient transport were given priority for discussion (Table 2).

Results

IABPs

The IABP is a percutaneous device inserted by the Seldinger technique usually via the femoral artery and advanced until its tip is distal to the left subclavian artery. In this position, the IABP consists of a helium-filled balloon operating with electrocardiographic or pressure-gated counterpulsations, reducing afterload and increasing coronary perfusion. The main indications for IABP counterpulsation are refractory angina, mechanical complications of myocardial infarction, refractory heart failure, and peripercutaneous coronary intervention for acute coronary syndromes.[5] Despite its long history of use, there were limited reported experiences addressing IABP air transport in the literature.

A case series described the successful transport of 38 patients on IABP support by helicopter aircraft in Switzerland by the Swiss Air-Rescue (Rega) service between September 2008 and October 2010.[6] The team reported no major adverse events resulting in successful discharge of 30 of the 38 patients. The helicopter was equipped with its own IABP module, and upon patient loading onto the aircraft, connections were switched from the hospital module to the helicopter module. The medical crew consisted of 2 physicians (1 anesthesiologist and 1 prehospital emergency physician) supplemented by a certified perfusionist.

A second report described an Australian experience of the Ambulance Service of New South Wales with transporting 22 IABP-supported patients between May 2007 and December 2009; 7 patients

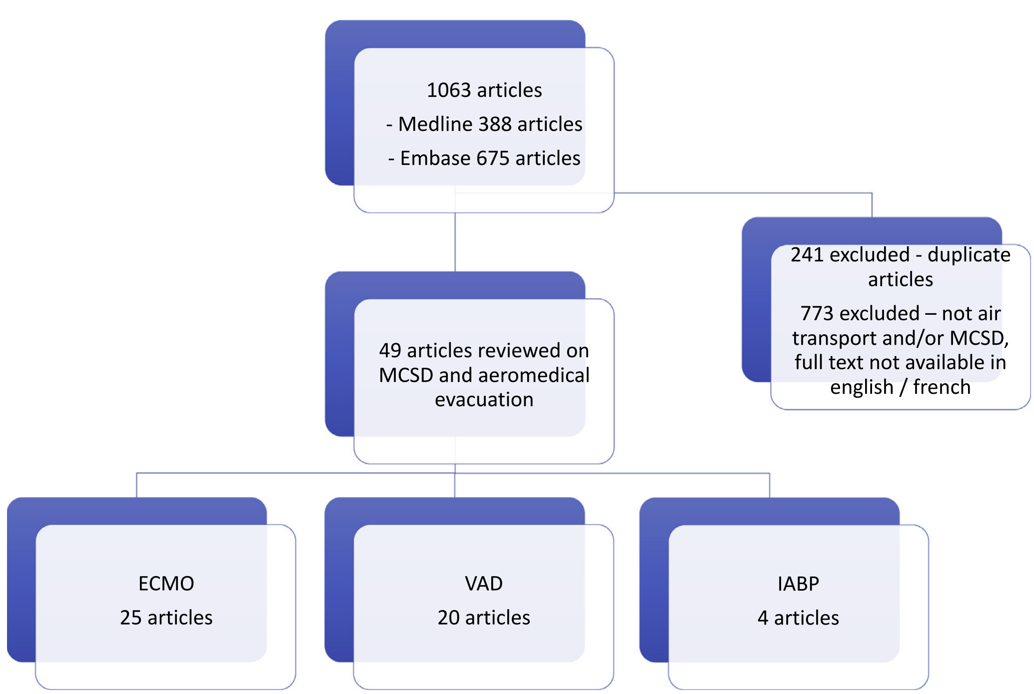

Figure 1. A systematic review of articles describing mechanical circulatory support devices and air medical transportation.

were transported by helicopters. In this case, the medical crew consisted of a physician and a critical care paramedic; the service performed hospital-to-hospital transfers within the Greater Sydney area. They reported 4 complications during transfer: 1 episode of malignant arrhythmia treated successfully with defibrillation, 1 case of bleeding at the insertion site, and 2 cases of hypotension. There were no reported in-flight mortalities.[7]

Sinclair and Werman[8] reported successful transports of IABP-supported patients by MedFlight (Columbus, OH), a regional critical care transport service, between January 1, 2004, and December 31, 2005. Among the 173 patients, 71 were flown by rotary wing aircraft and 36 by fixed wing aircraft; the rest were transported by ground. Their transport vehicles were staffed with critical care nurses and paramedics without physician presence. They reported no major complications during transport. Of the 173 patients, 20 had abnormalities with balloon inflation or deflation timing but no clinical deterioration. The authors attributed the success of their operations to hands-on, high-quality, and continuous training of crewmembers with the operation of IABP and the availability of real-time consultation with a perfusionist before and during transport.

