CONCISE CLINICAL REVIEW

CME

Extracorporeal Membrane Oxygenation during Respiratory Pandemics
Past, Present, and Future

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Abstract

The role of extracorporeal membrane oxygenation (ECMO) in the management of severe acute respiratory failure, including acute respiratory distress syndrome, has become better defined in recent years in light of emerging high-quality evidence and technological advances. Use of ECMO has consequently increased throughout many parts of the world. The coronavirus disease (COVID-19) pandemic, however, has highlighted deficiencies in organizational capacity, research capability, knowledge sharing, and resource use. Although governments, medical societies, hospital systems, and clinicians were collectively unprepared for the scope of this pandemic, the use of ECMO, a highly resource-intensive and specialized form of life support, presented specific logistical and ethical challenges. As the pandemic has evolved, there has been greater collaboration in the use of ECMO across centers and regions, together with more robust data reporting through international registries and observational studies. Nevertheless, centralization of ECMO capacity is lacking in many regions of the world, and equitable use of ECMO resources remains uneven. There are no widely available mechanisms to conduct large-scale, rigorous clinical trials in real time. In this critical care review, we outline lessons learned during COVID-19 and prior respiratory pandemics in which ECMO was used, and we describe how we might apply these lessons going forward, both during the ongoing COVID-19 pandemic and in the future.

Keywords: ECMO; extracorporeal circulation; COVID-19; acute respiratory distress syndrome; respiratory failure

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Coronavirus disease (COVID-19) has had the greatest global impact of any pandemic since the influenza A (H1N1) pandemic of 1918, with millions of deaths worldwide. Acute respiratory distress syndrome (ARDS) is a particularly prominent feature among critically ill patients with COVID-19, with extracorporeal membrane oxygenation (ECMO) used to support the most severely affected patients. However, ECMO is highly resource intensive, and its use during the pandemic has strained healthcare systems and presented difficult ethical challenges.

Historical Perspective

A literature search using PubMed was performed for literature published between January 1, 2003, and January 17, 2022. Search terms included extracorporeal membrane oxygenation, extracorporeal life support, ECMO, or ECLS, coupled with pandemic, acute respiratory distress syndrome, ARDS, severe acute respiratory syndrome, SARS, SARS-CoV-1, Middle East respiratory syndrome, MERS, Influenza A(H1N1), SARS-CoV-2, coronavirus disease 2019, COVID or COVID-19. Non–English-language articles, and articles pertaining primarily to use in the neonatal or pediatric populations, were excluded. Specific articles for inclusion related to the COVID-19 pandemic were selected with an emphasis on differential outcomes over time. Priority was given to clinical trials and large longitudinal observational studies.

Before 2009, there was a paucity of data supporting the efficacy of ECMO for adults with severe ARDS. Use of ECMO was limited to highly specialized centers, including during the severe acute respiratory syndrome coronavirus 1 (SARS-CoV-1) outbreak in 2003. However, interest in ECMO increased as advances in extracorporeal technology appeared to make ECMO safer and more efficient.

During the 2009 influenza A (H1N1) pandemic, matched-pair analyses suggested a potential but unclear benefit of ECMO (1, 2). Coinciding with the 2009 pandemic came the publication of the CESAR (Efficacy and Economic Assessment of Conventional Ventilatory Support versus Extracorporeal Membrane Oxygenation for Severe Adult Respiratory Failure) trial, a pragmatic randomized controlled trial (RCT) that found significantly lower 6-month mortality or severe disability in patients assigned to care in an ECMO center than in with those receiving usual care in a non-ECMO center (3). Subsequently, there was a notable increase in the number of centers providing ECMO (4).

In 2012, during an outbreak of the novel Middle East respiratory syndrome coronavirus, case series and uncontrolled cohort studies demonstrated a wide range of survival rates for patients supported with ECMO, with a case-control study suggesting a mortality benefit of ECMO over conventional care (65% vs. 100%; $P = 0.02$) despite similar baseline characteristics (5–7).

In 2018, the EOLIA (Extracorporeal Membrane Oxygenation in Severe Acute Respiratory Distress Syndrome) trial, the largest RCT of venovenous ECMO for severe ARDS, demonstrated a potentially large but not statistically significant mortality benefit of ECMO over conventional management (35% vs. 46%; relative risk [RR], 0.76; 95% confidence interval [CI], 0.55–1.04; $P = 0.09$), with acceptable rates of adverse events (8). These results, combined with a *post hoc* Bayesian analysis of EOLIA and a number of meta-analyses (9–12), helped to establish criteria for ECMO in severe ARDS refractory to conventional management (13). Of note, 21% and 16% of patients in the ECMO and control groups, respectively, were enrolled in EOLIA with viral pneumonia, with a point estimate favoring ECMO (RR, 0.77; 95% CI, 0.29–2.05), though the trial was not powered to detect differences in subgroups.

