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Contemporary extracorporeal membrane oxygenation for adult respiratory failure: life support in the new era

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Abstract *Background:* Extracorporeal membrane oxygenation (ECMO) has been used in clinical medicine for 40 years but remains controversial therapy, particularly in adult patients with severe respiratory failure. Over the last few years, there have been considerable advances in extracorporeal technology and clinical practice, ushering in a new era of ECMO. Many institutions adopted ECMO as rescue therapy during the recent H1N1 influenza pandemic, reigniting the controversy. *Discussion:* Hollow-fibre oxygenators and Mendler-designed centrifugal pumps have replaced the old silicon oxygenators and roller pumps. The advantages of these novel systems and the principles that underlie their function are outlined. Advances in cannula technology allow greater ease of patient positioning, in some cases facilitating extubation and ambulation on ECMO. Improvements in ECMO circuitry have led to a reduction in heparin and blood product requirements, with consequently fewer

complications. Greater understanding of severe acute respiratory distress syndrome has allowed clinicians to successfully support adults on ECMO for months at a time, as a bridge to either recovery or transplantation. *Conclusions:* ECMO is safer, cheaper, and simpler than in previous eras. Both circuit and patient can be cared for by a single trained nurse. Additional prospective studies of ECMO for adult respiratory failure are underway. Contemporary ECMO in awake, potentially ambulant patients to provide short-term support for those with acute, reversible respiratory failure and as a bridge to transplantation in those with irreversible respiratory failure is now ready for widespread evaluation.

Keywords Acute respiratory distress syndrome · Mechanical ventilation · Lung transplantation · H1N1 influenza

Introduction

Extracorporeal membrane oxygenation (ECMO) is the use of a substantially modified cardiopulmonary bypass circuit to provide short-term respiratory (and potentially circulatory) support to critically ill patients. ECMO is established as standard therapy in children with acute

respiratory or circulatory failure refractory to conventional management strategies [1–3], but substantial controversy lingers over its use in adult respiratory failure [4–7]. After the first successful case was reported in 1972, a multicentre randomized study of ECMO sponsored by the National Institutes of Health was conducted in the 1970s, showing 90% mortality in both ECMO and

conventional care groups [8]. Over the next two decades, ECMO for adult respiratory failure underwent further evaluation. Survival rates of approximately 50% were routinely reported in uncontrolled series [9], but the ECMO system was complicated, cumbersome, and potentially hazardous unless constantly attended to by trained specialists. Bleeding was a common, life-threatening complication. These factors meant that ECMO was rarely used outside a small number of dedicated centres.

There have been relatively recent, substantial technological improvements in ECMO circuitry, principal among them new pump and oxygenator designs. The new ECMO system is simpler, safer, and can be managed by one bedside nurse trained and experienced in circuit management. Major bleeding is much less frequent than in the past. Some of these new-generation devices have been recently approved by the Food and Drug Administration and are now used in parts of North America. Elsewhere in the world, e.g. Europe and Australasia, these devices have been in use for over a decade. These technological advances have been coupled to refinements in the clinical care of ECMO patients. It is now possible to support patients for weeks or even months at a time without any additional complications over and above those of critical illness. Furthermore, the role of ECMO in many of the conditions formerly regarded as contraindications, such as sepsis [10, 11], trauma [12, 13], malignancy [14, 15] and pulmonary haemorrhage [16],

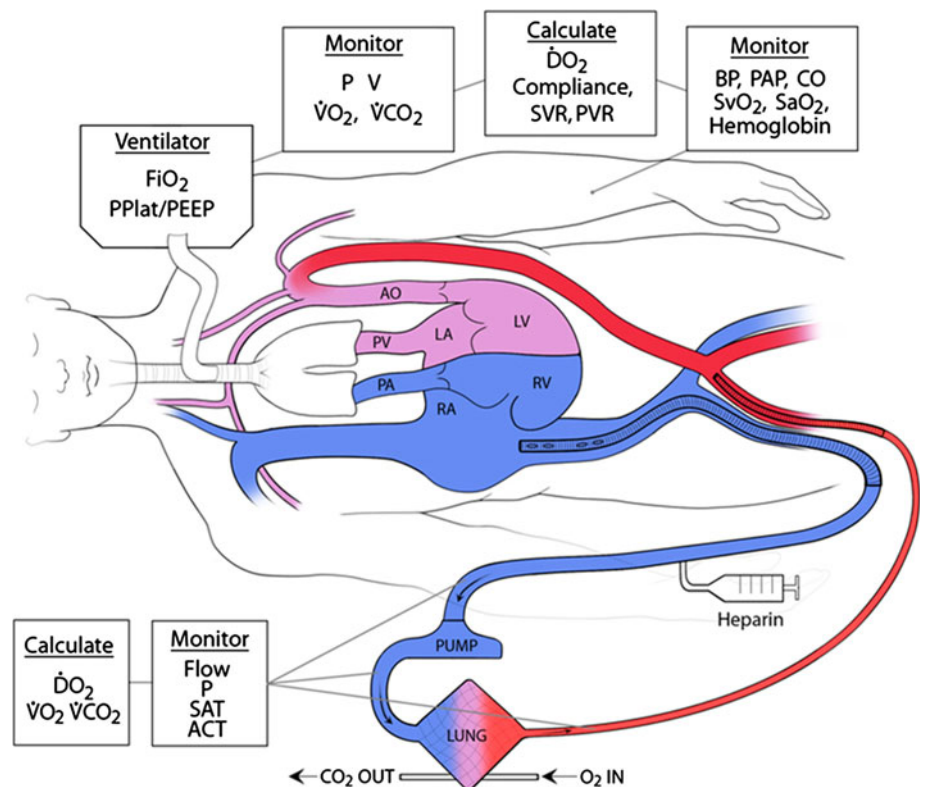
has been reappraised in the light of more recent research. All of these changes have ushered in a new era of extracorporeal life support.

The influenza A(H1N1) pandemic in 2009 created a resurgence of interest in ECMO and led many clinicians to incorporate it into their practice [17–19]. This review is written for intensivists experienced at managing critical illness but not necessarily expert in ECMO. Reviews on other indications for ECMO such as adult circulatory failure can be found elsewhere [20, 21], as can critiques of both ECMO research and its role in modern intensive care units (ICU) [6, 7]. This article focusses on contemporary circuit components and overviews the management of adult patients receiving ECMO for respiratory failure.