VADs

VADs are a heterogeneous group of MCSDs used to support patients in heart failure or cardiogenic shock. VADs can be implanted surgically or percutaneously.[9] They provide permanent or temporary support to the left and/or right ventricle and can offer patients variable mobility. Among the percutaneously implanted VADs, the Impella left ventricular assist device (LVAD) (AbioMed Inc, Danvers, MA), which can be implanted via the subclavian artery, provides a unique ability to mobilize the patient. Several long-term VADs can also offer patients full mobility and rehabilitation, improving quality of life.[10] Several case reports and case series describe the air transport of VADs, more so in the pediatric than the adult population.

McLean et al[11] reported the successful transport of a 47-year-old man supported by a Levitronix (Zurich, Switzerland) Centrimag biventricular assist device (BiVAD) as bridge to cardiac transplantation from Cambridge, UK, to Durham, NC, by a Gulfstream III fixed wing aircraft. The medical crew consisted of a cardiac surgeon, a perfusionist, and a respiratory therapist. The patient experienced a decrease in BiVAD flow during aircraft ascent and an increase in flow during aircraft descent because the patient was positioned with the head facing forward. This was most likely caused by intravascular fluid shifts and a transient change in venous return when exposed to g-forces during acceleration and deceleration.

Potapov et al[12] reported a successful transcontinental repatriation of a 59-year-old man on an AbioMed BVS 5000 BiVAD from Singapore to Berlin, Germany, by the Swiss Air Rescue company via Canadair Challenger 604. The flight duration was 19 hours, including 1 stopover. Of note, multiple units of packed red blood cells and fresh frozen plasma, stored in the aircraft's 4°C refrigerator, were transfused to mitigate a continuous bleed from the patient's chest tube.

Griffith and Jenkins[13] reported their experience transporting 2 patients on Impella 2.5 devices by helicopter over 56- and 100-mile distances without complications. The medical crew consisted of 2 flight nurses and a perfusionist.

Haddad et al[14] reported the case of a 26-year-old man on Novacor (Oakland, CA) LVAD support transported by a commercial flight from Tokyo, Japan, to Ottawa, Canada, with the escort of a registered nurse, a senior LVAD operator, and a perfusionist without complications.

Another report by McBride et al[15] presented local experiences from Saint Louis University Health Sciences Center, reporting transport of 12 VAD patients (four of which were by helicopter). One patient developed a cerebrovascular accident but recovered, and another patient had hemodynamic deterioration. There were no reported technical complications during transport.

The pediatric patient population has also experienced successes in the transport of VAD patients. In 2005, a 15-year-old boy on a Thoratec (Pleasanton, CA) BiVAD was successfully evacuated after the Hurricane Katrina disaster, from New Orleans to Texas Children's Hospital, by a helicopter. Because no electricity was available to power the Thoratec unit, a gasoline-powered generator and manual pumping were used to provide circulatory support. After an uncomplicated flight, the patient eventually received an orthotopic heart transplantation and was discharged from the hospital 32 days later.[16]

In 2013, the Artificial Heart Program of the University of Pittsburgh Medical Center published the successful transport of 2 pediatric cases ages 1 month and 5 months. Both patients, suffering from dilated cardiomyopathy, were supported with the Berlin Heart EXCOR BiVAD and the Ikus Stationary Driver module as a bridge to transplantation. Both patients were transported by a Gulfstream III fixed wing aircraft without complications. The authors reported 3 episodes of power losses during the ambulance transport.[17] The authors hypothesized that these may have been caused by transient spikes in the peak current within the Ikus driver operation. Backup batteries were used to recover support in all cases.

ECMO

ECMO is an invasive technique providing both respiratory and/or circulatory support to patients in whom conventional methods of hemodynamic support have failed. In ECMO, a patient's blood is drained from the venous system through an inflow cannula and oxygenated externally. There are 2 main types of ECMO: venovenous ECMO and venoarterial ECMO. Venovenous ECMO provides oxygenation and ventilation support in patients with severe respiratory failure. Venoarterial ECMO is used as a method of circulatory support in severe cardiogenic shock and extracorporeal cardiopulmonary resuscitation, in which externally oxygenated blood is returned to the arterial system, providing both respiratory and circulatory support.[18] Of all the MCSDs, ECMO is by far the most represented in published articles.

