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REVIEW

Extracorporeal membrane oxygenation: unmet needs and perspectives

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Abstract

Extracorporeal Membrane Oxygenation (ECMO) has become an essential lifesaving intervention for individuals with severe cardiovascular and respiratory failure. Its application is expanding across several therapeutic contexts, surpassing conventional indications. The COVID-19 pandemic has significantly stressed worldwide health systems to manage acute respiratory failure. ECMO has been employed as a vital intervention, particularly for patients with severe COVID-19-induced acute respiratory distress syndrome (ARDS). ECMO is applicable throughout pregnancy. The principal indications for ECMO in pregnant women align with those in the general population. However, pregnancy complicates issues, necessitating consideration of both mother's and infant's well-being. Patients with systemic rheumatic diseases are prone to experience life-threatening complications. While a majority of these patients respond to immunosuppressive drugs, a small percentage suffer organ failure and may benefit from ECMO as a bridge to recovery. The article addresses coagulation therapies, highlighting the necessity of precise anticoagulation to avert both bleeding and thrombosis, particularly in patients requiring extended ECMO support. Additionally, the pharmacokinetics of antibiotics in ECMO patients are summarized, including the influence of the ECMO circuit on drug metabolism. Survey-based research offers valuable insights into ECMO use, procedures, and challenges. The paper evaluates current survey-based research and ECMO guidelines, highlighting clinical practice, training, and resource availability discrepancies across ECMO centers globally. Particular focus is placed on the rehabilitation requirements of ECMO survivors, acknowledging the importance of early mobilization and post-discharge care in improving long-term outcomes and quality of life.

Keywords Extracorporeal membrane oxygenation · ECMO treatment · COVID-19 · Pregnancy · Rheumatic diseases · Practice guideline · Surveys and questionnaires · Rehabilitation

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Introduction

Extracorporeal membrane oxygenation (ECMO) is an interim procedure employed to maintain lifesaving care for cardiovascular disease, lung and respiratory dysfunction, or both of them until the patient's organ(s) and structures have fully recovered or before alternative definitive therapeutic options can be implemented [1]. ECMO functions by diverting blood via an extracorporeal circuit, where it undergoes oxygenation and carbon dioxide removal from the patient's body before reintroducing it into the patient's bloodstream [2]. This technology serves as a conduit for facilitating recovery, organ transplantation, or making decisions on end-of-life care [3]. In recent decades, the utilization of ECMO has increased worldwide due to advances in technology and a greater acknowledgment of its capacity to enhance outcomes in patients with severe conditions [4].

Veno-venous or veno-arterial ECMO involves extracting deoxygenated blood from the veins, filtering it through a membrane oxygenator to eliminate carbon dioxide and increase oxygen level, and then returning the oxygenated blood to either the veins or arteries, depending on the specific technique. This procedure is made easier by a straightforward cannula structure, a blood pump, an oxygenator, and a device that exchanges heat [5]. Veno-venous ECMO is an option for cases of primary respiratory failure that do not respond to standard medical treatment and care and if mechanical ventilation fails to recover sufficiently [6]. Veno-arterial ECMO offers both carbon dioxide-oxygen exchange and mechanical circulatory assistance simultaneously with the heart's natural function. This is particularly beneficial in situations of isolated heart dysfunction or a combination of cardiac-pulmonary failure [7].

ECMO services can vary in their organization and execution across countries. South Korea and Japan have well-established ECMO centers that prioritize quick implementation and employ highly qualified multidisciplinary teams. South Korea has established an effective ECMO network with dedicated centers that aim to ensure prompt access [8–11]. ECMO services in the United States are mostly found in tertiary care centers and teaching hospitals affiliated with specialized ECMO programs. These programs offer comprehensive care, educational resources, and research prospects. These initiatives receive support from national and international guidelines that aim to standardize the utilization of ECMO and improve patient outcomes [12, 13].

The growing utilization of ECMO has sparked discussions over its cost-effectiveness and the ethical considerations of allocating resources, especially given the risks of death and morbidity associated with its application [14]. Maximizing benefits of ECMO technology requires addressing unmet demands and gaining a better knowledge of the factors that affect results.

Aim

This article overviews current practices, issues, and perspectives on ECMO in diverse medical settings. The article focuses on the administration of ECMO in critical care for patients with severe cardiovascular and respiratory failure and its application in specialized areas such as COVID-19, pregnancy, and rheumatic diseases. This article examines coagulation management and the pharmacokinetics of antibiotic therapies in ECMO patients. An additional objective is to provide an overview of the recommended ECMO-related protocols. The paper summarizes survey-based studies on the use of ECMO, focusing on differences in practice, resource allocation, and education in different ECMO centers and assesses the rehabilitation needs of ECMO patients.

Search strategy

While retrieving a list of papers related to the topic, Web of Science, Scopus, Medline/PubMed, and Directory of Open Access Journals (DOAJ) were considered. Search phrases were organized as follows: ''Extracorporeal Membrane Oxygenation'' or ''ECMO Treatment'' and ''COVID-19'' or ''Pregnancy'' or ''Rheumatic Diseases'' or ''Blood Coagulation'' or ''Antibiotics'' or ''Practice Guideline'' or ''Surveys and Questionnaires'' or ''Rehabilitation''. English papers published up until June 2024 were considered. While the authors did not specify a particular article type as an exclusion criterion, they assessed each article for its topical relevance. Additionally, authors scanned through the references of relevant papers and, where needed, consulted the corresponding scientific articles. Gasparyan et al.'s criteria served as the basis for creating and modifying the aforementioned search approach [15].

Extracorporeal membrane oxygenation during the COVID-19 pandemic

The COVID-19 pandemic has created a significant burden on global health systems in the treatment of severe respiratory failure. ECMO has been utilized as a critical approach, particularly for individuals with severe COVID-19-related acute respiratory distress syndrome (ARDS) [16, 17].

Although preliminary findings have indicated negative outcomes with the use of the ECMO approach [18], data from international registries and larger studies have shown promising results in COVID-19-related ARDS [19]. An extensive meta-analysis conducted during the early stages of the pandemic examined COVID-19 patients who underwent

ECMO support. The findings indicated that this particular group of patients had similar results to those with COVID-19-unrelated ARDS. This underscores the potential efficacy of ECMO in managing COVID-19 patients who are meticulously and correctly selected [20]. Research undertaken during the later phases of the pandemic has indicated a higher mortality rate among COVID-19 patients who received ECMO intervention. This can be attributed to changes in concurrent treatments, patient selection, increased overlapping bacterial pneumonia during immunosuppressive therapies, limited experience of health centers, and changing virus variants [21, 22].

The pandemic has also revealed the logistical and operational difficulties of using ECMO on a big scale. Hospitals encountered deficiencies in ECMO equipment, proficient personnel, and essential supplies. The high demand for ECMO during the pandemic has resulted in advances in resource allocation, such as establishing regional ECMO services and creating mobile ECMO teams to transfer patients to specialized centers [23]. Amid the pandemic, national-level coordination of ECMO initiatives was employed to enhance the effectiveness of standardizing ECMO eligibility and appropriately distributing resources. A regional network in Paris coordinated the care of hospitals to combine resources, standardize assessments for ECMO candidature, and increase ECMO capacity. This strategy was carried out to improve the efficient use of resources, simplify the workflow, enhance the management of patients before ECMO treatment, and improve gathering data [24, 25]. The Extracorporeal Life Support Organisation (ELSO) promotes the establishment of national ECMO connections and encourages the coordination of these organizations via a mapping system [26].

