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Interhospital transportation of patients with severe lung failure on pumpless extracorporeal lung assist

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Background. To describe the use of pumpless extracorporeal interventional lung assist (iLA) for transportation of patients with severe life-threatening acute lung failure from tertiary hospitals to a specialized centre.

Methods. Retrospective analysis in eight patients with severe lung failure requiring inter-hospital transport, in whom implementation of an iLA system at a tertiary hospital for air/ground transportation was performed.

Results. After implementation of iLA, a rapid increase in CO_2-elimination (Pa_{CO_2} before iLA: 8.92 ± 2.9 kPa, immediately after implementation: 5.06 ± 0.93 kPa, 24 h after implementation: 4.53 ± 1.20 kPa [mean$\pm$SD], $P<0.05$) was observed and a significant improvement in oxygenation (Pa_{O_2} before iLA: 6.66 ± 2.26 kPa, immediately after implementation: 10.39 ± 3.33 kPa, 24 h after implementation: 10.25 ± 5.46 kPa, $P<0.05$) was noted. During transport, no severe complications occurred. Four patients died during further treatment due to multiple trauma or multiple organ failure.

Conclusions. Due to ease of handling, high effectiveness and relatively low costs, iLA seems to be a useful system for treatment and transportation of patients with severe acute lung injury or ARDS suffering from life-threatening hypoxia and/or hypercapnia.

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Keywords: complications; acute respiratory distress syndrome; complications; hypercapnia; ventilation; pumpless interventional lung assist; transportation

Introduction

The need for interhospital transport of critically ill patients has steadily increased over the past decade.[1] The decision to transport patients suffering from organ failure to a specialized centre is based on an assessment of the potential benefits weighed against the potential risks of increased morbidity and mortality during transport.[2]

The technique of extracorporeal membrane oxygenation (ECMO) using blood pumps and artificial oxygenators has been advocated in the treatment of patients with severe ARDS.[3 4] Today, technical advances allow the application of a pumpless extracorporeal lung assist system using an arteriovenous shunt [(interventional lung assist (iLA[5 6])]. Conventional inter-hospital transfer of patients with critically decreased lung function, in need of extracorporeal lung support, is associated with increased risk of complications.

In severely hypoxemic patients, it may be associated with cerebral hypoxia and fatal outcome. Therefore, we began offering an iLA system to assist in the use of transportation of patients with severe ARDS to specialized centres.

This report retrospectively reviews the technique and equipment required for interhospital pumpless extracorporeal lung assist transport and evaluates patient outcome.

Methods

During the past 3 yr the Air Medical Rescue Center, Regensburg (Christoph Regensburg), received 12 requests from referring hospitals to initiate pumpless extracorporeal lung assist in critically ill patients for subsequent transportation to our specialized facility. On 8 of these 12 occasions the patients fulfilled criteria for the initiation

of extracorporeal support,[7] but their critical condition did not allow conventional transport. Usually, the mode of transportation (ground or helicopter) is determined by the receiving physician based on the urgency of the medical condition, time saving anticipated with air transport, weather conditions, medical interventions necessary for ongoing life support during transport and the availability of resources. In all cases, there was direct physician to physician discussion of patient care and medical needs. Six patients were transported by helicopter, and two by ground mobile intensive care unit (ICU), due to the short distance involved or poor weather conditions.

The helicopter emergency medical service crew on call (24 h/day, all year round), as well as the ground mobile ICU, consists of an ICU skilled emergency physician/anaesthetist and a paramedic with critical care training. In cases involving iLA request, a perfusion specialist experienced in iLA techniques is added to our transport team, using a helicopter specially equipped for these purposes. The helicopter is part of the '*Deutsche Rettungsflugwacht*' (DRF German Air Rescue) emergency medical service team. In cases of ground transportation, a mobile ICU was chartered. Both helicopter and ground mobile ICUs are equipped with a full range of drugs, advanced ventilatory equipment, and capable of full invasive haemodynamic monitoring.

At the referring hospital, the patient's condition was again assessed including all radiographs and laboratory data. In all patients, an attempt was made to improve ventilator settings, haemodynamic stability and oxygenation. If standard ECMO criteria to withstand conventional transportion safely were met ($Pa_{O_2}/FI_{O_2} < 14$ kPa, persistant hypercapnia), iLA was inserted to allow patients to more safely undergo transportation. Contraindications to this included severe haemodynamic depression of cardiac origin and an extensive coagulation disorder with acute bleeding.