COVID-19

Early reports from Wuhan, China, suggested a poor prognosis for patients with COVID-19 ARDS who were treated with ECMO, with mortality rates exceeding 80% (14). Despite this, major medical societies recommended early on that ECMO should be considered for this indication using the same management algorithm applied to other forms of ARDS (15–17).

As the pandemic evolved, registry data and larger cohort studies supported the concept that outcomes with ECMO in patients with COVID-19–related ARDS were similar to those seen in patients with non–COVID-19–related ARDS. The largest initial single-center experience, from Paris, France ($N = 83$), reported an estimated probability of mortality of 31% at 60 days (18). A contemporaneous analysis of the Extracorporeal Life Support Organization (ELSO) registry, including 1,035 adults receiving ECMO for COVID-19 at 213 hospitals across 36 countries, estimated 90-day in-hospital mortality at 37.4% (19).

Despite these early encouraging data, later studies reported that mortality and duration of ECMO were increasing over time (Table 1) (20), raising concerns about whether patient selection should be reevaluated. A survey from the European chapter of ELSO reported 56% mortality for patients with COVID-19 receiving ECMO between September 15, 2020, and March 8, 2021, compared with 47% for those treated before that period (21). This pattern was also seen in 24 centers in Spain and Portugal, where 151 patients who received ECMO for COVID-19–related ARDS during a "first wave" had an in-hospital mortality of 41.1% compared with 60.1% in the 168 patients in a "second wave" (22). In the Paris-Sorbonne University Hospital Network, those managed after July 1, 2020, had an estimated 90-day mortality of 48%, compared with 36% in their initial cohort (hazard ratio, 2.27; 95% CI, 1.02–5.07) (23).

Similar trends were noted in an expanded analysis of the ELSO registry database, encompassing 4,812 patients across 349 centers in 41 countries in 2020. In centers that had used ECMO throughout 2020, the cumulative incidence of in-hospital mortality 90 days after initiation of ECMO was 36.9% for ECMO initiated on or before May 1 compared with 51.9% after May 1 (RR, 0.82; 95% CI, 0.7–0.96) (20). In those centers that only began performing ECMO for COVID-19 after May 1, mortality was 58.9%. Furthermore, there has been an increased duration of ECMO support needed later in the pandemic (20 d vs. 14 d) (20).

Although largely speculative, a number of factors have been proposed to explain the worsening mortality over time as noted from these observational studies (20–24). First is increased use of noninvasive respiratory support before endotracheal intubation (20, 22, 23), perhaps leading to more patient self-inflicted lung injury before ECMO, a factor that may not necessarily be adequately reflected in baseline assessments of severity of illness. Second is a selection bias for more treatment-refractory disease, given that those receiving ECMO would have progressed despite having been more likely to receive initial COVID-19–targeted therapies, such as corticosteroids and other immunosuppressants, therapies that had become more routine later in the pandemic (20–23). Third, such COVID-19–targeted therapies may also contribute to superimposed

Table 1. Studies Reporting Outcomes for Extracorporeal Membrane Oxygenation for COVID-19 in Which Cohorts Were Compared Over Time