A dramatic increase in ARDS cases associated with COVID-19 has led to a corresponding surge in the need for ECMO support. The utilization of ECMO during the pandemic has been complicated by several factors, such as insufficient familiarity and understanding of ECMO-related outcomes, obstacles in conducting comprehensive studies during the pandemic, challenges in selecting patients during severe capacity limitations, ethical issues, and overwhelming pressure on healthcare systems. Nevertheless, utilizing ECMO in precisely selected cases has been linked to favorable results in managing COVID-19-induced ARDS [27].

Extracorporeal membrane oxygenation in pregnant patients

ECMO is now widely acknowledged as a lifesaving option for pregnant individuals who are suffering from serious cardiac or respiratory failure. Pregnancy poses distinct physiological obstacles, including heightened cardiac and respiratory demands that may worsen pre-existing diseases such as ARDS, cardiomyopathy, or serious infections like influenza and COVID-19 [28, 29]. The primary indications for ECMO in pregnants are similar to those in the general population. However, it is clear that pregnancy complicates matters since both maternal and infant well-being needs to be considered [30]. Planning a multidisciplinary team for this particular population is crucial, including several medical and surgical specialties and other healthcare experts [31].

The maternal survival rate for pregnant and postpartum patients who need ECMO has significantly increased. Survival rates for obstetric patients in ELSO registries currently surpass those of the general adult population [32]. Fetal survival data are also positive [33]. Both vaginal and cesarean delivery can be considered viable options for pregnants undergoing ECMO treatment. Decisions about pregnancy follow-up and gynecological procedures are tailored to each individual, considering factors involving stage of pregnancy, fetal lung advancement, pregnant's cardiopulmonary capacity, duration of time on ECMO, and any other existing health conditions [30].

It is important to carefully examine and manage severe anemia while providing ECMO procedures, as the amount of oxygen that the blood can carry relies on the quantity of hemoglobin. Thrombocytopenia frequently occurs during ECMO due to platelet activation caused by circuit parts, chronic inflammation, drugs, and related medical conditions. Furthermore, while pregnancy is a hypercoagulable state with an increase in clotting-related factors, von Willebrand factor, and fibrinogen, there is limited evidence to suggest that pregnancy raises the likelihood of oxygenator or ECMO system thrombosis [34].

ECMO has become an acceptable therapeutic choice for pregnant patients experiencing severe respiratory or cardiac failure, providing a potential pathway to recovery for both the mother and fetus. There is increasing evidence that ECMO is an essential tool in managing high-risk pregnancies that are complicated by life-threatening issues. Further research is warranted to enhance the criteria for selecting patients and to improve outcomes for both the mother and fetus.

Perspectives of extracorporeal membrane oxygenation in rheumatology

Patients with systemic autoimmune and inflammatory disorders are more likely to develop life-threatening consequences such as serious interstitial lung disease, pulmonary arterial hypertension, and cardiac or respiratory failure [35]. While many of these patients respond to immunosuppressive drugs, a fraction suffers from refractory organ failure and may benefit from ECMO as a bridge to recovery [36, 37].

Bay et al. [37] presented one of the largest series (90 patients) on ECMO use and outcomes in rheumatic diseases. The vast majority of patients were admitted to the hospital for a worsening of their rheumatic disease, with just a quarter admitted for infection. Prior to hospitalization, the organs most frequently affected were the lungs, joints, skin, heart, and kidneys. Before being admitted to the intensive care unit, 47.8% of the patients consistently utilized corticosteroids, while 36.7% were on immunosuppressants. Intensive care unit mortality and in-hospital mortality rates were 48.9% and 51.1%, respectively. Emergency transplantation effectively cured nine patients with resistant cardiac ($n=5$) or pulmonary ($n=4$) failure.

Systemic lupus erythematosus (SLE) is a rheumatic disorder that may lead to severe and potentially life-threatening consequences, such as lupus myocarditis, extensive lung involvement, and thromboembolic events [38]. Leung et al. [39] presented a case of cardiogenic shock secondary to SLE and emphasized the positive effects of ECMO on disease management. Shi et al. [40] reported three hemodynamically unstable lupus myocarditis cases. ECMO support was provided to manage these cases. Gradual recovery of cardiac function was observed in all three patients after ECMO. Pacheco et al. [41] presented two patients with diffuse alveolar hemorrhage related to SLE. ECMO support was provided to manage both patients. The first patient died of hemodynamic failure caused by massive, severe bleeding and septic shock. The second patient successfully recovered and was removed from mechanical ventilation after a period of 10 days. During the follow-up of 1 year, the patient's condition remained stable, and he did not have any complications.

Zheng et al. [42] described 22 cases of acute lung injury associated with idiopathic inflammatory myopathies. All patients underwent ECMO. Eight patients died in the intensive care unit, six were successfully transitioned to recovery, and eight were properly transferred to transplantation. When comparing patients who were successfully supported till recovery and those who died, it was observed that the individuals who died were of older ages and had higher median comorbidity scores. Zulian et al. [43] presented a case of juvenile dermatomyositis with severe interstitial lung disease. Radiologic examination indicated diffuse interstitial pattern, alveolitis, pneumothorax, pneumomediastinum, and subcutaneous emphysema. The patient recovered with immunosuppressive therapy and ECMO support. Rubin et al. [44] reported a series of 9 cases on ECMO for myositis-associated rapidly progressive interstitial lung disease. One of the cases survived. Truong et al. [45] reported a patient with dermatomyositis with rapidly progressive interstitial pneumonia. The patient received ECMO support due to worsening respiratory failure. The patient died of hemorrhagic shock on the 14th day after ECMO.

Delvino et al. [46] documented two cases of diffuse alveolar hemorrhage caused by ANCA-associated vasculitis, which were successfully treated with ECMO support. ECMO provided a window of opportunity for lifesaving interventions in both patients. Alveolar hemorrhage did not worsen, and active bleeding ceased following the beginning of ECMO. Yusuff et al. [47] presented two patients without any prior vasculitis who experienced severe pulmonary hemorrhage caused by ANCA-positive vasculitis. The use of ECMO significantly assisted in their recovery. Matsumoto et al. [48] described two patients who experienced near-fatal respiratory failure due to pulmonary hemorrhage in ANCA-associated vasculitis. Following the use of ECMO, pulmonary hemorrhage diminished, and the patients were effectively withdrawn from ECMO.

ECMO support has been used in cases of mixed connective tissue disease-associated fulminant myocarditis [49], Kawasaki disease [50], and juvenile idiopathic arthritis [51]. Table 1 summarizes the main articles on ECMO support in rheumatic diseases.