Circuitry

In venoarterial (VA) ECMO, venous blood is oxygenated and returned to the aorta (usually via the femoral artery) (Fig. 1). This is an effective technique to provide emergency mechanical circulatory support for patients with cardiogenic shock refractory to conventional medical therapies and is considerably cheaper than employing ventricular assist devices (VAD) [21–26]. ECMO has been successfully used as a bridge to myocardial

Fig. 1 Venoarterial extracorporeal membrane oxygenation with femoral–femoral access. The pre-pump heparin is optional. FiO_2 fractional inspired oxygen, P_{plat} plateau airway pressure, $PEEP$ positive end-expiratory pressure, P pressure, V volume, VO_2 oxygen uptake, VCO_2 carbon dioxide uptake, $\dot{D}O_2$ oxygen delivery, SVR systemic vascular resistance, PVR pulmonary vascular resistance, BP blood pressure, PAP pulmonary artery pressure, CO cardiac output, SvO_2 mixed venous oxygen saturation, SaO_2 arterial oxygen saturation, Sat saturation, ACT activated clotting time, CO_2 carbon dioxide, O_2 oxygen



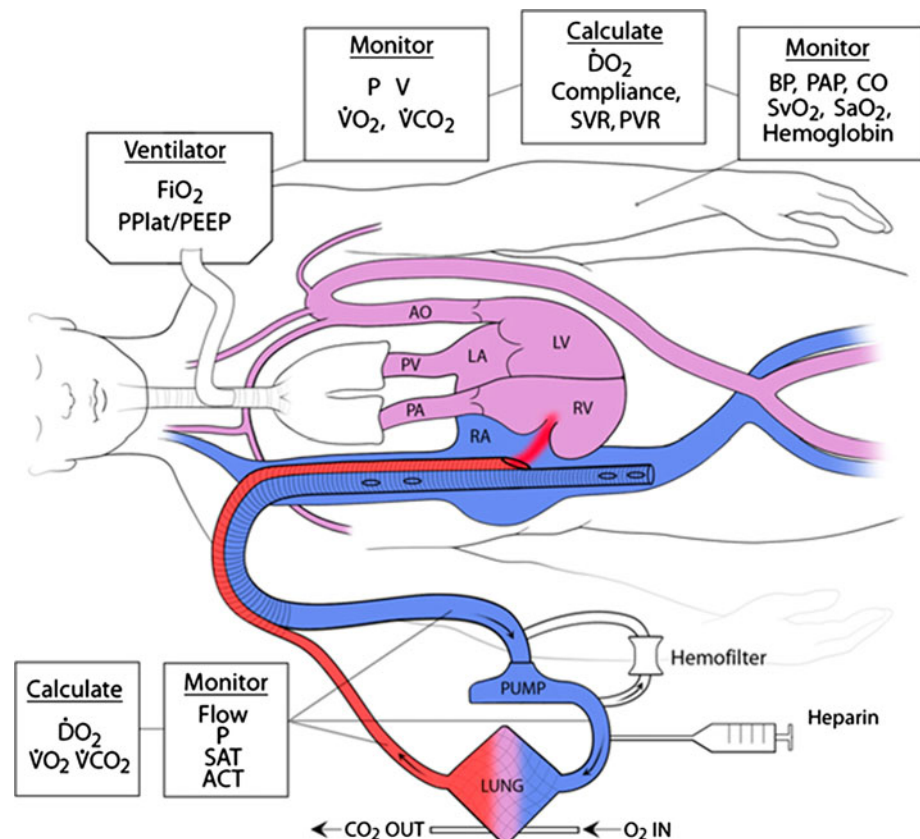
recovery, VAD implantation or cardiac transplantation in patients with various aetiologies of severe cardiac failure, e.g. acute myocardial infarction, end-stage dilated cardiomyopathy, viral myocarditis, complications of cardiac surgery or cardiac arrest [21, 22, 26–31].

In venovenous (VV) ECMO, blood is removed from one or both vena cavae via the jugular or femoral veins, pumped through an oxygenator and returned directly into the right atrium, thereby preserving pulmonary blood flow, pulsatile systemic flow, and oxygenation of blood in the left ventricle and aortic root. Except in cases of associated overt cardiac failure or refractory shock, patients with acute respiratory failure should be supported with VV-ECMO (Fig. 2), since VA-ECMO is associated with greater risk of complications, including systemic thromboembolism, limb ischaemia, maldistribution of oxygen and increased left ventricular wall tension. Acute right heart failure secondary to acute respiratory distress syndrome (ARDS) is not an indication per se for VA-ECMO in most cases, since oxygenation of pulmonary artery blood will decrease hypoxia-induced vasoconstriction and pulmonary artery pressure in the hours following VV-ECMO initiation. VV-ECMO also facilitates a substantial reduction in intrathoracic pressure via a reduction in mechanical ventilation, which may also improve right ventricular function.

ECMO circuits have two principal components: the oxygenator and the pump. Additional circuit components include cannulas, tubing and the heat exchanger. Each will be considered in turn.

Modern oxygenators comprise multiple hollow fibres <0.5 mm in diameter coated with polymethylpentene, allowing diffusion of gas but not liquid. As blood runs through the oxygenator, fresh gas flow ('sweep') is piped through the inside of the hollow fibres (Fig. 3). Carbon dioxide clearance is more effective than oxygenation because the greater solubility of CO₂ facilitates more rapid diffusion (Fick's law) and because of the relatively linear shape of the CO₂ dissociation curve, in contrast to the sigmoid shape of the O₂ dissociation curve. Although a minimum rate of fresh gas flow is necessary to oxygenate the blood, increasing the gas flow rate further will not lead to substantial improvement in oxygenation, but merely reduce PaCO₂. In order to increase PaO₂, blood flow through the circuit must be increased. The patient's PaCO₂ is principally determined by the rate of fresh gas flow, whereas the main determinant of PaO₂ is blood flow rate through the circuit. Effective CO₂ clearance can be achieved with as little as 10–15 ml/kg/min of blood flow, while effective oxygenation usually requires at least 50–60 ml/kg/min, although this value can be as high as 80–100 ml/kg/min and varies with both the amount of recirculation and total cardiac output.

Fig. 2 Venovenous extracorporeal membrane oxygenation with bicaval drainage. The heparin location and in-line haemofilter are optional. FiO_2 fractional inspired oxygen, P_{plat} plateau airway pressure, $PEEP$ positive end-expiratory pressure, P pressure, V volume, VO_2 oxygen uptake, VCO_2 carbon dioxide uptake, $\dot{D}O_2$ oxygen delivery, SVR systemic vascular resistance, PVR pulmonary vascular resistance, BP blood pressure, PAP pulmonary artery pressure, CO cardiac output, SvO_2 mixed venous oxygen saturation, SaO_2 arterial oxygen saturation, Sat saturation, ACT activated clotting time, CO_2 carbon dioxide, O_2 oxygen



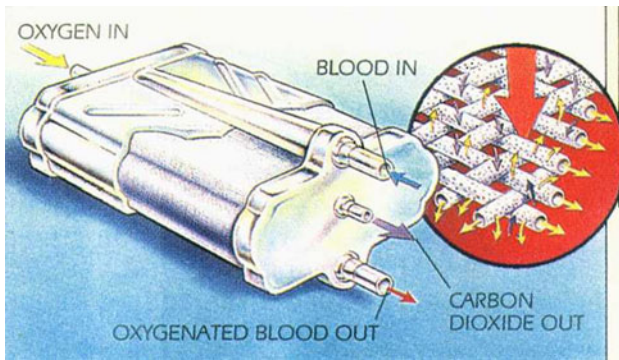


Fig. 3 Diagram of an oxygenator. See text for details

There are a number of advantages to modern hollow-fibre oxygenators over the old silicon membrane oxygenators. They cause less platelet and plasma protein consumption and have more effective gas exchange [32, 33]. Additionally, they offer lower resistance to blood flow and have small priming volumes of <300 ml. The devices are coated with thrombo-resistant coatings. These oxygenators are currently manufactured by a number of companies including Dideco, Maquet, Medos, Novalung and Sorin. Other systems that can effectively function for months without systemic anticoagulation are in development [34]. The low blood flow resistance of these newer oxygenators facilitates the use of centrifugal pumps.