Description of the system

The iLA is a single use, ultracompact, extrapulmonary gas exchange system, perfused by the heart. Apart from an oxygen supply (10–12 litre min^{-1}) the system does not require additional energy or substrate sources. The system is characterized by a membrane gas exchange system [lung assist device (LAD)] based on heparin-coated hollow fibre technology (polymethylpentene diffusion membrane, resistant to plasma leakage, as a separation layer between the blood and gas phases) with blood flow optimized by reduction of resistance. A passive femo-femoral shunt flow generated by the arterial blood pressure through the LAD (NovaLung® GmbH, Hechingen, Germany), produces effective CO_2 extraction and an improvement in arterial oxygenation at a blood flow rate of ~1.0–2.5 litre min^{-1}. The LAD is connected to the patient through arterial and venous cannulae inserted by Seldinger technique. The system does not need extended technical and staff support and the main advantage is easy handling. The system runs with a 'low-dose' heparin
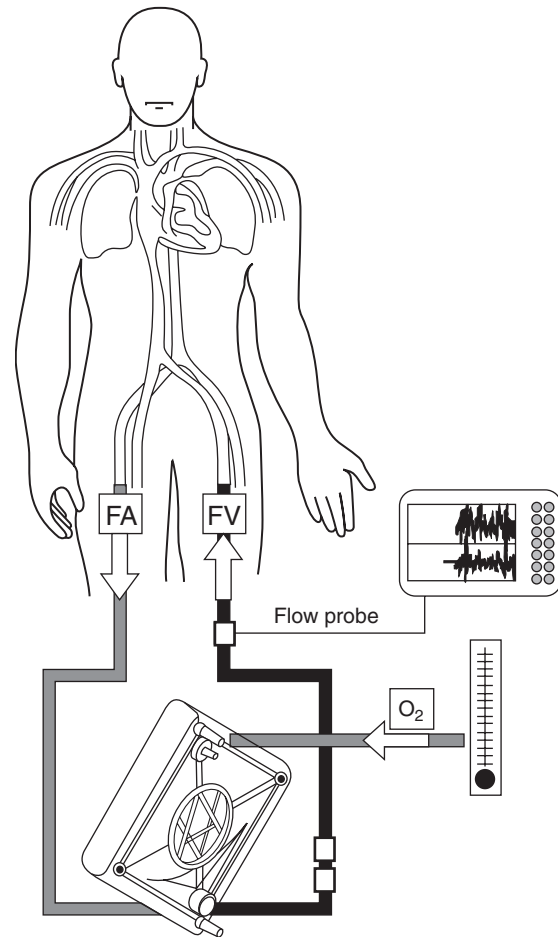
Fig 1 The iLA-system. A passive femo-femoral shunt flow generated by the arterial pressure passes a LAD (in the box), in which an oxygen flow is inserted.

infusion, which does not exceed normal antithrombotic anticoagulation requirements of the intensive care patient.

Vascular cannulation was achieved by percutaneous introduction of wire-reinforced heparin coated cannulae into a femoral artery (15–19F) and femoral vein (19F) (NovaLung®, Hechingen, Germany). The diameter of the arterial cannula was selected taking into account the patient's size or, if possible, the diameter of the vessel, using ultrasound evaluation. After cannulation of the femoral artery and vein, a bolus of unfractionated heparin (5000 IU i.v.) was given. The arteriovenous shunt was established by connecting a prefilled de-aired system (hydroxyethylic starch 250 ml) with a membrane oxygenator with low flow resistance (NovaLung®, Hechingen, Germany). Oxygen inflow to the oxygenator was 10–12 litre min^{-1} (Fig. 1). Functional control was achieved through a monitor (Blood Flow Monitor, NovaLung® GmbH, Hechingen, Germany) which calculates blood flow through the system using transit time Doppler technology. A continuous infusion of heparin was given (200–600 IU h^{-1}) into the arterial inflow cannula before the gas exchange system to achieve a mild prolongation of the activated partial thromboplastin

Table 1 Patient characteristics, gas exchange at first contact with patient, mode of transportation and outcome. PEEP, positive end-expiratory pressure. All patients were at fractional inspired concentration of oxygen=1.0