Although case reports and small studies have described the use of ECMO in patients with rheumatic diseases, there is still a paucity of comprehensive clinical trials and recommendations specifically tailored to this group. Additional investigation is required to determine the most effective application of ECMO in rheumatology, such as identifying patients who are most likely to experience positive outcomes and developing strategies to minimize risks associated with autoimmune diseases and immunosuppressive treatments.

Coagulation-related issues

Managing coagulation in ECMO patients is crucial for preventing both thrombotic and bleeding disorders. The thrombotic process is induced by hypercoagulability, microdamage to the vessel wall, and reduction and stagnation of blood flow. The ECMO circuit comprises non-biological surfaces, areas with extremely high shear stress, and places where blood remains for extended periods. These effects increase the likelihood of blood clot development. Anticoagulant strategies may induce bleeding-related issues [52, 53]. Patients undergoing ECMO generally experience severe illness, which heightens their probability of experiencing bleeding. Bleeding most commonly occurs at the cannula location, gastrointestinal tract, lungs, and central nervous system [54].

Although there are various agents that can be used as anticoagulants in ECMO patients, heparin and direct thrombin inhibitors are the most commonly preferred

Table 1 Summary of the main articles related to ECMO support in rheumatic diseases

Author	Article type	Sex	Age (years)	Rheumatic disease	ECMO indication	Concomitant treatment	Prognosis
Bay et al. [37]	Retrospective study	Ninety patients (male/female ratio: 0.5)	41.6 ± 15.2	Consisting of SRDs	69 patients flare related issues and 21 patients infection-related issues.	Corticosteroids and immunosuppressant(s)	ICU mortality and in-hospital mortality rates were 48.9% and 51.1%, respectively.
Leung et al. [39]	Case report	Female	24	SLE	Cardiac failure and cardiogenic shock	IV methylprednisolone (25O mg)	After ECMO, her condition stabilised.
Shi et al. [40]	Case report (3 cases)	Case 1: Female Case 2: Female Case 3: Female	Case 1: 43 Case 2: 32 Case 3: 22	SLE	Cardiac insufficiency and cardiogenic shock	Dexamethasone (case 1), 500 mg of methylprednisolone (case 2), and methylprednisolone (1 g/2 days) (case 3)	Recovery of cardiac function was observed in three patients. Case 2 died due to pulmonary infection.
Pacheco et al. [41]	Case report (2 cases)	Case 1: Female Case 2: Male	Case 1: 33 Case 2: 36	SLE	Severe respiratory failure	Pulse corticosteroids and intravenous cyclophosphamide (case 1), Pulse intravenous corticosteroids and cyclophosphamide (case 2)	Case 1died and case 2 recovered.
Zheng et al. [42]	Case series (22 cases)	11 female and 11 male	47 ± 12	Idiopathic inflammatory myopathies	Respiratory failure	Corticosteroids, immunosuppressor(s), and plasmapheresis	Eight patients died, six were successfully transitioned to recovery, and eight were transferred to transplantation.
Zulian et al. [43]	Case report	Female	3	Juvenile dermatomyositis	Severe interstitial lung disease and respiratory failure	Metylpredisolone (30 mg/kg), prednisone (2 mg/kg), and cyclophosphamide (2 mg/kg)	Patient recovered.
Rubin et al. [44]	Case series (9 cases)	5 female and 4 male	52.2 ± 10	Myositis	Rapidly progressive interstitial lung disease	Seven patients received triple immunosuppressive therapy with pulse-dosed steroids, rituximab, and IV immunoglobulins. Patient 2 received mycophenolate mofetil, and patients 3 and 5 also received cyclophosphamide.	One patient was discharged without any sequelae.
Truong et al. [45]	Case report	Male	51	Dermatomyositis	Acute respiratory distress syndrome	Pulse dose solumedrol, cyclophosphamide, and cyclosporine	Patient died of hemorrhagic shock on the 14th day after ECMO.
Delvino et al. [46]	Case report (2 cases)	Case 1:Female Case 2: Male	Case 1: 45 Case 2: 45	ANCA-associated vasculitis	Acute respiratory failure, massive alveolar haemorrhage	Methylprednisolone pulses (1 g intravenously/day on 3 consecutive days), plasma exchange, and cyclophosphamide pulses (case 1). Methylprednisolone pulse therapy (1 g intravenously/day on 3 consecutive days), followed by rescue therapy with rituximab (375 mg/m2/ week on 4 consecutive weeks) (case 2).	The general condition improved.
Yusuff et al. [47]	Case report (2 cases)	Case 1: Female Case 2: Male	Case 1: 23 Case 2: 27	ANCA-associated vasculitis	Pulmonary capillaritis complicated by diffuse alveolar hemorrhage	IV methylprednisolone, 1 g daily for 3 days (case 1); pulsed IV methylprednisolone followed by daily hydrocortisone dosed at 50 mg IV four times a day, plasma exchange followed by rituximab and IV immunoglobulin (case 2).	Clinical improvement was achieved.

Table 1 (continued)

Author	Article type	Sex	Age (years)	Rheumatic disease	ECMO indication	Concomitant treatment	Prognosis
Matsumoto et al. [48]	Case report (2 cases)	Case 1: Female Case 2: Male	Case 1: 19 Case 2: 29	ANCA-associated vasculitis	Respiratory failure	Methylprednisolone pulse theray (250 mg/day|3 days) combined with plasma exchange was instituted, followed by oral cyclophosphamide (case 1); The Methylprednisolone pulse therapy (1000 mg/day|3 days), plasma exchange and intravenous cyclophosphamide	Clinical improvement was achieved.
Hamana et al. [49]	Case report	Female	22	Mixed connective tissue disease	Fulminant myocarditis	Steroid pulse therapy (methylprednisolone, one1000 mg/day), continued with prednisolone (100 mg/day) and intravenous cyclophosphamide (1000 mg)	Patient recovered.
Cohen et al. [50]	Case report	Male	2	Kawasaki disease	Respiratory and circulatory failure	IL-1RA was administered (anakinra once daily, 1 mg/kg subcutaneously). IVIG with low-dose prednisone was used.	Beneficial effects reported.
Yang et al. [51]	Case report	Male	14	Juvenile idiopathic arthritis	Macrophage activation syndrome, respiratory and circulatory failure	Pulse methylprednisolone therapy, followed by a maintenance dosage of 10 mg/kg/day	Patient recovered.

SRDs: Systemic rheumatic diseases; ICU: Intensive care unit; SLE: Systemic lupus erythematosus; ECMO: Extracorporeal membrane oxygenation

agents [52]. Unfractionated heparin is the most frequently employed anticoagulant due to its affordable price, titratability, and ease of reversal. Heparin suppresses thrombin by attaching to the antithrombin. Antithrombin has limited anticoagulant action; however, when coupled with heparin, its anticoagulant capacity rises dramatically [55]. Heparin utilization is linked to immune-mediated adverse effects referred to as heparin-induced thrombocytopenia. This condition is characterized by paradoxical prothrombotic status and decrease in platelet count [56]. Direct thrombin inhibitors are a class of anticoagulants that specifically attach to the active sites on thrombin. In addition, they offer higher reliability and predictability in preventing blood clotting as they are not bound to other proteins in the circulatory system. Furthermore, they do not stimulate heparin-induced thrombocytopenia. Their main constraint is the absence of a pharmaceutical antidote [57].