Study and Setting	Cohorts by Date of ECMO Initiation	No. of Patients	Outcome (Earlier vs. Later Cohorts)	Notable Differences (Earlier vs. Later Cohorts)
Barbaro *et al*. (20),* international	January 1, 2020–May 1, 2020 (A1)	1,182	In-hospital mortality at Day 90	Duration of ECMO (A1 vs. A2): 14.1 vs. 20.0 d
	May 2, 2020–December 31, 2020 (A2)	2,824	A1 36.9% vs. A2 51.9% vs. B 58.9%	Preintubation noninvasive respiratory support: A1 58% A2 76% B 70%
	May 2, 2020–December 31, 2020 (B)	806	A1 vs. A2 HR 0.82 (0.70–0.96) B vs. A2 HR 1.42 (1.17–1.73)	Pre-ECMO IMV duration: A1 4.0 (1.7–6.3) d A2 3.1 (0.9–6.3) d B 2.7 (0.8–5.9) d Steroids: A1 43% A2 78% B 72%
Broman *et al*. (21), Europe	March 12, 2020–September 14, 2020	1,442	In-hospital mortality† 47% vs. 56%; $P < 0.0001$	—
	September 15, 2020–March 8, 2021	1,723		
Riera *et al*. (22), Spain and Portugal	March 1, 2020–June 30, 2020	151	In-hospital mortality 41.1% vs. 60.1%; $P = 0.001$	Age: 51.2 ± 10.5 yr vs. 54.6 ± 9.9 yr Age >65 yr: 5.3% vs. 13.1% ICU admission to ECMO: 6 vs. 8 d % of cases at high-volume‡ centers: 35.8% vs. 25.0% Steroids: 69.5% vs. 93.4%
	July 1, 2020–December 1, 2020	168		
Schmidt *et al*. (23), France	March 8, 2020–June 30, 2020	88	90-d mortality 36% (27–47%) vs. 48% (37–60%) HR, 2.27; 95% CI, 1.02–5.07	Dexamethasone: 18% vs. 82% HFNC: 19% vs. 82% NIV: 7% vs. 37%
	July 1, 2020–January 28, 2021	71		

Definition of abbreviations: CI = confidence interval; COVID-19 = coronavirus disease; ECMO = extracorporeal membrane oxygenation; HFNC = high-flow nasal cannula; HR = hazard ratio; IMV = invasive mechanical ventilation; NIV = noninvasive ventilation.
*A1 = patients who received ECMO for COVID-19 on or before May 1, 2020; A2 = patients who received ECMO for COVID-19 after May 1, 2020 at centers that had been performing ECMO for COVID-19 before May 2, 2020 (i.e., early-adopting centers); B = patients who received ECMO at centers that only started performing ECMO for COVID-19 after May 1, 2020 (i.e., late-adopting centers).
†Five percent and 25% remained on ECMO for the first and second phases, respectively, at the time analyses were performed.
‡"High volume" defined as at least 30 ECMO cases during the study period.

bacterial infections (22, 25, 26). Fourth, and likely most speculative, emergence of SARS-CoV-2 variants may have impacted patient trajectory. Fifth is the use of ECMO in centers less experienced with ECMO for COVID-19 in later phases of the pandemic, as suggested by the data (20, 22). Sixth, patient selection criteria are poorly reported in many of these studies, and initial success may have contributed to more liberal application of ECMO in later phases of the pandemic (22), although this was not detected in the ELSO registry data, where the latter cohort (with higher mortality) was expected to have a lower relative risk of mortality after adjusting for pre-ECMO characteristics (20).

The evolution of ECMO outcomes over time highlights the need for continuous reevaluation of outcome data, with potential modifications of guidelines. This is especially important as the world progresses through subsequent phases of the current pandemic with the emergence of more novel variants and further changes in practices (27).

Of note, recent unselected data from Germany, including all cases of venovenous ECMO for COVID-19 ($n = 3,397$), demonstrated a high in-hospital mortality (68%) for patients treated with ECMO through May 31, 2021 (28, 29). It is noteworthy that resource constraints were not common in Germany during this period and likely do not explain the high mortality rate.

Although recent systematic reviews and meta-analyses have corroborated the findings of cohort studies conducted early in the pandemic (e.g., mortality range 37–39%) (30, 31), they are heavily weighted toward one or two of the largest early studies (19, 32) and

do not yet account for the temporal trends in mortality observed in later phases of the pandemic (20, 21). To date, there are no RCTs of ECMO in COVID-19, though this is certainly not for a lack of case volume, and this highlights the challenges of conducting RCTs during a pandemic: a perceived lack of clinical equipoise (in light of the reasonably favorable EOLIA trial results for non–COVID-19–related ARDS), a lack of preexisting organization and infrastructure to conduct such a trial, and the necessary resources (e.g., staffing, funding) being overwhelmed by the burden of critically ill patients (33).

Specific considerations regarding ECMO for COVID-19. It is important to acknowledge that ECMO is not without potentially serious risk, given its degree of invasiveness, with risk of vascular injury and infection, the use of systemic anticoagulation, and the potential for worsening inflammation, thrombocytopenia, and coagulation abnormalities because of the blood–circuit interface (4). These risks may be amplified in the context of COVID-19, which is associated with greater risk of thrombosis than other etiologies of ARDS (Figure 1) (18, 34, 35). In addition, patients with COVID-19 appear to require a longer duration of ECMO support, which increases the potential for accumulating complications. For example, the initial ELSO COVID-19 registry study described a high rate of thrombotic complications that was comparable to pre–COVID-19 registry data only after normalizing for duration of support (36).