ECMO is indicated in patients with acute and potentially reversible cardiac and/or pulmonary failure and can be used as a bridge to definitive therapy (destination VAD therapy or heart transplantation) or as a bridge to recovery in, for example, cases of sepsis or acute respiratory distress syndrome.[19] Some risks of the procedure include neurologic complications such as intracranial hemorrhage, hypoxic brain injury and brain death, bleeding, and the development of heparin-induced thrombocytopenia.[18]

Broman et al[20] described the experience of the Stockholm ECMO Center in Karolinska, reporting a total of 322 ECMO-supported patients transported by their center's mobile team, of whom 59% were by fixed wing aircraft and 5% by rotary wing aircraft, to both national and international destinations. Their flight crew consisted of an ECMO physician (anesthetist), an intensive care unit nurse, and a cannulating surgeon at the minimum. During “primary ECMO transports,” the medical crew would cannulate the patient at the referring hospital before transport. During “secondary transport,” the medical team would only perform transport of patients already initiated on ECMO before their arrival. Between 2010 and 2013, the authors reported 282 primary ECMO transports and 40 secondary ECMO transports. Reported incidents during the transport were separated into 5 categories: patient-related incidents, equipment/technical incidents, staff flaw, vehicle/transportation incidents, and environmental incidents. Adverse events occurred in 27.3% of transports. Most of the incidents were patient related (bleeding, hypovolemia, and loss of tidal volume being the most common) and equipment related. The authors reported 1 death during transport in 2009 in a neonatal patient who developed cardiac failure during transport.

Foley et al[21] described their experience of the first 100 patients (from May 1990 to January 1999) with respiratory failure and hemodynamic instability transported while ECMO supported to the University of Michigan, Ann Arbor, MI. Fifteen and 5 of their 100 patients were transported by helicopter and fixed wing aircraft, respectively. They reported 10 cases of electrical failure, 4 of which had subsequent battery failure requiring temporary manual operation of the circuit pump. There were 3 cases of circuit tubing leakage and 1 case of circuit rupture, membrane lung thrombosis, and oxygenator leakage. However, despite the nature of the complications, none of the complications resulted in an adverse outcome. For their flight transport, the medical crew was composed of 2 physicians and 2 ECLS specialists, who performed on-site cannulation and supported the patient during transport. All 100 patients reached the receiving hospital safely.

Raspe et al[22] reported 36 primary ECMO transports using a portable ECMO system. Twenty-four patients were transported by an air ambulance rescue helicopter over a median of 46 km to the Halle-Wittenberg University hospital in Halle, Germany. The authors described the use of a portable miniaturized ECMO circuit conceptualized using commercially available components after consultation with the company Eurosets (Medolla, Italy). This circuit contains interchangeable centrifugal pumps and oxygenators. For the transport itself, the medical crew consisted of a cardiac anesthetist, a cardiac surgeon, and a perfusionist. No complications were reported during patient transport.

Philipp et al[23] reported the use of the portable Cardiohelp ECMO system in 6 primary ECMO transports (5 by helicopter and 1 by car) over a distance range of 80 to 5,850 km between July 2010 and October 2010. The Cardiohelp ECMO system is a lightweight (10 kg), compact, portable system with an internal battery life of 2 hours. The medical crew consisted of a cardiac anesthesiologist, a cardiac surgeon, and an ECLS specialist. Five patients had the ECMO system implanted as a venovenous circuit and 1 patient as a venoarterial circuit. The authors reported no complications; 5 of the 6 patients were discharged home neurologically intact.

The swine flu pandemic secondary to influenza A virus led to many cases of severe acute respiratory distress syndrome. D'Ancona et al[24] reported the experience of the Mediterranean Institute for Transplantation and Advanced Specialized Therapies based in Palermo, Italy, with the transport of 7 ECMO-supported patients in 2009 to 2010 during the H1N1 viral epidemic. The medical crew consisted of an anesthesiologist, a cardiac surgeon, and a perfusionist. The authors did not report any morbidities or mortalities secondary to the transport itself. However, 1 transport mission had electrical failure, and a manual pump was required. In New South Wales, Australia, Forrest et al[25] transported 40 patients on ECMO (10 by fixed wing aircraft and 4 by rotary wing aircraft) during the H1N1 epidemic. No complications were reported.

Kaliyev et al[26] also reported the successful transport of a mother in her 28th week of gestation over 1,155 km, from Kyzylorda to Astana, Kazakhstan, by fixed wing aircraft. The authors reported no complications during flight and a successful recovery and delivery of a healthy baby boy.