There are no consensus regimens for ECMO patients regarding anticoagulation procedures and monitoring approaches. According to a survey-based study covering ECMO facilities, the most frequently utilized anticoagulant is unfractionated heparin, titrated based on activated clotting time, activated partial thromboplastin time, or anti-Xa test outcomes. Because of the variability in practice, it is advised that each ECMO center develop the most beneficial algorithm for its needs [58].

Antibiotic therapies

ECMO is frequently employed in critically ill patients requiring antibiotics due to their susceptibility to infection resulting from their underlying medical conditions, invasive procedures, and extended hospitalization. ECMO therapy enhances vulnerability to infections, including bloodstream infections, ventilator-associated pneumonia, and cannula site infections. Many ECMO patients are immunocompromised, either as a result of the severe disease or due to other underlying disorders. In addition, certain individuals may be taking immunosuppressive drugs, which further weaken their immune system. The interplay between ECMO and antibiotic therapies poses distinct obstacles that necessitate meticulous deliberation, including diverse pharmacokinetics, dosage approaches, and concerns regarding antibiotic resistance [59, 60].

Several circuit characteristics may modify pharmacokinetics. These occurrences are contingent upon the characteristics of the drug, the type of circuit, and the formation of cylinders and biofilms. The ECMO circuit possesses a substantial surface area that may trap medications, while the coatings and components of the circuit itself diminish the bioavailability of antimicrobial substances [61]. The ECMO circuit's substantial volume augments the distribution volume. The dilution effect may decrease the plasma concentrations of certain antibiotics, resulting in subtherapeutic levels and ultimately leading to unsuccessful treatment [60, 62]. ECMO may affect the functioning of the kidneys and liver, both of which play a crucial role in the elimination of drugs. Renal and liver failure, prevalent among critically ill patients undergoing ECMO, may necessitate adjustments in antibiotic dose or intervals. However, individuals who have hyperdynamic circulation may show an increase in the rate at which the drug is eliminated from their body, which may necessitate a dose increase [63, 64].

The connection between ECMO and antibiotic treatment necessitates a specialized strategy due to changes in medication absorption, distribution, metabolism, excretion, heightened susceptibility to infections, and possibility of encountering multidrug-resistant pathogens.

Practice guidelines on extracorporeal membrane oxygenation

Organizations like ELSO have created extensive practice guidelines to standardize ECMO use and enhance patient outcomes (https://www.elso.org/ecmo-resources/elso-ecmo-guidelines.aspx). These guidelines include both the technical and clinical aspects of ECMO support, with evidence-based recommendations for commencement, treatment, and termination. The recommendations emphasize multidisciplinary teamwork, patient selection, and strict management measures to maximize safety and efficacy. ELSO has recommendations for general and specific patient groups:

- *ELSO General Guidelines for all Extracorporeal Life Support (ECLS) Cases* (https://www.elso.org/portals/0/elso%20guidelines%20general%20all%20ecls%20version%201_4.pdf).
- *ELSO Guidelines for Neonatal Respiratory Failure* [65].
- *ELSO Guideline for Adult Respiratory Failure Managed with Venovenous ECMO* [66].
- *ELSO Guidelines for Pediatric Respiratory Failure* [67].
- *Extracorporeal Cardiopulmonary Resuscitation in Adults. Interim Guideline Consensus Statement From the ELSO* [68].
- *Pediatric Extracorporeal Cardiopulmonary Resuscitation ELSO Guidelines* [69].
- *Guidelines for Pediatric Cardiac Failure* [70].
- *ELSO Interim Guidelines for Venoarterial Extracorporeal Membrane Oxygenation in Adult Cardiac Patients* [71].
- *ELSO Guidelines for Adult and Pediatric Extracorporeal Membrane Oxygenation Circuits* [72].
- *Guidelines for ECMO in COVID-19* [73].

Patient selection is crucial in determining ECMO results, and the ELSO guidelines include extensive criteria to help with decision-making. When conventional approaches fail, ECMO is typically considered in patients with potentially reversible cardiac or respiratory failure. The ELSO recommendations also include the use of ECMO in pediatric groups [67, 69, 72] and certain adult groups, such as those suffering from respiratory failure due to COVID-19 [73].

The ELSO guidelines highlight that the effectiveness of ECMO treatment relies on thorough supervision, particularly regarding hemodynamics, oxygenation, ventilation, and anticoagulation. Weaning off ECMO should be considered when the patient's lung or cardiac function improves, as demonstrated by normal blood gas levels, better echocardiographic parameters, or a reduction in the requirement for mechanical ventilation. The ELSO guidelines recommend employing lower ECMO flows to assess the patient's capacity to maintain appropriate oxygenation and perfusion.

The ELSO practice guidelines are an essential tool for healthcare professionals involved in managing ECMO. These guidelines include thorough and evidence-based recommendations on patient selection, treatment strategies, and safety precautions. By following these instructions, ECMO centers may enhance patient survival rates, minimize challenges, and deliver better care for critically ill patients.

Survey-based studies on extracorporeal membrane oxygenation

Survey-based studies provide useful insights into the use, methodologies, and difficulties related to ECMO in various institutions and countries. These investigations are valuable in uncovering trends, gaps, practice variations, and areas requiring more standardization or research [74].

Sharma et al. [75] performed a cross-sectional nationwide survey of adult intensive care education courses in the United States to ascertain the preferences of intensivists on the use of various treatments for severe ARDS, including the implementation of ECMO. Eighty percent of participants stated that ECMO is available at their institution. A large number of participants (83%) expressed their willingness to explore ECMO as a treatment option for patients who did not respond to appropriate mechanical ventilation. Additionally, a substantial percentage (60%) stated that ECMO could assist in implementing lung protective ventilation. Approximately 62% pointed to the lack of knowledge of ECMO and prioritized targeted ECMO training throughout their education.

Abrams et al. [76] conducted a multi-country study with 531 physicians; elderly age (46.9%), additional organ dysfunction (37.7%), and extended period of ventilatory support (35.1%) were the three major factors determined by the cohort that would restrict ECMO use.

Broman et al. [77] surveyed to investigate the organizational aspects of inter-hospital ECMO transport care in experienced medical centers. This survey involved fifteen mobile ECMO centers from nine different countries. Seven of them functioned using the "Hub-and-Spoke" concept. The team included three to nine individuals, with every center having at least one ECMO specialist. However, 69% of the teams included intensivists, and 50% included surgeons. The decision to commence ECMO was made collaboratively by all centers involved and was made directly at the patient's bedside in the referral hospital.

Bembea et al. [78] examined anticoagulants approaches during ECMO treatment. Of 117 responders, 84 (72%) stated that their institution had a documented institutional ECMO procedure for anticoagulation. Sixty-nine respondents (59%) stated that they utilized heparin-bonded circuits. All centers employed unfractionated heparin. Merely 8% indicated the use of other anticoagula.

Patel et al. [79] examined the implementation of ECMO education and certification for ECMO professionals worldwide. ECMO education was provided at 221 (92%) ECMO centers, and credentialing was implemented at 101 (42%) centers.