Blood flow through an ECMO circuit is driven by a centrifugal pump, in which a rotating impeller spins on a small bearing or is magnetically suspended (e.g. Rotaflow, Maquet, Hirrlingen, Germany; Revolution, Sorin, Milano, Italy; Centrimag, Levitronix LLC, Waltham, MA). The impeller spins at 2,000–5,000 revolutions per minute (rpm), creating a constrained vortex that suctions blood into the pumphead and propels it out toward the oxygenator (Fig. 4). These pumps are suitable for prolonged perfusion because there is a hole in the centre of the rotor (Mendler design) [35]. This eliminates the stagnation, thrombosis

and heat production of earlier centrifugal pumps. These pumps are preload and afterload dependent; i.e. blood flow is affected by both the volume of blood coming into pump as well as the post-pump pressure. Some of the newer pumps also offer the option of providing pulsatile flow (e.g. Deltastream, Medos, Stolberg, Germany), but these are primarily designed to enhance circulatory support on VA-ECMO. Pulsatile flow pumps generate greater surplus haemodynamic energy and thus theoretically better perfusion [36]. However, it is uncertain whether this translates into clinical benefit. It may be helpful in patients on VA-ECMO with combined respiratory and circulatory failure [37], but there is as yet little reason to believe that this mode would be beneficial in VV-ECMO.

Mendler-designed centrifugal pumps have a number of advantages over the older, roller pumps. They have smaller priming volumes of <40 ml, do not require gravity drainage, circuit bridges or venous reservoirs, operate effectively for weeks at a time with very little incidence of technical failure and are much simpler to care for and maintain. The suction created by centrifugal pumps can cause cavitation and haemolysis when the venous line is occluded, so careful attention must be paid to blood volume, venous line patency and maintaining a safe rotation velocity (i.e. rpm) of the pump.

Traditionally, two cannulas of 21–28 Fr size were used for adult VV-ECMO. A third cannula could be inserted as an additional drain to enhance flow if required. Recently a dual-lumen catheter designed by Wang and Zwischenberger is being manufactured by the Avalon company (Avalon Elite, Avalon Laboratories, Rancho Dominguez, CA) [38]. This cannula is inserted via the right internal jugular vein and positioned such that the tip rests in the inferior vena cava [39]. Blood is removed from ports in both vena cavae and returned directly into the right atrium (Fig. 5). The cannulas are currently manufactured in sizes ranging from 16 to 31 Fr. In addition to providing adequate flow and minimizing recirculation, these cannulas have the obvious advantage of facilitating ECMO using a

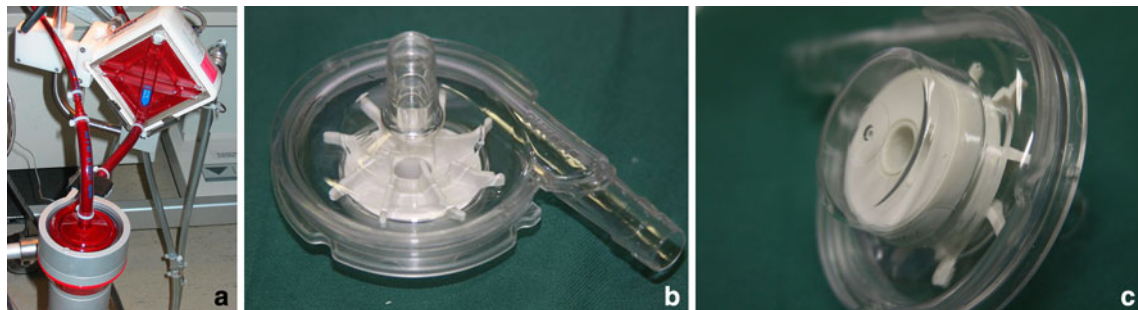


Fig. 4 **a** Centrifugal pump in active use. Blood is suctioned into the top of the pump and propelled toward the oxygenator (Courtesy of Derek Best, with permission). **b** Different centrifugal pump after use, showing Mendler-designed impeller. **c** The base of the same

pump, demonstrating the absence of an impeller pin or mounting. This pump is suspended in a magnetic field when in use (Courtesy of Si Guim Goh, with permission)

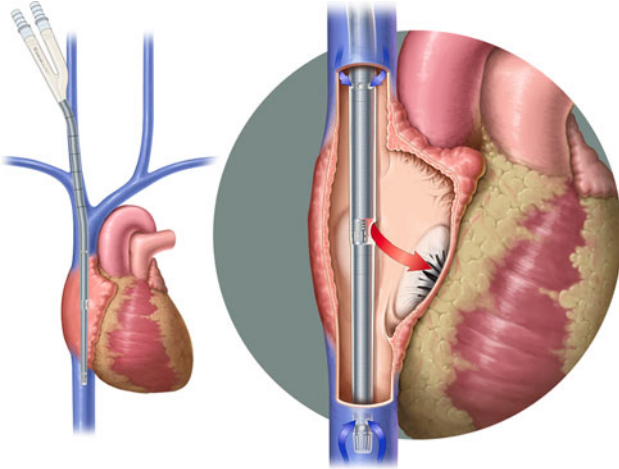


Fig. 5 Diagram of correctly positioned Avalon catheter. See text for details (with permission from Avalon Laboratories)

single access vein, reducing the chances of vascular trauma and permitting easier patient positioning. It is essential to insert them using either image intensification or echocardiography to position them correctly and minimize the risk of atrial or vessel perforation.

The tubing of an ECMO circuit is made of polyvinylchloride, polyurethane or silicone rubber and can be coated with a biocompatible lining to reduce the systemic inflammatory response and risk of thrombosis. Such coatings include poly(2-methoxyethyl acrylate), albumin, heparin or phosphorylcholine. Both coated and uncoated circuits adsorb many drugs, including sedatives and antibiotics [40–42]; for example, fentanyl and morphine availability can be reduced by as much as 65%, depending on the surface coating [43].

Body temperature is maintained by a circulating water bath and compact heat exchanger in the circuit. This is highly effective such that the patient's core temperature usually equals the temperature of the water bath. Consequently, ECMO patients may not become febrile.

Another extracorporeal approach to respiratory failure is selective extracorporeal CO₂ removal (ECCOR) [44, 45]. In ECCOR, CO₂ is removed, the ventilator is turned down to a low rate at low pressure and the patient is dependent on native lung function for oxygenation. The Novalung Company (Hechingen, Germany) produces a membrane lung which can be perfused using a femoral arteriovenous shunt. This provides enough blood flow for CO₂ removal, but not oxygenation [46, 47]. Limb ischaemia has been a problem in some series [48]. Low-flow VV CO₂ removal devices (e.g. Hemodec, Salerno, Italy; iLA active, Novalung, Hechingen, Germany; Hemolung, ALung, Pittsburgh, PA, USA) may be available in the near future, alleviating the serious limitations of the Novalung device such as limb ischaemia or the risk of systemic embolization.