ECMO evacuations have been successfully conducted in military environments as well.[27] Bein et al[27] reported the use of ECMO during evacuation and transport of military soldiers. The authors reported 4 soldiers cannulated in war zones and 6 at the Landstuhl Regional Medical Center, an overseas US military hospital in Germany, and then subsequently transferred to the University Hospital Regensburg Lung Failure Center, Regensburg, Germany, for stabilization and management. Nine of the 10 soldiers were weaned from ECMO support and recovered. Fang et al[28] described the performance of the US Air Force Landstuhl Acute Lung Rescue Team in transporting 6 patients on pumpless extracorporeal lung assistance and 2 full ECMO-supported patients from combat zones to Germany for definitive management.

Multiple other reports of successful ECMO-supported transport from services based from New York[29]; Scotland[30]; Martinique, France[31]; the French Antilles-Guiana region[32]; and Regensburg, Germany[33-35] have been published in the literature.

The pediatric patient population also showed success with air medical ECMO transports. Cabrera et al[36] reported the use of ECMO of 35 pediatric patients over a 20-year period in a university hospital center in Houston, TX. In addition, Coppola et al[37] reported a 22-year experience from a facility providing global ECMO transport. Between 1985 to 2007, 68 children on ECMO were transported to Wilford Hall Medical Center, San Antonio, TX or between 2 international institutions (North America, Asia, and Europe). Forty-six transports were performed by fixed wing aircraft. The medical team consisted of 10 to 15 members, including an ECMO director/mission commander, a pediatric intensivist/neonatologist, a pediatric cardiologist, a surgeon, a nurse, a respiratory therapist, and ECMO specialists. There were 2 cases of membrane oxygenator failure (thrombosis), 1 case of roller pump failure, and 2 cases of power failure. They also reported 1 case of blood warmer leakage and circuit tubing rupture. None of the complications resulted in significant interruption of extracorporeal support. The average survival was 65%.

Clement et al[38] also reported on 114 interhospital transfers from referring hospitals to Arkansas Children's Hospital. Of the 104 patients brought back to Arkansas Children's Hospital on ECMO, 75% were by helicopter, and 13% were by fixed wing aircraft. The medical team consisted of a pediatric cardiac surgeon, a surgical assistant, and an intensivist. There were no mortalities during transport, and the survival rates in transported patients did not differ from in-house ECMO patient mortality rates.

Discussion

General Considerations

General considerations and device-specific considerations are outlined in Table 1. Careful planning and staff training on recognizing and anticipating potential complications during travel can help mitigate adverse events. Authors have stressed the importance of strong continuing education programs and hands-on practice to train crewmembers.[8]

The choice of medical crew roster is crucial to a successful mission. It is also important to note that the Extracorporeal Life Support Organization recommends a minimum crew roster composed of an ECMO physician, a perfusionist, and a transport nurse and/or respiratory therapist.[39] Most transport services reviewed included a critical care medicine−trained physician familiar with MCSD operations as part of the crew roster as well as the presence of or close communication with an experienced perfusionist.

A thorough patient assessment to identify medical issues and potential causes of deterioration during transport should be addressed. Before transport, clinicians should aim to identify hidden causes of clinical disease that may lead to unanticipated deterioration in flight. Imaging tests may need to be performed before transport based on clinical suspicion. Invasive procedures such as central vascular access, intubation for airway protection, and tube thoracostomy should be performed before transport. The MCSD should be examined for appropriate placement and function. The cannulation site of the MCSD should be examined for signs of infection or bleeding. Device cannula should be appropriately fastened to the patient to prevent dislodgement during transport.

Proper equipment supplies should be available inside the aircraft to address possible contingencies. Transport services should strongly consider having backup batteries compatible with the MCSD in question and additional control modules in case of mechanical failure. An

Table 1
A Comparison of Mechanical Circulatory Support Device (MCSD) Characteristics During Air Medical Evacuation Transportation

	Intra-aortic Balloon Pump	Ventricular Assist Device	Extracorporeal Membrane Oxygenation
Frequency encountered	++	++++	+++++
Complexity of insertion	++	+++++	+++
	Percutaneous insertion and fluoroscopic position confirmation	Percutaneous vs open insertion; fluoroscopic position confirmation	Percutaneous vs cutdown technique; arterial cannulation may be required
Complexity of care	++++	++	+++++
Support	Left ventricular cardiac support only	Left and right ventricular support	Cardiovascular and oxygenation support
Medical crew	Physician w/ experience with specific device: critical care, emergency medicine physician Perfusionist/extracorporeal life support specialist Respiratory therapist + registered nurse		
Equipment and preparation	Experience with MCSD Continuous training and educational program for all members on a regular basis Preplanned custom support package (surgical instruments, cannula sizes), battery backup Adequate O_2 reservoir Communication between sending and receiving hospital		
Potential complications	Power failure Poor augmentation Helium leak Tip migration (distal, proximal)	Power failure Bleeding Thrombosis Device displacement	Power failure decannulation midflight Oxygenator failure (thrombosis) Pump failure

array of cannula of various sizes and surgical trays should be available in case invasive procedures are required. The team should also ensure adequate quantities of medications (vasopressors, inotropic agents, and sedation) for the flight duration.