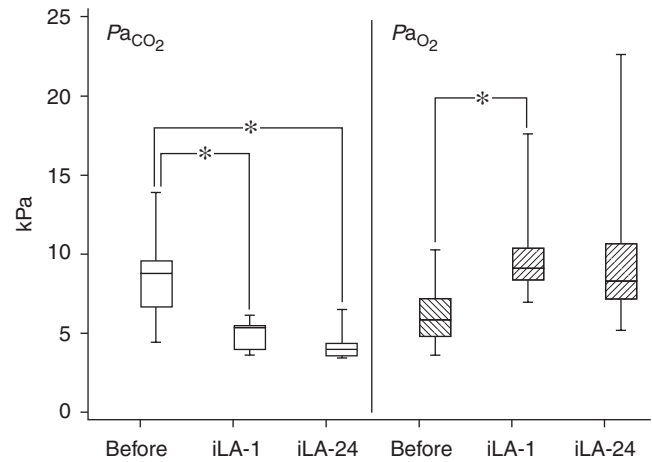| Patient No. Age/sex	Diagnosis or risk factor for ARDS	Pa_{O_2} (kPa)	Pa_{CO_2} (kPa)	PEEP (cm H_2O)	Ventilation prior to iLA (days)	Days on iLA	Mode of transportation (km)	Outcome
1 19/male	Multiple trauma	3.59	8.92	12	0.2	3.5	Helicopter (40)	Died traum. brain injury
2 51/male	Pneumonia	6.92	9.59	17	0.5	0.5	Helicopter (85)	Died hypoxaemia
3 41/female	ARDS	5.72	4.39	18	1.0	2.0	Helicopter (70)	Died sepsis
4 45/male	Multiple trauma	10.25	13.85	16	15	4	Helicopter (98)	Died sepsis
5 62/male	Pneumonia	5.86	9.58	16	1.0	5	Helicopter (40)	Good
6 20/male	Multiple trauma	4.79	10.65	15	1.0	7	Helicopter (98)	Good
7 25/male	ARDS	7.19	7.47	18	0.5	5	Ground (58)	Good
8 27/male	Multiple trauma	9.32	6.66	25	1.0	5	Ground (25)	Good

time between 50 and 60 s. After initiation of iLA, ventilator settings were adjusted to the decreased pulmonary gas exchange needs (reduction of breath frequency, tidal volume and fractional inspiratory concentration of oxygen). Infusion of vasoactive drugs was continued to achieve a mean arterial pressure ($\geq$70 mm Hg) resulting in an optimal arteriovenous shunt flow ($\geq$1.5 litre min^{-1}). A more detailed description of the iLA system has been published previously.[6]

After stabilization and preparation, the patient was moved to the helicopter/ground mobile ICU without being disconnected from the iLA system or ventilator. Ventilatory and haemodynamic variables were monitored continuously throughout the transfer.

Statistical analysis of our data was performed with SigmaStat, version 3.0 (Systat Software GmbH, Erkrath, Germany) using Friedman repeated measures ANOVA on ranks.

Fig 2 Individual patient data (dots) and box and whisker plots (95th, 75th, 50th, 25th and 5th percentiles) of arterial Pa_{CO_2} and Pa_{O_2} (at fractional inspired concentration of oxygen = 1.0) before, after flight, on admission at the ICU (iLA-1) and 24 h (iLA-24) after starting iLA. *$P<0.05$.

Results

All eight patients had severe impairment of pulmonary gas exchange, characterized by hypoxemia and hypercapnia, despite mechanical ventilation with high level positive end-expiratory pressure (PEEP) (Table 1). After connection to the iLA system, patients were transferred rapidly by helicopter (6 patients) or by ground (2 patients) to our centre. The ventilatory regimen during transport included ventilation in a pressure-controlled mode (target respiratory setting: peak inspiratory pressure <35 cm H_2O, inspiration:expiration ratio=1:1, optimization of PEEP to achieve a maximal gas exchange improvement without compromising cardiac output). After initiation of iLA, the pulmonary gas exchange improved promptly, and there were no major complications reported during transport. All patients received vasopressors continuously (norepinephrine 0.1–0.8 μg kg^{-1} min^{-1}) and