The longer average duration of support has implications for bed capacity, resource use, and potential need to shift from bridge-to-recovery to bridge-to-transplant for those who develop irreversible respiratory failure, historically an uncommon scenario before COVID-19 and one that may exacerbate already limited resources during a pandemic (24, 37).

Although right ventricular failure is known to occur in ARDS from hypoxemia- and hypercapnia-induced increases in pulmonary vascular resistance, and although it can be mitigated by correcting gas exchange with venovenous ECMO (38), it has been suggested that right ventricular dysfunction is more pronounced in COVID-19 (39). Mustafa and colleagues reported favorable outcomes in a cohort of patients ($n = 40$; mortality, 17.5%) early in the pandemic with an ECMO cannulation strategy that included right atrial drainage and pulmonary arterial reinfusion (thereby offloading the right ventricle) combined with a bundle of other interventions (40, 41). It is unclear which component(s) of these interventions may have contributed to the survival rate, though it is important to note that this was also an uncontrolled study and that a subsequent report by the same investigators shows an increase in mortality with later phases of the pandemic (42), as seen elsewhere.

Before the COVID-19 pandemic, an awake, extubated strategy during ECMO has been shown to facilitate early mobilization and avoid ventilator-associated complications, particularly for those supported as a bridge to lung transplantation (43–45). Although this approach was part of the bundle of interventions used by Mustafa and colleagues (occurring, on average, 13 days into ECMO support) (40), it has not been rigorously studied in patients with COVID-19 supported with ECMO, and more recent data suggest potentially worse outcomes with such a strategy (46). It may have particular relevance for those undergoing a longer duration of ECMO support, particularly for patients ultimately undergoing evaluation for lung transplantation (37).

Adapting the approach to ECMO in times of crisis. ECMO requires substantial investment of resources because of expensive equipment, the need for dedicated and specialized staff, and high potential for prolonged consumption of critical care services even under ideal circumstances (47). Early in the pandemic, COVID-19 case volumes outstripped available resources in many centers (48), leading to the institution of contingency and crisis standards of care. Triage of life-sustaining therapies, including staffing, ICU beds, and medical supplies, was required (49–52). In some cases, institutions prioritized conventional management strategies at the expense of ECMO to maximize care for the greatest number of patients (48).

Simultaneously, there was increased demand for ECMO. Some regions coordinated care to more effectively allocate resources and standardize processes for ECMO candidates. In Paris, a network of 17 hospitals pooled resources, unified indications and contraindications, centralized ECMO initiation decision making, and expanded mobile ECMO retrieval capacity (53). This organizational structure facilitated workflow for overburdened clinicians, optimized pre-ECMO management, standardized access to ECMO, and facilitated collection of follow-up data for patients not offered ECMO (54).

In Chile, ECMO allocation was overseen by a national advisory commission to improve capacity, coordinate referrals, provide consistency in patient selection, and disseminate recommendations and educational materials (55). In the United Kingdom, a preexisting sophisticated hub-and-spoke model was modified to balance ECMO case volumes across centers, with support and oversight provided to ECMO centers created in the pandemic to handle surge capacity (56).