Patient management

The latest generation of low-resistance oxygenators and pumps has led to a safer, simpler approach to management, sometimes referred to as ECMO II. Until recently, an ECMO specialist with lengthy training in both perfusion and ICU nursing care was required to safely employ ECMO, in addition to a regular ICU nurse. Now ICU nurses with additional training in ECMO technology and management can care for both circuit and patient. The ECMO specialist team provides the education and consultation management as well as overseeing the programme, preparing the circuits and managing cannulation, weaning and decannulation. ECMO II is less expensive than original ECMO. The cost per case is around US \$10,000, comparable to many other therapies in modern medicine [49].

The exact indications for VV-ECMO have not been the subject of comprehensive prospective research, although it is recommended that it be considered in situations when patient mortality is predicted to be >80% despite optimal use of less invasive therapy [20, 50]. In principle, it should be used when less invasive therapies fail but before lasting injury occurs, e.g. iatrogenic barotrauma or sustained cerebral hypoxia. Some specific indications for ECMO in adult respiratory failure are listed in Table 1. However, the rate of physiological decline may be more important than the absolute amount of ventilatory support, and it is important that ECMO referrals are made in sufficient time to allow patient assessment, cannulation and, in some instances, transfer to another institution. Ideally, this means discussing individual cases with an ECMO service at the same time as other advanced therapies are being considered or instituted, as well as tailoring the criteria for ECMO referrals to local institutional resources, such as availability of a cannulation team or distance to the nearest referral centre. If transport to another institution is required, a specialized ECMO retrieval team should travel to the referring institution, cannulate and transport the patient back. Outcomes in such instances can be excellent [53].

Contraindications to ECMO are few but include advanced age, severe disability and incurable malignancy. Relative contraindications include uncontrolled coagulopathy, intracranial bleeding and high-pressure positive-pressure ventilation for more than 1 week prior to ECMO [50, 54]. Complications from VV-ECMO include bleeding, venous thromboembolism and infection.

Cannulation is accomplished percutaneously using the Seldinger technique, then unfractionated heparin is started by infusion. A bolus dose (50–75 U/kg) is optional. As newer devices are less thrombogenic, heparin can usually be titrated to maintain activated partial thromboplastin times (APTT) at 1.2–1.8 times normal (measured daily). Alternatively, activated clotting times (ACT) 1.5 times normal (measured hourly) can be targeted. Anticoagulation is one of

Table 1 Indications for ECMO in adult respiratory failure

Title	Year of publication	Indications for ECMO	References
Zapol et al.	1979	PaO ₂ /FiO ₂ ratio <50 for >2 h, or PaO ₂ /FiO ₂ ratio <83 with FiO ₂ ≥0.6 and ≥5 cmH ₂ O PEEP for >12 h, and intrapulmonary shunt >30% of cardiac output when measured at FiO ₂ 1.0 and ≥5 cmH ₂ O PEEP	[8]
CESAR	2009	Murray score ≥3.0, or uncompensated hypercapnia with pH <7.20	[4]
EOLIA	Ongoing	Severe ARDS defined according to usual criteria, and meeting one of the three following criteria of severity: (a) PaO ₂ /FiO ₂ ratio <50 with FiO ₂ ≥0.8 for >3 h, despite optimization of mechanical ventilation and despite possible recourse to usual adjunctive therapies (NO, recruitment maneuvers, prone position, HFO ventilation, almitrine infusion) (b) PaO ₂ /FiO ₂ ratio <80 with FiO ₂ ≥0.8 for >6 h, despite optimization of mechanical ventilation and despite possible recourse to usual adjunctive therapies (NO, recruitment maneuvers, prone position, HFO ventilation, almitrine infusion) (c) pH <7.25 for >6 h (RR increased to 35/min) resulting from MV settings adjusted to keep Pplat ≤32 cmH ₂ O (first, Vt reduction by steps of 1 ml/kg to 4 ml/kg then PEEP reduction to a minimum of 8 cmH ₂ O)	[51]
ELSO guidelines	2009	PaO ₂ /FiO ₂ ratio <80 with FiO ₂ ≥0.9 and Murray score 3–4, or CO ₂ retention with PaCO ₂ >80 mmHg or inability to achieve adequate ventilation with Pplat ≤30 cmH ₂ O, or severe air leak syndromes	[52]

CESAR conventional ventilatory support versus extracorporeal membrane oxygenation for severe adult respiratory failure study, *EOLIA* extracorporeal membrane oxygenation for severe acute respiratory distress syndrome trial, *ELSO* extracorporeal life support organization, *PEEP* positive end-expiratory pressure, *ARDS* acute respiratory distress syndrome, *NO* nitric oxide, *HFO* high-frequency oscillation, *RR* respiratory rate, *MV* minute ventilation, *Vt* tidal volume

the most important issues in patients on ECMO and requires frequent review. Detailed guidelines for management of anticoagulation and bleeding are published by the Extracorporeal Life Support Organization (ELSO) and are freely available [50].

Guidelines from ELSO recommend maintaining normal haematocrit in patients on ECMO to enhance tissue oxygen delivery and maximize extracorporeal circuit efficiency [50]. However, some institutions have more restrictive transfusion thresholds and will accept lower haemoglobin levels (e.g. 8–9 g/dL) in patients with SaO₂ >85%, in the absence of bleeding or coronary artery disease. In bleeding patients, coagulation disturbances should be treated with blood product replacement and the platelet count maintained within the low-normal range (e.g. >50–100 × 10⁹/L). In patients who have no bleeding diatheses (e.g. hypofibrinogenaemia), the platelet count can be safely monitored unless <20 × 10⁹/L. Thromboelastography can be useful in complex cases such as disseminated intravascular coagulation. Plasma free haemoglobin should be measured daily to detect haemolysis. The cause of haemolysis is usually cavitation created by excessive suction from the centrifugal pump. Thrombosis in the circuit can occur and is detected as small clots at connectors and low-flow zones. This can lead to both small emboli (which are not a serious problem during VV access) or haemolysis. If plasma free haemoglobin is consistently >0.5–1.0 g/L, the anticoagulation strategy, cannula position and pump speed should be reviewed and consideration be given to electively changing the circuit.

Circuit flow is maintained at 50–100 ml/kg/min and titrated to achieve SaO₂ >80%. Fresh gas flow is initiated at the same rate as circuit blood flow and then adjusted to maintain PaCO₂ in the normal range. Positive-pressure ventilation is reduced to minimize the risk of iatrogenic injury (e.g. inspiratory pressure <25 cmH₂O, PEEP 10–20 cmH₂O, rate 4–6 breaths per minute; or CPAP at 10–20 cmH₂O). In those in whom prolonged respiratory support is anticipated, consideration should be given to early tracheostomy while on ECMO to facilitate patient comfort and ease of care [55, 56].

The ECMO circuit should be monitored several times daily by the medical and nursing team caring for the patient and at least once every 24 h by a perfusionist or other ECMO specialist. Circuit and cannula surveillance is intended to verify the correct functioning of the device and identify evolving complications early, including fibrin deposits or clots on the ECMO membrane; clots in the cannulas or pump; bleeding; signs of inflammation or infection at the cannula insertion sites; unexpected drops in ECMO outflow; or the appearance of clinical or biochemical signs of intravascular haemolysis. If any of these complications occur, a combined multidisciplinary consultation should be conducted to establish the best therapeutic approach [50].