Most MCSDs require anticoagulation to prevent thrombus formation. Most commonly, intravenous unfractionated heparin is used. The use of unfractionated heparin also requires proper monitoring to prevent under- and over-heparinization. Authors have reported the use of activated clotting time measurements every 2 hours. An appropriate supply of heparin and activated clotting time testing equipment should be planned before departure.

The estimation of the power requirement of operating several devices simultaneously should be undertaken before departure. The specifications and power availability should be known and can vary widely depending on the aircraft used. A critical care transport aircraft will require adequate power to support multiple devices such as an invasive positive-pressure ventilator, cardiac monitor, infusion pumps, and an MCSD. Thankfully, the size and energy requirement of MCSDs have decreased over time, and very few cases of power failure were reported. Many times, the cause of power failure was an intrinsic power supply failure/shutdown and not because of insufficient energy delivery from the aircraft. Proper testing of the necessary equipment before transport may help mitigate these errors. It would also be wise to anticipate and use appropriate power converters if intercontinental flights are planned.

Although the added weight of an MCSD module is oftentimes trivial, the capability of transporting MCSDs may require reorganization of the available space on aircrafts according to the module's size, equipment, and personnel. Several services made use of an overbed rack to store the MCSD module. Other services had specific modified aircrafts for the sole purpose of MCSD transportation. In general, the size of MCSD modules has decreased over time, and several companies have developed very portable MCSDs specifically conceptualized for transport.

One other important factor to address is the geographic challenges anticipated during interfacility transfers. One needs to be prepared for the type of aircraft used (including space and size, power and oxygen supply, the MCSD characteristics, and other support devices involved during the transport) in addition to the clinical status of the patient. Logistical details such as the need for ground ambulance transport should be anticipated. The predetermined number and location of refueling stops should be planned, along with the support services offered by different fixed-base operators during landing. Emergency landing planning should also be anticipated and discussed before flight.

Specific Considerations: IABPs

Air transport of IABP devices poses specific concerns during transport. It is important to realize that during takeoff and landing, because of Boyle's law, helium found inside the IABP balloon will expand and contract, respectively. Under normal circumstances, IABP will detect and adjust for gas inflation/deflation. However, during rapid ascent or descent, the IABP may not have time to adjust to the change in volume. The IABP module may detect helium inflation as high fill pressure during rapid ascent or helium loss or leak during descent.[40] Upon such detection, the IABP module will automatically shut off counterpulsation as a safety mechanism. The appropriate solution during these circumstances is to ensure the clinical stability of the patient, verify the reason of the machine arrest, check the tubing for actual leakage, and turn the IABP counterpulsation back on.

Balloon migration during transport can potentially compromise circulation to the subclavian arteries and central nervous system during proximal migration in the aorta or renal perfusion during distal migration.[40] Before the flight, a chest x-ray is recommended to ascertain the position of the IABP tip before takeoff. Proper prevention of IABP line displacement should be made at each patient transfer. During the flight, it is important to monitor the upper extremity radial pulses regularly as well as the hourly urine output rate to be able to detect proximal and distal tip migration, respectively.

Repositioning the IABP during flight is not recommended. It is also contraindicated to leave the balloon on standby for prolonged periods of time because of the risk of thrombosis and embolization. Should the IABP tip have migrated significantly, one should continue to allow for counterpulsations but reduce the filling volume of the balloon, preventing the occlusion of blood flow to vital organs.[40]

Specific Considerations: VADs

Impella devices should be positioned properly to optimize function. Predeparture assessment of positioning by x-ray and careful patient transfers during loading and unloading maneuvers are crucial to maintain adequate function.