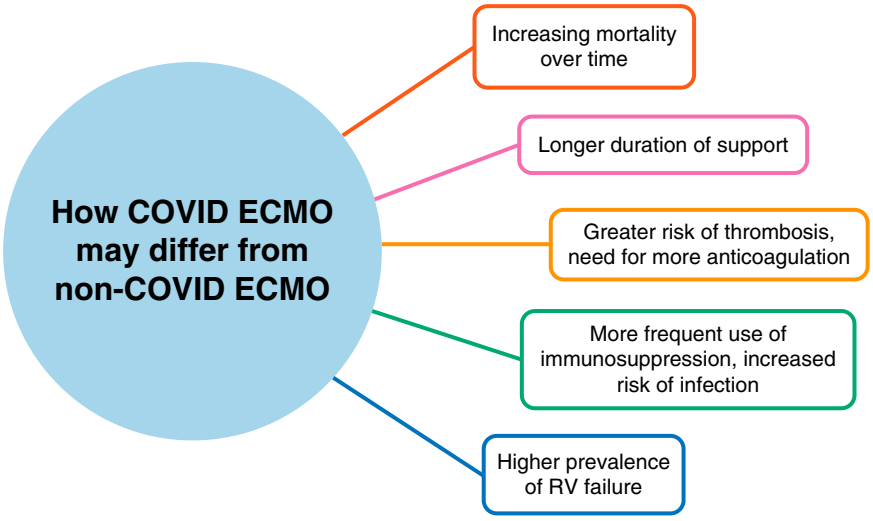

Figure 1. Specific considerations for extracorporeal membrane oxygenation (ECMO) for coronavirus disease (COVID-19) that may differ from ECMO for non–COVID-19 indications. RV = right ventricular.

Adaptations in staffing models and intake processes allowed continued operation of existing ECMO programs under severe resource constraints, including adult patients being treated in pediatric programs (57). Contrary to initial guidelines advising against the establishment of new ECMO programs in the midst of the pandemic (17), some initiatives were successful, including in low- and middle-income countries, especially when created in collaboration with experienced centers and networks and when proper training and educational resources were provided (58). Notably, some of these new ECMO programs provided service to regions of the world where patients would otherwise not have had access to ECMO.

Preparing for the Next Respiratory Pandemic

Early identification and pandemic preparation. COVID-19 exposed an overall lack of preparedness for a respiratory pandemic by governmental and nongovernmental organizations in many regions of the world. In the context of ECMO, the consequences of this were, to varying degrees, inadequate resources and a lack of coordination across centers and regions. For later phases of the current pandemic as well as future pandemics, it will be critical to understand the most appropriate role, if any, for ECMO at a local or regional level.

First and foremost, there needs to be close vigilance, collaboration, and transparency internationally among healthcare organizations and societies to identify the emergence of pathogens with respiratory pandemic potential (Figure 2). In relation to ECMO, governments should work with manufacturers of extracorporeal technology to increase production, secure supply chains, and stockpile equipment, as appropriate, before the next pandemic, similar to a national stockpile of personal protective equipment and ventilators. Unfortunately, stockpiling of these resources by individual centers could easily slip into hoarding of supplies, with detrimental consequences overall. This is perhaps where nongovernmental organizations could guide appropriate resource allocation across regions. ELSO, with chapters across the world and the largest membership of ECMO centers internationally, may be well positioned to assess the state of ECMO supplies at the center, regional, and national levels (59).

Understanding the disease. Fundamental to understanding the potential role for ECMO in a pandemic is an early identification of the mechanisms of disease, including mode of transmission and affinity of the pathogen for particular organs. For pathogens that appear to target the respiratory system, venovenous ECMO would likely be the primary form of extracorporeal support needed. However, pathogens leading to severe cardiac failure, for instance, would be expected to increase the use of venoarterial ECMO.

Defining the scope of the problem. Once it appears that ECMO could be beneficial in an emerging outbreak, it is important to estimate the anticipated case volume that might warrant ECMO support and the expected duration of support. A critical tension that will have to be addressed is to what degree resources (staff, beds, equipment) could be better used to serve a greater number of patients (52, 60), because ECMO is particularly resource intensive.

Preliminary data from initial sites of outbreaks may be informative or misleading, depending on data collection and reporting as well as the population studied. National and international registries could provide centralized databases to help with rapid analysis and dissemination of information. Of course, the higher the case volume, the greater the burden of manual data collection, highlighting the potential role of automated data collection infrastructure for both research and quality.

Understanding the efficacy and effectiveness of ECMO during a pandemic. Coordinated efforts to implement preventive measures and identify disease-specific treatments are essential to avoid the need for more invasive interventions such as ECMO (61). However, the effectiveness of ECMO in reducing morbidity and mortality associated with COVID-19 will vary depending on the cohort considered eligible for ECMO.

To clarify the role of ECMO, there is a need both for real-time registry data collection (which will help define ECMO effectiveness) (59) and for studies assessing short-term (e.g., in-hospital, 60-d) and longer-term (e.g., 90-d, 6-mo, and 1-yr) mortality, resource use (including hospital and ICU lengths of stay), and long-term patient-centered outcomes (e.g., health-related quality of life and long-term pulmonary function). These data are essential not only for future pandemics but also for the current pandemic. A randomized, embedded, multifactorial, adaptive platform trial design could be quickly modified to provide more rapid assessment of short-term ECMO efficacy (62). Other methods, such as traditional RCTs, emulation trials (63), registry RCTs, and matched pairs analyses, all have their advantages and drawbacks (33). Predictive modeling, as has been used for other aspects of care in the current pandemic, may likewise be helpful in anticipating the need for and outcomes of ECMO.