The management of ECMO patients has been transformed in recent times as a direct result of the improvement in circuitry; for example, one of the advantages of the novel, single-lumen ECMO cannulas is the ease of patient positioning. Patients can sit up or out of bed. In more experienced

centres, patients awaiting lung transplantation can be extubated and encouraged to ambulate on ECMO (Fig. 6) [57, 58]. This may help prevent deconditioning and improve long-term outcome [59]. The realization that patients can be bridged to transplant awake and ambulatory for months is beginning to influence care of acute lung failure patients. The ECMO centre at Karolinska Institute, Stockholm, has emphasized for years that awake, spontaneous breathing leads to better results in acute disease in children and adults, although this strategy has not been subjected to controlled investigation. In addition to the benefits of spontaneous breathing, awake management may avoid many potential complications of intensive care such as excessive sedation, dependent oedema and pressure sores.

In patients not intended for extubation, light sedation can be administered to ensure comfort and prevent inadvertent dislodging of the ECMO cannulas. As noted above, sedative dosage may be higher than expected because of reduced drug availability and an effective increase in volume of distribution. Muscle relaxation is rarely necessary except in occasional patients with $\text{SaO}_2 < 80\%$ despite ECMO, in whom neuromuscular blockers may be helpful early in the course of disease [60].

Patients should be fluid restricted and every attempt made to restore patient dry weight [61, 62]. Diuretic infusions are often used, although extracorporeal ultrafiltration can easily be performed by connecting continuous renal replacement therapy (CRRT) to the ECMO circuit. Post-oxygenator blood is drained into the CRRT circuit and returned pre-oxygenator. The oxygenator functions as an effective bubble trap so the risk of air or clot embolization is minimized.



Fig. 6 Patient on venovenous ECMO awaiting lung transplantation (Courtesy of Charles Hoopes, MD, with permission)

Weaning off VV-ECMO is simple. A weaning trial is conducted when pulmonary function has recovered sufficiently to allow adequate ventilation on modest amounts of positive-pressure ventilation, assessed on the basis of improvements in clinical assessment, lung compliance and radiological appearance. The ventilator is set to moderate levels of mechanical support (e.g. tidal volume 6 ml/kg, plateau pressure < 30 cmH₂O, PEEP 5–12 cmH₂O, $\text{FiO}_2 < 0.6$) then the fresh gas flow to the oxygenator is switched off while blood flow continues. If the patient remains stable and adequately ventilated after 1–4 h of observation, the ECMO cannulas can be removed. In most instances, this can be done without surgical repair of the vessel but simply by pulling out the cannula and applying pressure for 30 min. As the cannula is removed, the patient should perform a Valsalva maneuver to reduce the chance of air embolism.

Some clinicians may consider withdrawal of support in patients who have minimal improvement in lung function after an arbitrary period of extracorporeal support (e.g. 2–3 weeks) [54, 63]. However, there are no effective means of confidently predicting recovery or death. Alveolar capillary dysplasia in babies is incompatible with life but no comparable disease state exists in adults. Lung recovery may take weeks or months in some conditions, including ARDS, and successful recovery has been reported after > 50 –100 days of ECMO support [55, 64].

Clinicians providing ECMO should co-ordinate their services at a regional level and collaborate in multicentre research [65]. This regional co-ordination should include at least one centre with high-volume activity which heads a regional or national network of ECMO-capable institutions, with mobile ECMO teams capable of both respiratory and cardiac support. The Extracorporeal Life Support Organization, formed in 1989, provides additional resources to clinicians and maintains a large international registry which now has data on over 45,000 patients supported with ECMO (<http://www.elso.med.umich.edu>) [9]. All centres providing ECMO to patients should be encouraged to join ELSO and participate in its efforts to answer important research questions, including how to refine patient selection, optimize the timing of ECMO initiation and quantify long-term changes in outcome as ongoing improvements in technology are made. ELSO conducts regular courses in ECMO technique, holds an annual meeting, and publishes both guidelines for patient management and the 'Red Book', the standard reference text of ECMO.

Results of ECMO in the recent H1N1 pandemic

In Australia and New Zealand between June and August 2009, 15 hospitals provided ECMO for refractory influenza A(H1N1)-associated respiratory failure, with existing

ECMO centres helping the others to start [17]. Many of the 201 patients treated in these centres recovered with conventional care. However, 68 of these patients continued to deteriorate despite advanced mechanical ventilatory support (as indicated by median PaO₂/FiO₂ ratio 56, median PEEP 18 cmH₂O and median acute lung injury score 3.8) and were placed on ECMO. Over 80% failed other attempts at rescue therapy including prone positioning, inhaled nitric oxide, prostacyclin and high-frequency oscillatory ventilation. Mortality was 21%. Bleeding was the most frequent complication, and death was attributed to intracranial haemorrhage in six patients [17].

Intensivists elsewhere read about this experience and prepared for the pandemic in the northern hemisphere winter. Established ECMO centres expanded their capabilities, new centres were initiated and regional triage plans were developed [19, 66]; for example, Italy nationally coordinated 14 ECMO centres to manage the pandemic. The Scottish government commissioned an expert working group which subsequently recommended the establishment of a national adult respiratory ECMO centre [66]. ELSO created an H1N1 registry, which ultimately collated data on 256 ECMO cases with a case fatality rate of 34% [67]. Similar results were seen with the French Réseau Européen de Recherche en Ventilation Artificielle (REVA) registry [68, 69].

Firm conclusions regarding the efficacy of contemporary ECMO cannot be drawn from these nonrandomized cohort studies [6, 7]. Nonetheless, the majority of patients survived in most published series and the pandemic caused an international resurgence in ECMO use [9]. A major factor in the rapid mobilization of ECMO during this pandemic was the new oxygenators, pumps and access cannulas. Centrifugal pumps and polymethylpentene-coated oxygenators were universally employed in the largest series [17].

Conclusions

ECMO is more complex and less commonly used than CRRT, but some parallels may be drawn between them.

In the 1980s and early 1990s, CRRT was perceived as too specialized for use in many ICUs. However, it has been widely adopted and is now routinely available in most high-income countries [70]. Access is provided by one dual-lumen catheter, and care of both patient and circuit is provided by a critical care nurse without the need for specialized input from a nephrology service. The evolution of extracorporeal circuitry has created a comparable situation with ECMO. Bedside care can be provided by a single trained nurse, and many intensivists perform ECMO cannulation without the aid of specialty surgical services.

A prospective study in adult respiratory failure is currently underway in France, the ECMO for Severe Acute Respiratory Distress Syndrome (EOLIA) trial [51], which may avoid the methodological issues criticized by some in the earlier CESAR study [4]. This study is designed to test the efficacy of early VV-ECMO in ARDS with tight control of mechanical ventilation in the control group, initiation of ECMO prior to transportation to ECMO centres and use of ECMO in every patient randomly assigned to receive it.

Despite the technological advances in extracorporeal respiratory support, chronic artificial respiratory support lags behind comparable developments in circulatory support, where progressive miniaturization and substantial amounts of national funding have created a new world with VADs either as a bridge to transplantation or as possible destination therapy. Nonetheless, the improvements in ECMO technology have allowed some centres to use ambulatory ECMO or other extracorporeal devices to liberate patients from mechanical ventilation and successfully bridge them to lung transplantation [58, 71–74]. Whether it will ever be feasible to safely use fully implantable, miniaturized respiratory devices as destination therapy remains an open question at present [75]. However, the use of contemporary ECMO in awake, potentially ambulant patients to provide both short-term support for those with acute, reversible respiratory failure and a bridge to transplantation in those with irreversible respiratory failure is now ready for widespread evaluation.