Milewski et al. [80] evaluated the ECMO implementation during the COVID-19 pandemic. During the pandemic, the proportion of high-volume ECMO operations (exceeding 20 patients annually) increased. More organizations established criteria for allocating resources, and various initiatives developed sharing partnerships.

Survey-based studies yield important insights into the practical implementation of ECMO support, highlighting critical trends, challenges, and avenues for enhancement. These surveys underscore the need for standardization, improved resource allocation, and continuous research to optimize patient outcomes.

Rehabilitation of extracorporeal membrane oxygenation patients

Rehabilitation is an essential aspect of the treatment strategy for patients on ECMO support. These patients frequently encounter substantial physical, cognitive, and mental challenges following ECMO care, attributable to the severity of their underlying condition, immobilization, and complications. Timely and structured rehabilitation is essential for enhancing recovery outcomes, reinstating functional independence, and improving quality of life. Rehabilitation approaches are comprehensive, encompassing physical, occupational, and psychological therapy customized to the specific requirements of ECMO survivors [81, 82].

One of the main objectives is to begin mobilization as soon as feasible, preferably during ECMO. Early mobilization can help relieve profound muscular weakness and deconditioning. However, early mobilization necessitates careful coordination because of the patient's complicated state and the hazards connected with cannulation and ECMO circuits [83]. A systematic review indicated that while active mobilization and rehabilitation did not influence short- or long-term mortality, it resulted in enhanced muscle strength at discharge from the intensive care unit, an increased probability of unassisted ambulation upon leaving the hospital, and a higher number of days lived outside the hospital at six months [84].

After decannulation and intensive care unit discharge, ECMO patients frequently experience severe muscular weakness, known as intensive care unit-acquired weakness, impacting both peripheral muscles and respiratory function. The rehabilitation program following intensive care unit release emphasizes the progressive restoration of strength, endurance, and overall physical function [85]. Respiratory muscle weakness is prevalent, particularly in ECMO patients on mechanical breathing. Pulmonary rehabilitation, encompassing breathing exercises, inspiratory muscle training, and lung secretion-clearing procedures, is crucial for enhancing respiratory function and facilitating the weaning of patients from oxygen supplementation [86].

Mortality in ECMO-supported patients with transplants is linked to the extent of organ failure; however, pre-transplant deconditioning is an important further contributor. Deconditioning, prevalent in critically ill individuals, is intensified in those requiring ECMO due to cannulation methods, immobilization, and anesthetic protocols [87]. Fuehner et al. [88] demonstrated enhanced survivability for individuals bridged to lung transplantation employing an "awake ECMO" technique compared to those treated with standard mechanical ventilation, highlighting the potential benefits of reducing sedation. In addition to reducing sedation, proactive early rehabilitation is the subsequent measure that might enhance outcomes for patients receiving ECMO as a bridge to lung transplantation [89].

Rehabilitation is essential for the recovery of ECMO patients. Early mobilization, structured rehabilitation programs, and long-term follow-up are crucial for enhancing results and assisting ECMO survivors in achieving functional independence. A multidisciplinary approach is necessary for achieving a comprehensive and effective rehabilitation process.

Conclusion

ECMO has become essential in managing severe cardiovascular and pulmonary conditions, providing vital support to patients who require life-saving intervention. Technological advances and improved knowledge of ECMO benefits have led to its widespread application in various medical specialties. The COVID-19 pandemic underlined the need for ECMO, particularly in treating severe respiratory failure, such as COVID-19-induced ARDS. Despite resource allocation and logistics issues, the pandemic demonstrated the benefits of regional ECMO services and national coordination in enhancing patient outcomes.

The use of ECMO in rheumatology has shown promise, notably in the treatment of severe organ failure in patients with autoimmune and inflammatory disorders. While clinical research and recommendations for this group remain limited, emerging data suggests that ECMO can serve as a bridge to recovery in certain situations of refractory disease.

ECMO requires a structured rehabilitation approach to tackle physical, psychological, and cognitive impairments. Early mobilization, extensive rehabilitation, and prolonged follow-up are essential for enhancing functional results and quality of life in ECMO survivors.

Continuous research, multidisciplinary interaction, and standardized ECMO processes are crucial for enhancing patient care and results in various clinical contexts.

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Declarations

Conflict of interest The authors declare no conficts of interest.

References

1. Rossong H, Debreuil S, Yan W et al (2023) Long-term survival and quality of life after extracorporeal membrane oxygenation. J Thorac Cardiovasc Surg 166:555–566e2. https://doi.org/10.1016/j.jtcvs.2021.10.077
2. Wrisinger WC, Thompson SL (2022) Basics of extracorporeal membrane oxygenation. Surg Clin North Am 102:23–35. https://doi.org/10.1016/j.suc.2021.09.001
3. Fainberg NA, Morrison WE, West S, Hasz R, Kirschen MP (2022) Organ donation from patients on extracorporeal membrane oxygenation at the time of death. Crit Care Explor 4:e0812. https://doi.org/10.1097/CCE.0000000000000812
4. Mastoris I, Tonna JE, Hu J et al (2022) Use of extracorporeal membrane oxygenation as bridge to replacement therapies in cardiogenic shock: insights from the extracorporeal life support Organization. Circ Heart Fail 15:e008777. https://doi.org/10.1161/CIRCHEARTFAILURE.121.008777
5. Squiers JJ, Lima B, DiMaio JM (2016) Contemporary extracorporeal membrane oxygenation therapy in adults: fundamental principles and systematic review of the evidence. J Thorac Cardiovasc Surg 152:20–32. https://doi.org/10.1016/j.jtcvs.2016.02.067
6. Mang S, Reichert L, Muellenbach RM et al (2023) Transfer of Veno-venous extracorporeal membrane oxygenation patients with COVID-19 Associated Acute Respiratory Distress Syndrome. ASAIO J 69:789–794. https://doi.org/10.1097/MAT.0000000000001954
7. Ezad SM, Ryan M, Donker DW et al (2023) Unloading the left ventricle in venoarterial ECMO: in whom, when, and how? Circulation 147:1237–1250. https://doi.org/10.1161/CIRCULATIONAHA.122.062371
8. Oh TK, Song IA (2022) Trend of extracorporeal membrane oxygenation support in patients with acute respiratory distress syndrome in South Korea. Sci Rep 12:5225. https://doi.org/10.1038/s41598-022-09230-9
9. Choi YH, Jhang WK, Park SJ et al (2024) Pediatric extracorporeal membrane oxygenation in Korea: a Multicenter Retrospective Study on utilization and outcomes spanning over a Decade. J Korean Med Sci 39:e33. https://doi.org/10.3346/jkms.2024.39.e33
10. Nagaoka E, Arai H, Ugawa T et al (2021) Efficacy of multidisciplinary team approach with extracorporeal membrane oxygenation for COVID-19 in a low volume ECMO center. Artif Organs 45:1061–1067. https://doi.org/10.1111/aor.13947
11. Okada Y, Fujita K, Ogura T et al (2023) Novel and innovative resuscitation systems in Japan. Resusc Plus 17:100541. https://doi.org/10.1016/j.resplu.2023.100541
12. Owyang CG, Donnat C, Brodie D et al (2022) Similarities in extracorporeal membrane oxygenation management across intensive care unit types in the United States: an analysis of the extracorporeal life support Organization Registry. Artif Organs 46:1369–1381. https://doi.org/10.1111/aor.14193
13. Moll V, Teo EY, Grenda DS et al (2016) Rapid Development and implementation of an ECMO program. ASAIO J 62:354–358. https://doi.org/10.1097/MAT.0000000000000331
14. Hayanga JWA, Aboagye J, Bush E et al (2020) Contemporary analysis of charges and mortality in the use of extracorporeal membrane oxygenation: a cautionary tale. JTCVS Open 1:61–70. https://doi.org/10.1016/j.xjon.2020.02.003
15. Gasparyan AY, Ayvazyan L, Blackmore H, Kitas GD (2011) Writing a narrative biomedical review: considerations for authors, peer reviewers, and editors. Rheumatol Int 31(11):1409–1417. https://doi.org/10.1007/s00296-011-1999-3
16. Broman LM, Eksborg S, Lo Coco V et al (2021) Extracorporeal membrane oxygenation for COVID-19 during first and second waves. Lancet Respir Med 9:e80–e81. https://doi.org/10.1016/S2213-2600(21)00262-9
17. Barbaro RP, MacLaren G, Boonstra PS et al (2020) Extracorporeal membrane oxygenation support in COVID-19: an international cohort study of the extracorporeal life support Organization registry. Lancet 396:1071–1078. https://doi.org/10.1016/S0140-6736(20)32008-0
18. Henry BM, Lippi G (2020) Poor survival with extracorporeal membrane oxygenation in acute respiratory distress syndrome (ARDS) due to coronavirus disease 2019 (COVID-19): pooled analysis of early reports. J Crit Care 58:27–28. https://doi.org/10.1016/j.jcrc.2020.03.011