Potential complications from Impella support include catheter malposition. It must be stressed that repositioning of the Impella during flight should not be attempted. In the event of malposition or displacement of the Impella device, the system should be kept running to prevent thrombus formation. Both in the event of malposition and pump failure, hemodynamics should be supported by any other means, optimizing ventricular filling conditions and maximizing pharmacologic support.[13]

Certain common types of VADs generate cardiac output through a rotational continuous flow pattern. The amount of rotation per

Table 2
A Summary of the Articles Describing Mechanical Circulatory Support Device Air Medical Transports

Author	Year	Country of Operation	Altitude	Patient	Transport Aircraft	Device	Type	Distance/Time/Range	Physician Presence	Number of Transports
McBride et al	2000	US (St Louis, MO)	NA	Adult	Rotary wing	BIVAD + LVAD	National	Mean = 212 km, max = 497 km	Y	4
Foley et al	2002	US (Michigan)	NA	Adult	Rotary and fixed	VV & VA ECMO	National	1271km	Y	20
Potapov et al	2004	Switzerland, Swiss Air Rescue Company (Singapore to Berlin)	40,000 ft	Adult	Fixed wing	BiVAD	Transoceanic	19 h	Y	1
Haddad et al	2004	Commercial flight Air Canada (Tokyo, Japan, to Ontario, Canada)	NA	Adult	Fixed wing	LVAD	Transoceanic	21.5 h	N	1
Owens et al	2006	US (New Orleans, LA, to Houston, TX)	2,500 ft	Pediatric	Rotary wing	BiVAD	National	527 km	Y	1
Zimmerman et al	2007	Regensburg, Germany	NA	Adult	Fixed wing	ECMO	International	NA	Y	6
Coppola et al	2008	US (San Antonio, TX)	NA	Pediatrics	Fixed wing	VV & VA ECMO	Transoceanic	Mean = 2,220 km; max = 12,070 km	Y	45
Sinclair et al	2009	US (Ohio)	NA	Adult	Rotary and fixed	IABP	National, regional	NA	N	107
Haneya et al	2009	Regensburg, Germany	NA	Adult	Rotary wing	ECMO	International	NA	Y	28
Griffith et al	2010	US (Michigan)	2,500 ft	Adult	Rotary wing	Impella 2.5	National	90 km & 160 km	N	2
Clement et al	2010	US (Arkansas)	NA	Pediatrics	Rotary and fixed	VV & VA ECMO	National	402 km mean	Y	114
Mclean et al	2011	Canada, SkyService (Cambridge to Durham, NC)	43,000 ft	Adult	Fixed wing	BiVAD	Transoceanic	NA	Y	1
Philipp et al	2011	Regensburg, Germany	NA	Adult	Rotary wing	VV & VA ECMO	National	5,850 km	Y	5
D'Ancona et al	2011	Palermo, Italy	NA	Adult	Rotary wing	ECMO	National	NA	Y	7
Forrest et al	2011	New South Wales, Australia	NA	Both	Rotary and fixed	VV & VA ECMO	Transoceanic	402 (82-692) km	Y	14
Lebreton et al	2011	France	5,000 ft	Adult	Rotary and fixed	VV & VA ECMO	Transoceanic	912 km (198-1,585 km)	Y	8
Cabrera et al	2011	US (Texas)	NA	Pediatrics	Rotary and fixed	VV & VA ECMO	National	482 km	Y	35
Berset et al	2012	Switzerland	NA	Adult	Rotary wing	IABP	International	1/2-2.5 h, mean = 1 h	Y	38
Bein et al	2012	Regensburg, Germany, US military	NA	Adult	Fixed wing	PECLA & ECMO	National	NA	Y	10
Burns et al	2013	Australia, New South Wales	NA	Adult	Rotary wing	IABP	National	500 km	Y	7
Woolleyet al	2013	US (origin: NA, destination: Pittsburgh, PA)	NA	Pediatric	Fixed wing	BiVAD	National	885 km & 563 km	NA	2
Lunz et al	2013	Regensburg, Germany	NA	Adult	Rotary wing	VV-ECMO	National	66-178 km	Y	6
Roger et al	2013	France	5,000 ft	Adult	Rotary and fixed	ECMO	Transoceanic	1,430 km	Y	15
Biscottiet al	2015	US (New York, Columbia University)	NA	Adult	Fixed wing	ECMO	International	11,400 km	Y	3
Broman et al	2015	Regensburg, Germany	NA	Both	Fixed wing	ECMO	Transoceanic	13,447 km max	Y	413
Raspe et al	2015	Halle, Germany	NA	Both	Rotary wing	ECMO	National	45.5 km (3.5-115 km)	Y	24
Kaliyev et al	2015	Astana, Kazakhstan	NA	Adult	Fixed wing	VV-ECMO	National	1155 km	NA	1
									Total	918