References

1. UK Collaborative ECMO Trial Group (1996) UK collaborative randomized trial of neonatal extracorporeal membrane oxygenation. *Lancet* 348:75–82
2. Green TP, Timmons OD, Fackler JC, Moler FW, Thompson AE, Sweeney MF (1996) The impact of extracorporeal membrane oxygenation on survival in pediatric patients with acute respiratory failure. Pediatric Critical Care Study Group. *Crit Care Med* 24:323–329
3. Cooper DS, Jacobs JP, Moore L, Stock A, Gaynor JW, Chancy T, Parpard M, Griffin DA, Owens T, Checchia PA, Thiagarajan RR, Spray TL, Ravishankar C (2007) Cardiac extracorporeal life support: start of the art in 2007. *Cardiol Young* 17:104–115

4. Peek GJ, Mugford M, Tiruvoipati R, Wilson A, Allen E, Thalanany MM, Hibbert CL, Truesdale A, Clemens F, Cooper N, Firmin RK, Elbourne D, CESAR trial collaboration (2009) Efficacy and economic assessment of conventional ventilatory support versus extracorporeal membrane oxygenation for severe adult respiratory failure (CESAR): a multicentre randomized controlled trial. *Lancet* 374:1351–1363
5. Zwischenberger JB, Lynch JE (2009) Will CESAR answer the adult ECMO debate? *Lancet* 374:1307–1308
6. Park PK, Dalton HJ, Bartlett RH (2010) Point: efficacy of extracorporeal membrane oxygenation in 2009 influenza A(H1N1): sufficient evidence? *Chest* 138:776–778
7. Morris AH, Hirshberg E, Miller RR 3rd, Statler KD, Hite RD (2010) Counterpoint: efficacy of extracorporeal membrane oxygenation in 2009 influenza A(H1N1): sufficient evidence? *Chest* 138:778–781
8. Zapol WM, Snider MT, Hill JD, Fallat RJ, Bartlett RH, Edmunds LH, Morris AH, Peirce EC 2nd, Thomas AN, Proctor HJ, Drinker PA, Pratt PC, Bagniewski A, Miller RG Jr (1979) Extracorporeal membrane oxygenation in severe acute respiratory failure. A randomized prospective study. *JAMA* 242:2193–2196
9. Extracorporeal Life Support Organization (2011) ECLS registry report. International Summary, Ann Arbor
10. MacLaren G, Butt W, Best D, Donath S, Taylor A (2007) Extracorporeal membrane oxygenation for refractory septic shock in children: one institution's experience. *Pediatr Crit Care Med* 8:447–451
11. MacLaren G, Butt W, Best D, Donath S (2011) Central extracorporeal membrane oxygenation for refractory pediatric septic shock. *Pediatr Crit Care Med* 12:133–136
12. Michaels AJ, Schriener RJ, Kolla S, Awad SS, Rich PB, Reickert C, Younger J, Hirschl RB, Bartlett RH (1999) Extracorporeal life support in pulmonary failure after trauma. *J Trauma* 46:638–645
13. Fortenberry JD, Meier AH, Pettignano R, Heard M, Chambliss CR, Wulkan M (2003) Extracorporeal life support for posttraumatic acute respiratory distress syndrome at a children's medical center. *J Pediatr Surg* 38:1221–1226
14. Gow KW, Lao OB, Leong T, Fortenberry JD (2010) Extracorporeal life support for adults with malignancy and respiratory or cardiac failure: the extracorporeal life support experience. *Am J Surg* 199:669–675
15. Gow KW, Heiss KF, Wulkan ML, Katzenstein HM, Rosenberg ES, Heard ML, Rycus PT, Fortenberry JD (2009) Extracorporeal life support for support of children with malignancy and respiratory or cardiac failure: the extracorporeal life support experience. *Crit Care Med* 37:1308–1316
16. Kolovos NS, Schuerer DJ, Moler FW, Bratton SL, Swaniker F, Bartlett RH, Custer JR, Annich G (2002) Extracorporeal life support for pulmonary hemorrhage in children: a case series. *Crit Care Med* 30:577–580
17. Australia and New Zealand Extracorporeal Membrane Oxygenation (ANZ ECMO) Influenza Investigators, Davies A, Jones D, Bailey M, Beca J, Bellomo R, Blackwell N, Forrest P, Gattas D, Granger E, Herkes R, Jackson A, McGuinness S, Nair P, Pellegrino V, Pettila V, Plunkett B, Pye R, Torzillo P, Webb S, Wilson M, Ziegenfuss M (2009) Extracorporeal membrane oxygenation for 2009 influenza A(H1N1) acute respiratory distress syndrome. *JAMA* 302:1888–1895
18. Chan KK, Lee KL, Lam PK, Law KI, Joynt GM, Yan WW (2010) Hong Kong's experience on the use of extracorporeal membrane oxygenation for the treatment of influenza A(H1N1). *Hong Kong Med J* 16:447–454
19. Turner DA, Williford WL, Peters MA, Thalman JJ, Shearer IR, Walczak RJ Jr, Griffs M, Olson SA, Sowers KW, Govert JA, Macintyre NR, Cheifetz IM (Epub 2011) Development of a collaborative program to provide extracorporeal membrane oxygenation for adults with refractory hypoxemia within the framework of a pandemic. *Pediatr Crit Care Med* 12:426–430
20. Bartlett RH, Gattinoni L (2010) Current status of extracorporeal life support (ECMO) for cardiopulmonary failure. *Minerva Anestesiol* 76:534–540
21. Cove ME, MacLaren G (2010) Clinical review: mechanical circulatory support for cardiogenic shock complicating acute myocardial infarction. *Crit Care* 14:235
22. Chen YS, Chao A, Yu HY, Ko WJ, Wu IH, Chen RJ, Huang SC, Lin FY, Wang SS (2003) Analysis and results of prolonged resuscitation in cardiac arrest patients rescued by extracorporeal membrane oxygenation. *J Am Coll Cardiol* 41:197–203
23. Magovern GJ Jr, Simpson KA (1999) Extracorporeal membrane oxygenation for adult cardiac support: the Allegheny experience. *Ann Thorac Surg* 68:655–661
24. Pagani FD, Lynch W, Swaniker F, Dyke DB, Bartlett R, Koelling T, Mosucci M, Deeb GM, Bolling S, Monaghan H, Aaronson KD (1999) Extracorporeal life support to left ventricular assist device bridge to heart transplant: a strategy to optimize survival and resource utilization. *Circulation* 100:II206–II210
25. Smedira NG, Moazami N, Golding CM, McCarthy PM, Apperson-Hansen C, Blackstone EH, Cosgrove DM 3rd (2001) Clinical experience with 202 adults receiving extracorporeal membrane oxygenation for cardiac failure: survival at 5 years. *J Thorac Cardiovasc Surg* 122:92–102
26. Combes A, Leprince P, Luyt CE, Bonnet N, Trouillet JL, Leger P, Pavie A, Chastre J (2008) Outcomes and long-term quality-of-life of patients supported by extracorporeal membrane oxygenation for refractory cardiogenic shock. *Crit Care Med* 36:1404–1411
27. Chen JS, Ko WJ, Yu HY, Lai LP, Huang SC, Chi NH, Tsai CH, Wang SS, Lin FY, Chen YS (2006) Analysis of the outcome for patients experiencing myocardial infarction and cardiopulmonary resuscitation refractory to conventional therapies necessitating extracorporeal life support rescue. *Crit Care Med* 34:950–957
28. Schwarz B, Mair P, Margreiter J, Pomaroli A, Hoermann C, Bonatti J, Lindner KH (2003) Experience with percutaneous venoarterial cardiopulmonary bypass for emergency circulatory support. *Crit Care Med* 31:758–764
29. Asaumi Y, Yasuda S, Morii I, Kakuchi H, Otsuka Y, Kawamura A, Sasako Y, Nakatani T, Nonogi H, Miyazaki S (2005) Favourable clinical outcome in patients with cardiogenic shock due to fulminant myocarditis supported by percutaneous extracorporeal membrane oxygenation. *Eur Heart J* 26:2185–2192
30. Massetti M, Tasle M, Le Page O, Deredec R, Babatasi G, Buklas D, Thuaudet S, Charbonneau P, Hamon M, Grollier G, Gerard JL, Khayat A (2005) Back from irreversibility: extracorporeal life support for prolonged cardiac arrest. *Ann Thorac Surg* 79:178–183
31. Doll N, Kiaii B, Borger M, Buceri J, Kramer K, Schmitt DV, Walther T, Mohr FW (2004) Five-year results of 219 consecutive patients treated with extracorporeal membrane oxygenation for refractory postoperative cardiogenic shock. *Ann Thorac Surg* 77:151–157
32. Peek GJ, Killer HM, Reeves R, Sosnowski AW, Firmin RK (2002) Early experience with a polymethyl pentene oxygenator for adult extracorporeal life support. *ASAIO J* 48:480–482