19. Bartlett RH, Ogino MT, Brodie D et al (2020) Initial ELSO Guidance Document: ECMO for COVID-19 patients with severe cardiopulmonary failure. ASAIO J 66:472–474. https://doi.org/10.1097/MAT.0000000000001173
20. Ramanathan K, Shekar K, Ling RR et al (2021) Extracorporeal membrane oxygenation for COVID-19: a systematic review and meta-analysis. Crit Care 25:211. https://doi.org/10.1186/s13054-021-03634-1
21. Barbaro RP, MacLaren G, Boonstra PS et al (2021) Extracorporeal membrane oxygenation for COVID-19: evolving outcomes from the international extracorporeal life support Organization Registry. Lancet 398:1230–1238. https://doi.org/10.1016/S0140-6736(21)01960-7
22. Riera J, Roncon-Albuquerque R Jr, Fuset MP et al (2021) Increased mortality in patients with COVID-19 receiving extracorporeal respiratory support during the second wave of the pandemic. Intensive Care Med 47:1490–1493. https://doi.org/10.1007/s00134-021-06517-9
23. Camporota L, Meadows C, Ledot S et al (2021) Consensus on the referral and admission of patients with severe respiratory failure to the NHS ECMO service. Lancet Respir Med 9:e16–e17. https://doi.org/10.1016/S2213-2600(20)30581-6
24. Lebreton G, Schmidt M, Ponnaiah M et al (2021) Extracorporeal membrane oxygenation network organization and clinical outcomes during the COVID-19 pandemic in Greater Paris, France: a multicentre cohort study. Lancet Respir Med 9:851–862. https://doi.org/10.1016/S2213-2600(21)00096-5
25. Levy D, Lebreton G, Pineton de Chambrun M et al (2021) Outcomes of patients denied extracorporeal membrane oxygenation during the COVID-19 pandemic in Greater Paris, France. Am J Respir Crit Care Med 204:994–997. https://doi.org/10.1164/rccm.202105-1312LE
26. Parekh M, Abrams D, Agerstrand C et al (2023) The use of extracorporeal membrane oxygenation for COVID-19: lessons learned. Clin Chest Med 44:335–346. https://doi.org/10.1016/j.ccm.2022.11.016
27. Kim WY, Jung SY, Kim JY et al (2024) ECMO is associated with decreased hospital mortality in COVID-19 ARDS. Sci Rep 14:14835. https://doi.org/10.1038/s41598-024-64949-x
28. Mohammed Bamasood O, Shamsah M, Alfoudri H et al (2022) Extracorporeal membrane oxygenation in pregnant women with COVID-19. ASAIO J 68:471–477. https://doi.org/10.1097/MAT.0000000000001646
29. Richley M, Rao R (2023) Extracorporeal membrane oxygenation in pregnancy during the SARS-CoV-2 pandemic. Semin Fetal Neonatal Med 28:101435. https://doi.org/10.1016/j.siny.2023.101435
30. Wong MJ, Bharadwaj S, Galey JL, Lankford AS, Galvagno S, Kodali BS (2022) Extracorporeal membrane oxygenation for pregnant and Postpartum patients. Anesth Analg 135:277–289. https://doi.org/10.1213/ANE.0000000000005861
31. American College of Obstetricians and Gynecologists' Presidential Task Force on Pregnancy and Heart Disease and Committee on Practice Bulletins—Obstetrics (2019) ACOG Practice Bulletin 212: pregnancy and heart disease. Obstet Gynecol 133:e320–e356. https://doi.org/10.1097/AOG.0000000000003243
32. Ramanathan K, Tan CS, Rycus P et al (2020) Extracorporeal membrane oxygenation in pregnancy: an analysis of the extracorporeal life support Organization Registry. Crit Care Med 48:696–703. https://doi.org/10.1097/CCM.0000000000004269
33. Malfertheiner SF, Brodie D, Burrell A et al (2023) Extracorporeal membrane oxygenation during pregnancy and peripartal. An international retrospective multicenter study. Perfusion 38:966–972. https://doi.org/10.1177/02676591221090668
34. Jiritano F, Serraino GF, Ten Cate H et al (2020) Platelets and extracorporeal membrane oxygenation in adult patients: a systematic review and meta-analysis. Intensive Care Med 46:1154–1169. https://doi.org/10.1007/s00134-020-06031-4
35. Auyezkhankyzy D, Izekenova A, Kocyigit BF (2024) Emergencies in inflammatory rheumatic diseases. Rheumatol Int 44:1637–1646. https://doi.org/10.1007/s00296-024-05660-y
36. Larcher R, Pineton de Chambrun M, Garnier F et al (2020) One-year outcome of critically ill patients with systemic rheumatic disease: a Multicenter Cohort Study. Chest 158:1017–1026. https://doi.org/10.1016/j.chest.2020.03.050
37. Bay P, Lebreton G, Mathian A et al (2021) Outcomes of severe systemic rheumatic disease patients requiring extracorporeal membrane oxygenation. Ann Intensive Care 11:29. https://doi.org/10.1186/s13613-021-00819-3
38. Siegel CH, Sammaritano LR (2024) Systemic lupus erythematosus: a review. JAMA 331:1480–1491. https://doi.org/10.1001/jama.2024.2315
39. Leung MC, Harper RW, Boxall J (2002) Extracorporeal membrane oxygenation in fulminant myocarditis complicating systemic lupus erythematosus. Med J Aust 176:374–375. https://doi.org/10.5694/j.1326-5377.2002.tb04458.x
40. Shi YJ, Wang LF, Ma J, Chen Y, Wang WJ, Xie CY (2022) Veno-arterial extracorporeal membrane oxygenation in the treatment of Hemodynamically unstable lupus myocarditis: a retrospective Case Series Study. J Inflamm Res 15:3761–3768. https://doi.org/10.2147/JIR.S365399
41. Pacheco Claudio C, Charbonney E, Durand M, Kolan C, Laskine M (2014) Extracorporeal membrane oxygenation in diffuse alveolar hemorrhage secondary to systemic lupus erythematosus. J Clin Med Res 6:145–148. https://doi.org/10.14740/jocmr1685w
42. Zheng B, Eline E, Xu L et al (2024) Extracorporeal membrane oxygenation for Acute Lung Injury in Idiopathic Inflammatory Myopathies-A potential lifesaving intervention. Rheumatology (Oxford). https://doi.org/10.1093/rheumatology/keae311
43. Zulian F, Martinez Toledo MM, Amigoni A, Martini G, Agosto C, Pettenazzo A (2007) Successful use of extracorporeal membrane oxygenation for severe interstitial lung disease in a child with dermatomyositis. Intensive Care Med 33:1663–1666. https://doi.org/10.1007/s00134-007-0763-3
44. Rubin J, Black KE, Hallowell RW et al (2021) Veno-venous extracorporeal membrane oxygenation for Myositis-Associated Rapidly Progressive interstitial lung disease. Chest 160:2163–2167. https://doi.org/10.1016/j.chest.2021.06.075
45. Truong L, Youssef FA, Ajaz U, Desai S (2021) Extracorporeal membrane oxygenation used in the Treatment of Rapidly Progressive Interstitial Pneumonia in a patient with Amyopathic Dermatomyositis and positive melanoma differentiation-Associated Gene 5. J Clin Rheumatol 27:e215–e217. https://doi.org/10.1097/RHU.0000000000000934
46. Delvino P, Monti S, Balduzzi S, Belliato M, Montecucco C, Caporali R (2019) The role of extracorporeal membrane oxygenation (ECMO) in the treatment of diffuse alveolar hemorrhage secondary to ANCA-associated vasculitis: report of two cases and review of the literature. Rheumatol Int 39:367–375. https://doi.org/10.1007/s00296-018-4116-z
47. Yusuff H, Malagon I, Robson K, Parmar J, Hamilton P, Falter F (2015) Extracorporeal membrane oxygenation for life-threatening ANCA-positive pulmonary capillaritis. A review of UK experience. Heart Lung Vessel 7:159–167
48. Matsumoto T, Ueki K, Tamura S et al (2000) Extracorporeal membrane oxygenation for the management of respiratory failure due to ANCA-associated vasculitis. Scand J Rheumatol 29:195–197. https://doi.org/10.1080/030097400750002111
49. Hamana T, Kawamori H, Satomi-Kobayashi S, Yamamoto Y, Ikeda Y, Hirata KI (2023) Fulminant myocarditis in a young woman with mixed connective tissue disease: a case report.