ECMO = extracorporeal membrane oxygenation; IABP = intra-aortic balloon pump; LVAD = left ventricular assist device; N = no; NA = not applicable; PECLA = pumpless extracorporeal lung assist device; VA = venoarterial; VV = venovenous; Y = yes.

minute is a good indicator of pump output. Many machines also feature cardiac output measurements on the VAD module itself, allowing for adjustments and real-time monitoring. Certain cases have experienced changes in hemodynamics from VAD systems during takeoff and landings because of g-force variations, and careful attention during these periods allows for quick adjustments to hemodynamic support.[11]

VAD systems can be large implanted devices. This in combination with anticoagulation to prevent thrombus formation has led to frequent bleeding episodes during air transport through the VAD implantation site. Before departure, careful examination of the site and history of bleeding should be obtained to anticipate potential blood loss and change in hemodynamics during flight. Frequent examination of the dressing site can help identify potential causes of hemodynamic changes.

Hemodynamic deterioration has been reported in certain cases.[15] Changes in VAD output may respond to preload replacement, either through crystalloid infusion or blood product transfusions. Some transport teams have reported the use of blood products during intercontinental air medical transports of VAD patients, and having an appropriate amount of these products on board is strongly recommended before departure.[12]

Specific Considerations: ECMO

ECMO support may be more technically complex to transport and may require more space because of the presence of both invasive ventilation and the ECMO module itself. This also demands more expertise and more energy requirements because of the simultaneous use of both devices. Fortunately, recent models of ECMO machines are smaller and more mobile. These models allow for more flexibility while retaining the same function.

ECMO tubing must be carefully monitored to prevent unintentional disconnection. Before departure, the medical team should verify the cannulation sites for signs of bleeding, developing hematoma, and/or instability. Any concerns over the excess risk of dislodgment or migration should be addressed before departure by securing the cannula. In specific circumstances, proper position of the cannula may need to be confirmed by radiography and/or cardiac ultrasonography.

Among the different MCSDs, ECMO is the only device with oxygenation capabilities. A reliable and plentiful source of oxygen reserve is critical for proper ECMO function, considering both oxygen consumption and duration of travel. Two different oxygen ports should be available for transport, 1 for the sweep gas and 1 for the ventilator.[21]

ECMO filters must be monitored for thrombosis and failure. Ensuring proper anticoagulation and good blood flow and minimizing idle time can also help prevent filter thrombosis. Carrying replacement filters on board also allows for filters to be replaced midflight, ensuring proper patient support. Electrical failure of both the main power supply and backup battery systems has occurred in some case reports, requiring temporary manual support.[21] The medical crew should be trained in the manual hand crank function in case of mechanical failures.

Increasing Necessity for MCSD Transporation

With increasing world tourism because of affordable travel and the increasing use of MCSDs, familiarity with MCSD transport and repatriation will become an essential part of air medical evacuation services. More and more institutions are becoming familiar with MCSD use, and the rate of interfacility transport is expected to rise.

Among the top reasons for acute medical illness in foreign countries include acute coronary/cardiac diseases and infectious etiologies. These pathologies may lead to circulatory collapse and respiratory failure, requiring MCSD implementation as a bridge to recovery or definitive therapy. In the pediatric population for example, interfacility transport of patients on MCSD support for a bridge to organ transplantation has significantly driven the need for air medical transfers.[16,17] ECMO devices have gained significant traction as a bridge before lung transplantation. Since 2010, more than 1% of patients were bridged to transplant with ECMO support in the United States, and this proportion has been increasing progressively.[41] To facilitate the process by bringing together matched donors with recipients, we anticipate a further rise in the use of long-distance transport of ECMO-supported transplant recipients in the future.

Although low to moderate distance travels can be accomplished by ground ambulance, rotary wing aircraft and fixed wing aircraft offer the capacity of farther travel distances and speed. Helicopter flights offer more flexibility over medium range distances, yet fixed wing aircraft transportation is the only accepted mode for long-distance international flight. This review addresses interfacility international and intercontinental air transports worldwide of safe and successfully completed MCSD transports. Few articles reported complications during transport. Some of the most common complications included periods of hemodynamic instability and bleeding.[20] Very few complications were caused by flaws in knowledge from the medical team. This highlights the importance of staff experience, training, and preparation before transport.[8] Many centers conducting MCSD transports have had several years of experience, with the most experienced center conducting over 160 ECMO air transports.[20]

ECMO devices are becoming increasingly used in intensive care units for both respiratory failure and cardiovascular collapse. ECMO allows the option to provide oxygenation/ventilation capabilities in addition to hemodynamic support. The current medical literature also provides more experience in ECMO transport compared with other MCSDs.