33. Khoshbin E, Roberts N, Harvey C, Machin D, Killer H, Peek GJ, Sosnowski AW, Firmin RK (2005) Poly-methyl pentene oxygenators have improved gas exchange capability and reduced transfusion requirements in adult extracorporeal membrane oxygenation. *ASAIO J* 51:281–287
34. Nishinaka T, Tatsumi E, Katagiri N, Ohnishi H, Mizuno T, Shioya K, Tsukiya T, Homma A, Kashiwabara S, Tanaka H, Sato M, Taenaka Y (2007) Up to 151 days of continuous animal perfusion with trivial heparin infusion by the application of a long-term durable antithrombogenic coating to a combination of a seal-less centrifugal pump and a diffusion membrane oxygenator. *J Artif Organs* 10:240–244
35. Mendler N, Podecht F, Feil G, Hiltmann P, Sebening F (1995) Seal-less centrifugal blood pump with magnetically suspended rotor: rot-a-flot. *Artif Organs* 19:620–624
36. Talor J, Yee S, Rider A, Kunselman AR, Guan Y, Undar A (2010) Comparison of perfusion quality in hollow-fiber membrane oxygenators for neonatal extracorporeal life support. *Artif Organs* 34:E110–E116
37. Rho YR, Choi H, Lee JC, Choi SW, Chung YM, Lee HS, Hwang CM, Lee HS, Ahn SS, Lee RY, Son HS, Choi MJ, Baek KJ, Kim JS, Suh GJ, Won YS, Sun K, Min BG (2003) Applications of the pulsatile flow versatile ECLS: in vivo studies. *Int J Artif Organs* 26:428–435
38. Wang D, Zhou X, Liu X, Sidor B, Lynch J, Zwischenberger JB (2008) Wang-Zwische double lumen cannula—toward a percutaneous and ambulatory paracorporeal artificial lung. *ASAIO J* 54:606–611
39. Bermudez CA, Rocha RV, Sappington PL, Toyoda Y, Murray HN, Boujoukos AJ (2010) Initial experience with single cannulation for venovenous extracorporeal oxygenation in adults. *Ann Thorac Surg* 90:991–995
40. Preston TJ, Hodge AB, Riley JB, Leib-Sargel C, Nicol KK (2007) In vitro drug adsorption and plasma free hemoglobin levels associated with hollow fiber oxygenators in the extracorporeal life support (ECLS) circuit. *J Extra Corpor Technol* 39:234–237
41. Mehta NM, Halwick DR, Dodson BL, Thompson JE, Arnold JH (2007) Potential drug sequestration during extracorporeal membrane oxygenation: results from an ex vivo experiment. *Intensive Care Med* 33:1018–1124
42. Wildschut ED, Ahsman MJ, Allegaert K, Mathot RA, Tibboel D (2010) Determinants of drug adsorption in different ECMO circuits. *Intensive Care Med* 36:2109–2116
43. Preston TJ, Ratliff TM, Gomez D, Olshove VE Jr, Nicol KK, Sargel CL, Chicoine LG (2010) Modified surface coatings and their effect on drug adsorption within the extracorporeal life support circuit. *J Extra Corpor Technol* 42:199–202
44. Gattinoni L, Agostini A, Pesenti A, Pelizzola A, Rossi GP, Langer M, Vesconi S, Uziel L, Fox U, Longoni F, Kolobow T, Damia G (1980) Treatment of acute respiratory failure with low-frequency positive-pressure ventilation and extracorporeal removal of CO₂. *Lancet* 2:292–294
45. Morris AH, Wallace CJ, Menlove RL, Clemmer TP, Orme JF Jr, Weaver LK, Dean NC, Thomas F, East TD, Pace NL, Suchyta MR, Beck E, Bombino M, Sittig DF, Bohm S, Hoffmann B, Becks H, Butler S, Pearl J, Rasmusson B (1994) Randomized clinical trial of pressure-controlled inverse ratio ventilation and extracorporeal CO₂ removal for adult respiratory distress syndrome. *Am J Respir Crit Care Med* 149:295–305
46. Floerchinger B, Philipp A, Foltan M, Rupprecht L, Klose A, Camboni D, Bruenger F, Schopka S, Hilker M, Schmid C (2010) Switch from venoarterial extracorporeal membrane oxygenation to arteriovenous pumpless extracorporeal lung assist. *Ann Thorac Surg* 89:125–131
47. Liebold A, Reng CM, Philipp A, Pfeifer M, Birndaum DE (2000) Pumpless extracorporeal lung assist—experience with the first 20 cases. *Eur J Cardiothorac Surg* 17:608–613
48. Bein T, Weber F, Philipp A, Prasser C, Pfeifer M, Schmid FX, Butz B, Birnbaum D, Taeger K, Schlitt HJ (2006) A new pumpless extracorporeal interventional lung assist in critical hypoxemia/hypercapnia. *Crit Care Med* 34:1372–1377
49. Bartlett RH, Chapman R (2005) Economics of ECLS. In: Van Meurs KP, Lally KP, Peek GJ, Zwischenberger JB (eds) *ECMO, Extracorporeal cardiopulmonary support in critical care*, 3rd edn. Extracorporeal Life Support Organization, Ann Arbor, pp 203–215
50. Extracorporeal Life Support Organization (2009) ELSO guidelines. <http://www.else.med.umich.edu/WordForms/ELSO%20Guidelines%20General%20All%20ECLS%20Version1.1.pdf>. Accessed 5 July 2011
51. Combes A (2011) Extracorporeal membrane oxygenation (ECMO) for severe acute respiratory distress syndrome (SARS). <http://revaweb.org/gb/etudes.php#e2>. Accessed 29 March 2011
52. Extracorporeal Life Support Organization (2009) ELSO patient specific guidelines. <http://www.else.med.umich.edu/WordForms/ELSO%20Pt%20Specific%20Guidelines.pdf>. Accessed 5 July 2011
53. Linden V, Palmer K, Reinhard J, Westman R, Ehren H, Granholm T, Frenckner B (2001) Inter-hospital transportation of patients with severe acute respiratory failure on extracorporeal membrane oxygenation—national and international experience. *Intensive Care Med* 27:1643–1648
54. Nehra D, Goldstein AM, Doody DP, Ryan DP, Chang Y, Masiakos PT (2009) Extracorporeal membrane oxygenation for nonneonatal acute respiratory failure: the Massachusetts general hospital experience from 1990 to 2008. *Arch Surg* 144:427–432
55. Linden V, Palmer K, Reinhard J, Westman R, Ehren H, Granholm T, Frenckner B (2000) High survival in adults patients with acute respiratory distress syndrome treated by extracorporeal membrane oxygenation, minimal sedation, and pressure supported ventilation. *Intensive Care Med* 26:1630–1637
56. Trouillet JL, Luyt CE, Guiquet M, Ouattara A, Vaissier E, Makri R, Nieszkowska A, Leprince P, Pavie A, Chastre J, Combes A (2011) Early percutaneous tracheotomy versus prolonged intubation of mechanically ventilated patients after cardiac surgery: a randomized trial. *Ann Intern Med* 154:373–383
57. Olsson KM, Simon A, Strueber M, Hadem J, Wiesner O, Gottlieb J, Fuehner T, Fischer S, Warnecke G, Kuhn C, Haverich A, Welte T, Hoepfer MM (2010) Extracorporeal membrane oxygenation in nonintubated patients as a bridge to lung transplantation. *Am J Transpl* 10:2173–2178
58. Garcia JP, Iacono A, Kon ZN, Griffith BP (2010) Ambulatory extracorporeal membrane oxygenation: a new approach for bridge-to-lung transplantation. *J Thorac Cardiovasc Surg* 139:e137–e139
59. Schweickert WD, Pohlman MC, Pohlman AS, Nigos C, Pawlik AJ, Esbrook CL, Spears L, Miller M, Franczyk M, Deprizio D, Schmidt GA, Bowman A, Barr R, McCallister KE, Hall JB, Kress JP (2009) Early physical and occupational therapy in mechanically ventilated, critically ill patients: a randomized controlled trial. *Lancet* 373:1874–1882