Eur Heart J Case Rep 7:ytad174. https://doi.org/10.1093/ehjcr/ytad174
50. Cohen S, Tacke CE, Straver B, Meijer N, Kuipers IM, Kuijpers TW (2012) A child with severe relapsing Kawasaki disease rescued by IL-1 receptor blockade and extracorporeal membrane oxygenation. Ann Rheum Dis 71:2059–2061. https://doi.org/10.1136/annrheumdis-2012-201658
51. Yang X, Chen Y, Dai R et al (2023) Successful use of extracorporeal membrane oxygenation for life-threatening macrophage activation syndrome after treatment with tocilizumab in an systemic juvenile idiopathic arthritis patient. Pediatr Discovery 1:e32. https://doi.org/10.1002/pdi3.32
52. Zeibi Shirejini S, Carberry J, McQuilten ZK, Burrell AJC, Gregory SD, Hagemeyer CE (2023) Current and future strategies to monitor and manage coagulation in ECMO patients. Thromb J 21:11. https://doi.org/10.1186/s12959-023-00452-z
53. Levy JH, Staudinger T, Steiner ME (2022) How to manage anticoagulation during extracorporeal membrane oxygenation. Intensive Care Med 48:1076–1079. https://doi.org/10.1007/s00134-022-06723-z
54. Thiagarajan RR, Barbaro RP, Rycus PT et al (2017) Extracorporeal life support Organization Registry International Report 2016. ASAIO J 63:60–67. https://doi.org/10.1097/MAT.0000000000000475
55. Northrop MS, Sidonio RF, Phillips SE et al (2015) The use of an extracorporeal membrane oxygenation anticoagulation laboratory protocol is associated with decreased blood product use, decreased hemorrhagic complications, and increased circuit life. Pediatr Crit Care Med 16:66–74. https://doi.org/10.1097/PCC.0000000000000278
56. Kumar G, Maskey A (2021) Anticoagulation in ECMO patients: an overview. Indian J Thorac Cardiovasc Surg 37:241–247. https://doi.org/10.1007/s12055-021-01176-3
57. Gates R, Yost P, Parker B (2010) The use of bivalirudin for cardiopulmonary bypass anticoagulation in pediatric heparin-induced thrombocytopenia patients. Artif Organs 34:667–669. https://doi.org/10.1111/j.1525-1594.2009.00961.x
58. Esper SA, Welsby IJ, Subramaniam K et al (2017) Adult extracorporeal membrane oxygenation: an international survey of transfusion and anticoagulation techniques. Vox Sang 112:443–452. https://doi.org/10.1111/vox.12514
59. Gomez F, Veita J, Laudanski K (2022) Antibiotics and ECMO in the Adult Population-Persistent challenges and practical guides. Antibiot (Basel) 11:338. https://doi.org/10.3390/antibiotics11030338
60. Kühn D, Metz C, Seiler F et al (2020) Antibiotic therapeutic drug monitoring in intensive care patients treated with different modalities of extracorporeal membrane oxygenation (ECMO) and renal replacement therapy: a prospective, observational single-center study. Crit Care 24:664. https://doi.org/10.1186/s13054-020-03397-1
61. Cota JM, FakhriRavari A, Rowan MP, Chung KK, Murray CK, Akers KS (2016) Intravenous antibiotic and antifungal Agent Pharmacokinetic-Pharmacodynamic dosing in adults with severe burn Injury. Clin Ther 38:2016–2031. https://doi.org/10.1016/j.clinthera.2016.08.001
62. Zhang Y, Hu H, Zhang Q et al (2021) Effects of ex vivo extracorporeal membrane oxygenation circuits on sequestration of Antimicrobial agents. Front Med (Lausanne) 8:748769. https://doi.org/10.3389/fmed.2021.748769
63. Thongprayoon C, Cheungpasitporn W, Lertjitbanjong P et al (2019) Incidence and impact of Acute kidney Injury in patients receiving extracorporeal membrane oxygenation: a Meta-analysis. J Clin Med 8:981. https://doi.org/10.3390/jcm8070981
64. Hites M, Dell'Anna AM, Scolletta S, Taccone FS (2014) The challenges of multiple organ dysfunction syndrome and extracorporeal circuits for drug delivery in critically ill patients. Adv Drug Deliv Rev 77:12–21. https://doi.org/10.1016/j.addr.2014.05.007
65. Wild KT, Rintoul N, Kattan J, Gray B (2020) Extracorporeal life support Organization (ELSO): guidelines for neonatal respiratory failure. ASAIO J 66:463–470. https://doi.org/10.1097/MAT.0000000000001153
66. Tonna JE, Abrams D, Brodie D et al (2021) Management of adult patients supported with venovenous extracorporeal membrane oxygenation (VV ECMO): Guideline from the Extracorporeal Life Support Organization (ELSO). ASAIO J 67:601–610. https://doi.org/10.1097/MAT.0000000000001432
67. Maratta C, Potera RM, van Leeuwen G, Castillo Moya A, Raman L, Annich GM (2020) Extracorporeal life support Organization (ELSO): 2020 Pediatric Respiratory ELSO Guideline. ASAIO J 66:975–979. https://doi.org/10.1097/MAT.0000000000001223
68. Richardson ASC, Tonna JE, Nanjayya V et al (2021) Extracorporeal cardiopulmonary resuscitation in adults. Interim Guideline Consensus Statement from the extracorporeal life support Organization. ASAIO J 67:221–228. https://doi.org/10.1097/MAT.0000000000001344
69. Guerguerian AM, Sano M, Todd M, Honjo O, Alexander P, Raman L (2021) Pediatric extracorporeal cardiopulmonary resuscitation ELSO guidelines. ASAIO J 67:229–237. https://doi.org/10.1097/MAT.0000000000001345
70. Brown G, Moynihan KM, Deatrick KB et al (2021) Extracorporeal life support Organization (ELSO): guidelines for Pediatric Cardiac failure. ASAIO J 67:463–475. https://doi.org/10.1097/MAT.0000000000001431
71. Lorusso R, Shekar K, MacLaren G et al (2021) ELSO Interim Guidelines for venoarterial extracorporeal membrane oxygenation in adult Cardiac patients. ASAIO J 67:827–844. https://doi.org/10.1097/MAT.0000000000001510
72. Gajkowski EF, Herrera G, Hatton L, Velia Antonini M, Vercaemst L, Cooley E (2022) ELSO guidelines for Adult and Pediatric extracorporeal membrane oxygenation circuits. ASAIO J 68:133–152. https://doi.org/10.1097/MAT.0000000000001630
73. Badulak J, Antonini MV, Stead CM et al (2021) Extracorporeal membrane oxygenation for COVID-19: updated 2021 guidelines from the extracorporeal life support Organization. ASAIO J 67:485–495. https://doi.org/10.1097/MAT.0000000000001422
74. van Minnen O, Jolink FEJ, van den Bergh WM et al (2024) International Survey on mechanical ventilation during extracorporeal membrane oxygenation. ASAIO J 70:300–304. https://doi.org/10.1097/MAT.0000000000002101
75. Sharma NS, Wille KM, Zhi D et al (2015) Use of ECMO in the management of severe Acute Respiratory Distress Syndrome: a Survey of Academic Medical centers in the United States. ASAIO J 61:556–563. https://doi.org/10.1097/MAT.0000000000000245
76. Abrams D, Pham T, Burns KEA et al (2019) Practice patterns and ethical considerations in the management of venovenous extracorporeal membrane oxygenation patients: an International Survey. Crit Care Med 47:1346–1355. https://doi.org/10.1097/CCM.0000000000003910
77. Broman LM, Dirnberger DR, Malfertheiner MV et al (2020) International survey on extracorporeal membrane oxygenation transport. ASAIO J 66:214–225. https://doi.org/10.1097/MAT.0000000000000997
78. Bembea MM, Annich G, Rycus P, Oldenburg G, Berkowitz I, Pronovost P (2013) Variability in anticoagulation management of patients on extracorporeal membrane oxygenation: an international survey. Pediatr Crit Care Med 14:e77–84. https://doi.org/10.1097/PCC.0b013e31827127e4
79. Patel B, Said AS, Justus A et al (2023) An international survey of extracorporeal membrane Oxygenation Education and Credentialing practices. ATS Sch 5:71–83. https://doi.org/10.34197/ats-scholar.2022-0132OC