ECMO devices enables long-distance transport of patients with severe respiratory and/or hemodynamic failure by which conventional support methods (eg, an invasive ventilator) may be considered too high risk for safe transport. In cases of severely hypoxemic patients and/or patients on high doses of pharmacologic hemodynamic support, the stress of multiple transfers, subjecting the patient to decreased cabin pressures and acceleration/deceleration during landing/takeoffs, may be unacceptable using conventional methods. The use of an ECMO circuit may offer the enhanced hemodynamic and respiratory stability required to perform such long-distance transports and has allowed transfers in cases that were deemed higher risk using conventional support.[23]

Air transport of MCSD-supported patients was also shown to be effective in military transports[27] and during infection epidemics. Several experiences report the successful use of ECMO in military soldiers who have sustained combat injuries. The availability of ECMO has allowed the long-distance air medical transport and evacuation of injured military soldiers with limited cardiopulmonary reserve to facilities offering more definitive care.[27,42]

In addition, during the H1N1 epidemic, several authors reported transporting patients in whom severe acute respiratory distress syndrome would have precluded them from long-distance travel using ECMO support.[24,25] Having an ECMO transport program can enhance the capacity of an organization to handle a surge in demand during natural disasters and/or epidemics.[25]

Safety and Adverse Events

The inherent risks of air medical transport are further compounded by the complexity of maintaining MSCD function throughout the mission. A good understanding of the potential risks allows for anticipation and prevention. As initially advanced by Broman et al,[20] potential adverse events can be labeled into 5 different categories: patient related, equipment/technical related, staff flaw, vehicle/transportation, and environmental events. Although there was a report of mechanical/electrical failure of an ECMO device requiring an external manual pump to maintain patient support during transport,[24] no negative patient outcome was associated with this complication. Patients are at increased risk of rapid and sudden hemodynamic collapse because of the nature of their disease.[15] Only 1 death was reported of a neonatal patient on ECMO support who developed heart failure during transport.[20] Also, there have been reported mortalities during the cannulation process for ECMO initiation in primary ECMO transports,[21,24] which cautions us about the potential complications of these invasive procedures and that they should only be performed by experienced hands. These safety concerns highlight the importance of appropriate training, the awareness of such potential complications before transport, and careful monitoring during transport.

Costs

Without a doubt, MCSD transportation is often accompanied by significant costs. The cost of interfacility transport has been reported to range from US $10,000 to $20,000 depending on the distance and type of aircraft.[21] A case series of 7 transports, with an average mission time of 9 hours (6-16 hours) by helicopter, reported an average transportation cost of 4,000 Euro.[24] In comparison, military flight costs vary between US $70,000 and $160,000.[37] Other expenses including medical crew, fuel, medication, and a low-level flight with lower cabin pressures[37] can further impact the cost of MCSD air transport. In France, the total cost of an air medical transport (either by helicopter or fixed wing aircraft) was reported to be between 17,936 Euro and 37,786 Euro.[32] Potapov et al[12] reported the cost of a transcontinental fixed wing aircraft evacuation of a VAD-supported patient to be in the range of US $140,000 for the aircraft and US $10,000 for the medical crew.

Limitations

It is important to note certain limitations of this current review. First, there is likely to be significant publication bias in the literature regarding such uncommon and high-risk transport operations. For authors, it is more likely for successful transport missions to be published in the literature as opposed to ones with bad outcomes. Although we believe that air medical transport of MCSDs remains safe given the results of our review, one must acknowledge this bias when reviewing the literature. Second, our review spans multiple eras, with significant technological advancements changing the feasibility of air medical transport significantly. Looking ahead, further changes to current MCSDs as well as the development of new devices may alter the landscape of air medical transportation in a way that is not entirely predictable at the current time. Articles reviewed often combined transport by fixed wing and rotary wing aircrafts. Although there are differences between these 2 types of transportation methods, none of the articles made a significant distinction between the 2 during our review.

Conclusion

Current worldwide experiences show that interfacility air medical MCSD transport can be safely performed. We believe provider expertise, training, and logistical preparation are of paramount importance to mission success, and this has been echoed by other authors as well.[8] The number of ECMO and VAD interfacility transfers using air medical aircrafts is likely to increase in the future as technologies improve and global experience grows. Different MCSDs present their own set of intricacies, and specific considerations should be addressed before transport. Whether one is on the sending, transporting, or receiving end of the operation, familiarity with the device, adequate predeparture preparation, and in-flight vigilance to potential complications can help ensure patient safety and successful completion of each transport mission.

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