The use of a weighted lottery system has been advocated as a way to turn the scarcity of resources in a pandemic (in this case, ECMO) into an advantage (64). By distributing a particular resource through a regionally or nationally regulated lottery system, equity is favored as compared with a first-come-first-served approach. Random allocation (if paired with registries of clinical outcomes, including in those not allocated the resource) allows for the assessment of effectiveness in real time, potentially with large sample sizes. A weighted lottery system could give advantage to those most likely to benefit or those disproportionately harmed by the pandemic (64). Conducting a lottery system for ECMO, similar to other proposed triage systems that allocate life-sustaining therapies (e.g., ventilators, dialysis), will be context dependent and only applicable in certain jurisdictions based on local laws and customs.

Studies for this and future pandemics should ideally assess the impact of pre-ECMO duration of noninvasive and invasive mechanical ventilation, optimal cannulation strategies, and ECMO management approaches (e.g., anticoagulation targets or early mobilization) (Figure 3A). Cost analyses (not yet rigorously conducted in this population) are also important, given the financial strain ECMO can impose. Separate from COVID-19, the high ECMO volume affords an opportunity to study other ECMO-related questions (e.g., the role of prone positioning during ECMO), though the results may not necessarily be generalizable to the use of ECMO in patients with non–COVID-19–related ARDS (Figure 3B).

Building research networks to implement such investigations in ECMO-capable centers would be particularly challenging in the midst of a pandemic. To be effective, such networks would ideally be functional ahead of time and may benefit from involvement by scientific consortia