60. Papazian L, Forel JM, Gacouin A, Penot-Ragon C, Perrin G, Loundou A, Jaber S, Arnal JM, Perez D, Seghboyan JM, Constantin JM, Courant P, Lefrant JY, Guerin C, Prat G, Morange S, Roch A (2010) Neuromuscular blockers in early acute respiratory distress syndrome. *N Engl J Med* 363:1107–1116
61. National Heart Blood Lung Institute Acute Respiratory Distress Syndrome (ARDS) Clinical Trials Network, Wiedemann HP, Wheeler AP, Bernard GR, Thompson BT, Hayden D, deBoisblanc B, Connors AF Jr, Hite RD, Harabin AL (2006) Comparison of two fluid-management strategies in acute lung injury. *N Engl J Med* 354:2564–2575
62. Rosenberg AL, Dechert RE, Park PK, Bartlett RH (2009) Review of a large clinical series: association of cumulative fluid balance on outcome in acute lung injury: a retrospective review of the ARDSnet tidal volume study cohort. *J Intensive Care Med* 24:35–46
63. Green TP, Moler FW, Goodman DM (1995) Probability of survival after prolonged extracorporeal membrane oxygenation in pediatric patients with acute respiratory failure. *Extracorporeal life support organization. Crit Care Med* 23:1132–1139
64. Wang CH, Chou CC, Ko WJ, Lee YC (2010) Rescue a drowning patient by prolonged extracorporeal membrane oxygenation support for 117 days. *Am J Emerg Med* 28:e5–e7
65. Dalton HJ, MacLaren G (2010) Extracorporeal membrane oxygenation in pandemic flu: insufficient evidence or worth the effort? *Crit Care Med* 38:1484–1485
66. Scottish ECMO Expert Group (2009) www.scotland.gov.uk/Resource/Doc/309738/0097693.pdf. Accessed 2 May 2011
67. Extracorporeal Life Support Organization (2010) H1N1 Registry. <http://www.elseo.med.umich.edu/H1N1Registry.html>. Accessed 17 March 2011
68. Pham T, Richard JCM, Brun-Buisson C, Reigner J, Brochard L (2011) Epidémie de grippe A H1N1 en réanimation: description du register REVA grippe SRLF. http://revaweb.org/pdf/abstract%20srlf%20004670_FR.pdf. Accessed 29 March 2011
69. Mercat A, Richard JCM, Combes A, Chastre J, Ricard JD, Dreyfuss D, Brochard L (2011) SDRA lié à la grippe A (H1N1)-2009, Recommandations pour l'assistance respiratoire. <http://www.srlf.org/Data/upload/file/Grippe%20A/reco%20REVA%20SDRA-H1N1.pdf>. Accessed 29 March 2011
70. Uchino S, Kellum JA, Bellomo R, Doig GS, Morimatsu H, Morgera S, Schetz M, Tan I, Bouman C, Macedo E, Gibney N, Tolwani A, Ronco C (2005) Acute renal failure in critically ill patients: a multinational, multicenter study. *JAMA* 294:813–818
71. Haneya A, Phillip A, Mueller T, Lubnow M, Pfeifer M, Zink W, Hilker M, Schmid C, Hirt S (2011) Extracorporeal circulatory systems as a bridge to lung transplantation at remote transplant centers. *Ann Thorac Surg* 91:250–255
72. Ricci D, Boffini M, Del Sorbo L, El Quarra S, Comoglio C, Ribezzo M, Bonato R, Ranieri VM, Rinaldi M (2010) The use of CO₂ removal devices in patients awaiting lung transplantation: an initial experience. *Transpl Proc* 42:1255–1258
73. Strueber M, Hoepfer MM, Fischer S, Cypel M, Warnecke G, Gottlieb J, Pierre A, Welte A, Haverich A, Simon AR, Keshavjee S (2009) Bridge to thoracic organ transplantation in patients with pulmonary arterial hypertension using a pumpless lung assist device. *Am J Transpl* 9:853–857
74. Fischer S, Simon AR, Welte T, Hoepfer MM, Meyer A, Tessmann R, Gohrbandt B, Gottlieb J, Haverich A, Strueber M (2006) Bridge to lung transplantation with the novel pumpless interventional lung assist device NovaLung. *J Thorac Cardiovasc Surg* 131:719–723
75. Strueber M (2010) Extracorporeal support as a bridge to lung transplantation. *Curr Opin Crit Care* 16:69–73