remained haemodynamically stable during transportation. In all patients, vascular cannulation was performed without problems, but in two patients removal of the arterial cannula was accompanied by bleeding, which resulted in a surgical revision. A transient ischaemia of a lower limb was observed in one patient a few days after arterial cannulation. A normal perfusion of the limb was restored after removal of the cannulae. The blood flow rates through the LAD ranged between 1.2 and 2.8 litre min^{-1}. The individual changes in pulmonary gas exchange are presented in Figure 2. After starting iLA, a rapid increase in CO_2 elimination [Pa_{CO_2} before iLA: 8.92±2.9 kPa, immediately after: 5.06±0.93 kPa, 24 h after: 4.53±1.20 kPa (mean±SD), $P<0.05$] was observed and a significant improvement in oxygenation (Pa_{O_2} before iLA: 6.66±2.26 kPa, immediately after: 10.39±3.33 kPa, 24 h after: 10.25±5.46 kPa, $P<0.05$)

Table 2 Haemodynamic and respiratory variables before starting iLA (pre iLA), after flight/admission at the ICU, and after 24 h on iLA treatment. *$P<0.05$ 24 h *vs* pre

	Pre iLA	After admission at the ICU	24 h
Mean arterial pressure (mm Hg)	88±12	92±16	83±8
Heart rate (b.p.m.)	95±14	93±18	94±11
Norepinephrine (μg kg^{-1} min^{-1})	0.33±0.29	0.26±0.31	0.12±0.13*
Minute ventilation (litre min^{-1})	16.6±4.5	13.8±2.5	10.9±2.0*
Respiratory frequency (b.p.m.)	33±15	30±15	27±17*
Peak inspiratory pressure (cm H$_2$O)	37.8±6	36.0±7	34.8±7*
iLA flow (litre min^{-1})		2.18±0.28	2.23±0.34

was noted. Four patients died during further treatment due to multiple trauma or multiple organ failure (Table 2).

Discussion

Treatment in specialized centres using extracorporeal lung assist is required for patients with hypoxia or hypercapnia due to severe acute respiratory failure or ARDS which has not responded to conventional therapy, The transfer of these patients is associated with a high incidence of potentially life threatening complications. The use of a special mobile ECMO car for transportation of ARDS patients has been developed and described.[8] Such a technique (pump driven veno-arterial lung assist) is characterized by a high demand on technical and staff support and may be limited by technical resources.

We report on a new system of iLA for transportation of critically ill patients which uses a pumpless extracorporeal technique. The main advantage of the system over pump driven ECMO is that there is no interruption to function during transport. After cannulation and initiation of the system at a tertiary hospital, the only requirements for helicopter or ground transportation are a ventilator, haemodynamic monitoring (intraarterial measurement) and a simple system for oxygen insufflation (12 litre min^{-1}) into the iLA membrane. Helicopters usually are equipped with unpressurized cabins and they do not exceed an altitude of 5000 feet (1500 m), barometric pressure, partial pressures of ambient air, and of alveolar air decline with altitude. At 5000 feet and above, a marked drop in alveolar oxygen partial pressure occurs and in potentially hypoxaemic patients a further fall in arterial partial pressure of oxygen ($\sim$20%) can be expected. When using fixed wing aircraft flying at higher altitude for transportation of critically ill patients with iLA-system, pressurization is required to keep ambient pressure below the equivalent of 5000 feet, since membrane gas transfer is limited beyond the 'physiological zone'.

After an initial 'learning curve' and gaining experience through several uses, the system does not require a high degree of technical and staff support and is low cost. Following transportation of the patient, the system can be continued at the ICU of the centre, where a strategy of 'lung protective ventilation' can be modified. On the other hand, the blood-gas exchange capacity of iLA, particularly for oxygen, is limited in comparison with pump-driven ECMO for two reasons. First, the arteriovenous shunt limits oxygen transfer capacity. Second, iLA is unable to achieve the flow rates of ECMO (4–6 litre min^{-1}). Nevertheless, we have shown that iLA exerts effective removal of carbon dioxide and a moderate increase in oxygenation in severe ARDS. Possible major complications using the iLA-system are episodes of transient ischaemia of a lower limb after arterial cannulation. In our patients one ischaemic complication was observed in the period following transportation, but normal perfusion of the limb was restored after withdrawal of the cannulae.

In conclusion, iLA seems to be a useful system for treatment and transportation of patients with severe acute lung injury or ARDS, who are haemodynamically stable. Ease of use, effectiveness and relatively low costs make the method attractive for the transfer of patients between centres.

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