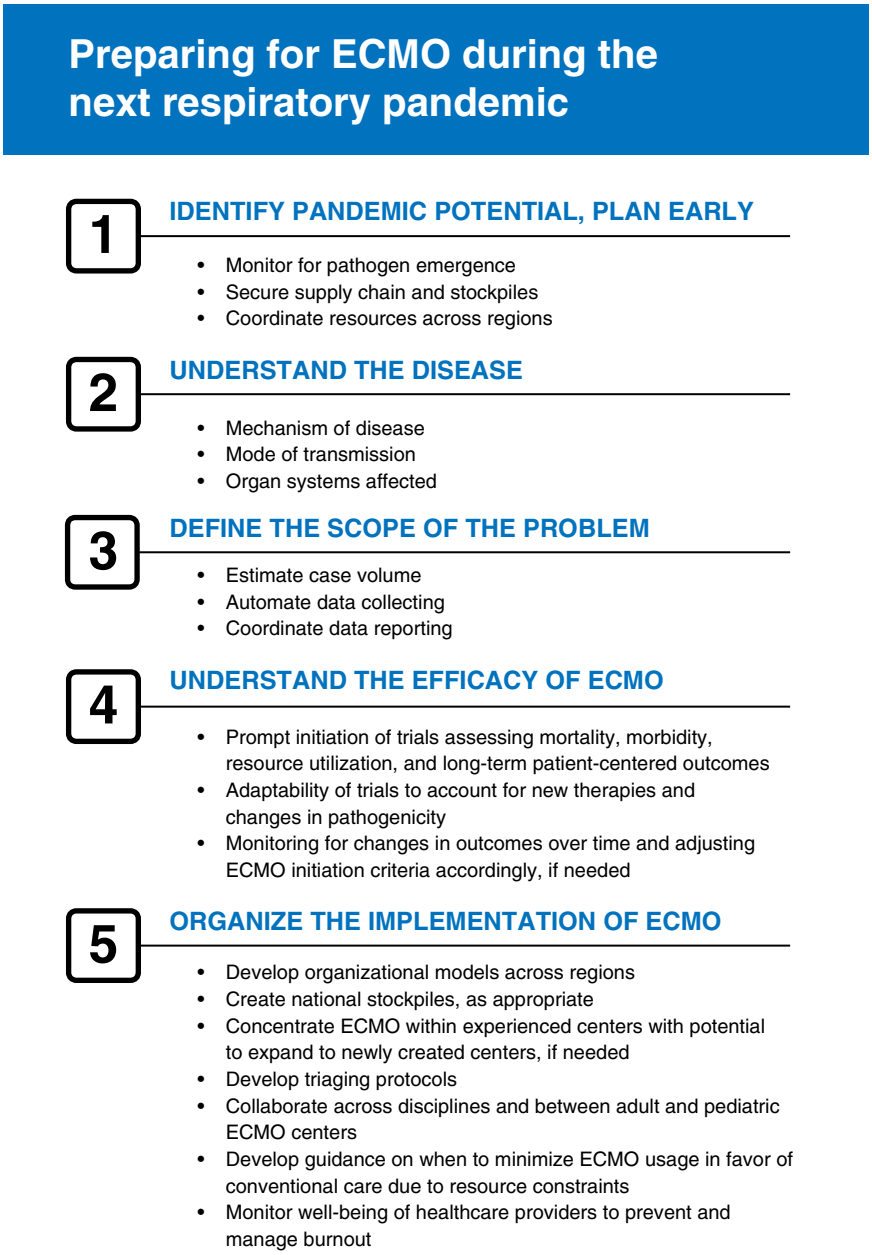

Figure 2. Preparing for extracorporeal membrane oxygenation (ECMO) during the next respiratory pandemic.

such as the International ECMO Network (65).

Simultaneously, as highlighted by the increasing mortality of ECMO-supported patients over time during the current pandemic, investigators must anticipate potential variability in the pathogenicity of a given viral variant, together with changes in clinical management, which may favorably or unfavorably impact ECMO effectiveness. Trials should be designed to adapt to these changes and ensure that concurrently enrolled controls are used to account for any temporal changes.

Organizing the implementation of ECMO in a pandemic. During a pandemic, the number of ECMO-eligible patients may exceed capacity at different times across different regions. To plan for this, it will be important to anticipate the numbers of patients, expected duration of ECMO support, and associated complication rates. This is evident in the current pandemic, given the longer durations of support reported for ECMO for COVID-19 than for other etiologies of ARDS (20, 36). Prolonged duration of support may limit access to care for other critically ill patients and may be a deterrent to offering ECMO when capacity is already severely limited. A triaging system should be established, ideally before it is required, to prioritize which, if any, patients should receive ECMO. Such a system will have to take into consideration prognosis (both with and without ECMO) and resource availability, including supplies, bed capacity, and staffing, made worse if staff themselves are unable to work due to infection with an infectious virus (49–51). Palliative care consultations may help in setting expectations and providing continuity for patients' families and surrogates. Triggers for palliative care involvement in ECMO cases should ideally be defined ahead of time, with consideration of automatic palliative care consultation when resources permit.

Although certain risk factors may be identified as portending worse prognosis with ECMO, care must be taken to avoid inequitable access to ECMO based on factors that would amount to discrimination, such as age, race, ethnicity, disability, or socioeconomic status. This may be accomplished through standardization of initiation criteria, correction factors to triage scores, and stakeholder input on triage algorithms and allocation policies (66). Consideration for allocation of scarce resources, such as ECMO, especially in crises, has been discussed elsewhere (49–51, 66, 67).

An important step in optimizing ECMO outcomes during a pandemic is development of organizational models, ideally before a crisis, to coordinate responses across regions. These models should take into account concentration of resources and expertise, equitable access for patients, consistency in selection criteria, and optimal clinical management (53, 55, 56). Strong communication channels across ECMO centers within a given region should be established to help in the efficient allocation of resources. These should ideally have clearly delineated referral pathways and should be transparent regarding capacity.

Given the association between ECMO case volume and outcomes (18, 22, 53, 68), resources may be best concentrated at experienced, high-performing ECMO centers in a hub-and-spoke model (47), with the hubs simultaneously serving as centers with expertise in managing acute respiratory