80. Milewski RC, Chatterjee S, Merritt-Genore H et al (2023) ECMO during COVID-19: a society of thoracic Surgeons/Extracorporeal life support Organization Survey. Ann Thorac Surg Short Rep 1:168–173. https://doi.org/10.1016/j.atssr.2022.10.017
81. Eden A, Purkiss C, Cork G et al (2017) In-patient physiotherapy for adults on veno-venous extracorporeal membrane oxygenation - United Kingdom ECMO Physiotherapy Network: A consensus agreement for best practice. J Intensive Care Soc 18:212–220. https://doi.org/10.1177/1751143717705801
82. Liu Y, Xin C, Wei L, Guo X, Zhang Y, Zhang M, Xing J, Gai Y (2024) Effect of an evidence-based early rehabilitation program on adult patients with venovenous extracorporeal membrane oxygenation: a cohort study. Intensive Crit Care Nurs 84:103744. https://doi.org/10.1016/j.iccn.2024.103744
83. Abrams D, Javidfar J, Farrand E et al (2014) Early mobilization of patients receiving extracorporeal membrane oxygenation: a retrospective cohort study. Crit Care 18:R38. https://doi.org/10.1186/cc13746
84. Tipping CJ, Harrold M, Holland A, Romero L, Nisbet T, Hodgson CL (2017) The effects of active mobilization and rehabilitation in ICU on mortality and function: a systematic review. Intensive Care Med 43:171–183. https://doi.org/10.1007/s00134-016-4612-0
85. Kourek C, Nanas S, Kotanidou A et al (2022) Modalities of Exercise Training in patients with extracorporeal membrane oxygenation support. J Cardiovasc Dev Dis 9:34. https://doi.org/10.3390/jcdd9020034
86. Polastri M, Loforte A, Dell'Amore A (2016) Physiotherapy for patients on awake extracorporeal membrane oxygenation: a systematic review. Physiother Res Int 21:203–209. https://doi.org/10.1002/pri.1644
87. Griffiths RD, Hall JB (2010) Intensive care unit-acquired weakness. Crit Care Med 38:779–787. https://doi.org/10.1097/CCM.0b013e3181cc4b53
88. Fuehner T, Kuehn C, Hadem J et al (2012) Extracorporeal membrane oxygenation in awake patients as bridge to lung transplantation. Am J Respir Crit Care Med 185:763–768. https://doi.org/10.1164/rccm.201109-1599OC
89. Rehder KJ, Turner DA, Hartwig MG et al (2013) Active rehabilitation during extracorporeal membrane oxygenation as a bridge to lung transplantation. Respir Care 58:1291–1298. https://doi.org/10.4187/respcare.02155