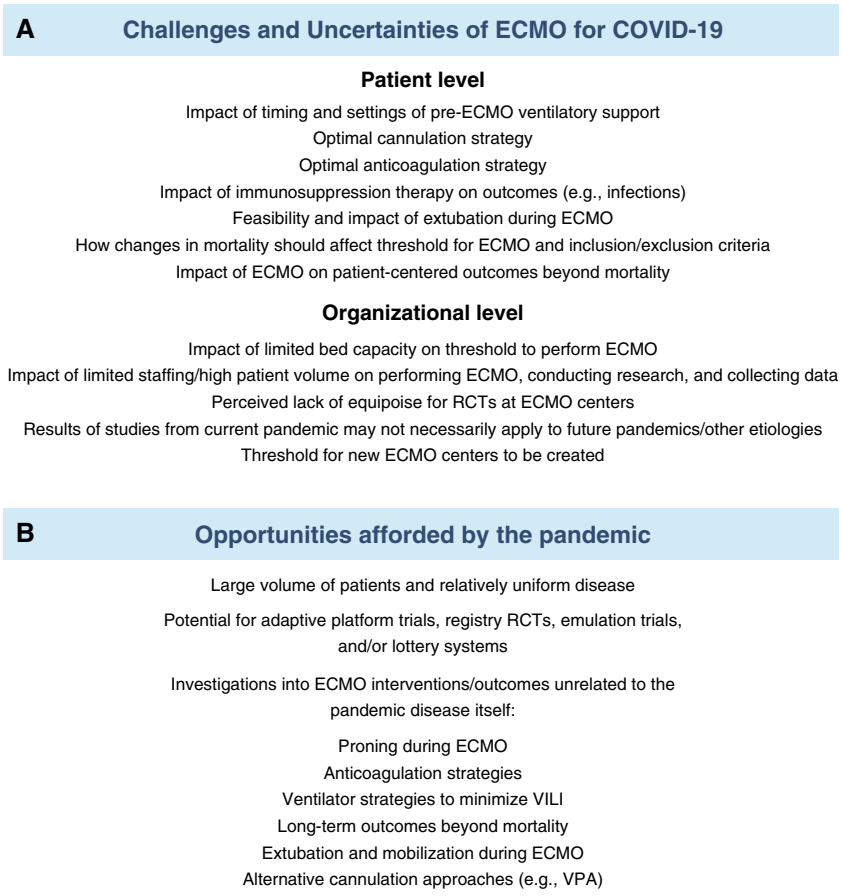

Figure 3. (*A* and *B*) Extracorporeal membrane oxygenation (ECMO)-related challenges and uncertainties encountered during the coronavirus disease (COVID-19) pandemic (*A*) and opportunities afforded by the pandemic (*B*). RCT = randomized controlled trial; VILI = ventilator-induced lung injury; VPA = venous drainage combined with pulmonary arterial reinfusion.

failure more broadly (53, 54, 69). As demand for ECMO grows, it appears reasonable to create new centers under the guidance of experienced centers to increase access to care, including in low- and middle-income countries where resources are potentially even more limited (58). However, this is not to say that ECMO necessarily *should* be offered, including in resource-poor settings. It remains at the discretion of the individual jurisdiction whether the resources required for performing ECMO, with potential diversion of resources away from other critically ill patients, are sufficiently offset by any potential benefits. Real-time data regarding effectiveness are essential for this purpose.

Additional Considerations

Although much of the focus of ECMO during the COVID-19 pandemic has been on adults because of substantially higher rates of severe disease in adults and the infrequent need for ECMO in children with COVID-19 (70), the considerations discussed above may also be applied to pediatric populations. At the onset of an outbreak or pandemic, planning for allocation of ECMO resources and for research should proceed across the entire population until the disease is better defined. Much in the way pediatric ECMO practitioners' expertise and availability have proved vital in assisting adult ECMO programs (57), adult programs could provide valuable resources and knowledge in a pandemic predominantly impacting pediatric populations.

Mobile ECMO teams are key to providing support to regional referral centers, as are critical care transport teams for non-ECMO patients to load balance between hospitals, thereby preserving capacity at ECMO centers. Staffing needs have proved particularly vulnerable during this pandemic, with all key members of the interprofessional team impacted. It will be crucial to monitor the well-being of healthcare providers to prevent and manage burnout, both for humane reasons and to further preserve capacity. An approach that incorporates the expertise, input, and availability of all essential team members should be considered when deciding whether and how to deploy ECMO under any circumstances, most especially during a pandemic when resources are most strained.

As a pandemic recedes and resources to provide ECMO potentially become relatively more plentiful, it is important to maintain responsible use of ECMO, adhering to appropriate criteria within established algorithms for the management of ARDS and tailored, as needed, to the underlying etiology and expected prognosis.

Conclusions

The optimal use of ECMO during a respiratory pandemic requires detailed data, investment in research, and an understanding of clinical outcomes over time. This must be balanced against the high resource intensity of ECMO competing with the provision of other forms of critical care. Both for later phases of this pandemic and for future pandemics, coordination between centers, optimization and use of resources, and development of collaborative research platforms should be undertaken by stakeholders at every level. ■

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