Review article

Med Lasers 2023;12(4):205-211
https://doi.org/10.25289/ML.23.039
pISSN 2287-8300 · eISSN 2288-0224

MEDICAL LASERS
Engineering Basic Research and Clinical Application

Advances in extracorporeal membrane oxygenation (ECMO) technology: navigating toward a wearable solution

Kyoung Min Ryu

Department of Thoracic and Cardivascular Surgery, Dankook University Hospital, Cheonan, Republic of Korea

Extracorporeal membrane oxygenation (ECMO) is a therapeutic apparatus designed for oxygen delivery and carbon dioxide removal in patients facing profound pulmonary or cardiac dysfunction. While the fundamental principles of ECMO application in critically ill cardiorespiratory patients have endured for over three decades, a continuous progression in various constituent elements has been observed. In particular, the demand for ECMO has surged in diverse clinical scenarios, particularly during the recent COVID-19 pandemic, underscoring the emerging imperative for wearable ECMO solutions. Ongoing interdisciplinary research and development efforts are indispensable for addressing this evolving landscape. This paper seeks to provide a comprehensive analysis of the contemporary advancements in ECMO circuitry and delineate the prospective avenues for developing wearable ECMO, positioning this exploration within the broader context of the escalating demand for advanced life support technologies.

Key words: Extracorporeal membrane oxygenation; Cardiopulmonary bypass; Wearable electronic divices; Critical illness; Transportation

INTRODUCTION

Over the past 3 decade, extracorporeal membrane oxygenation (ECMO) has emerged as a crucial intervention for sustaining and enhancing therapeutic outcomes in critically ill patients afflicted with severe cardiopulmonary failure. As 2023 statistical data released by the ELSO (Extracorporeal Life Support Organization), ECMO has been administered to 198,623 patients, demonstrating a commendable survival rate of 67%, with 54% successfully discharged (Table 1, Fig. 1) [1]. The application of ECMO as a therapeutic modality has experienced notable growth, particularly during the challenging milieu of the COVID-19 (coronavirus disease 2019) pandemic.

This escalating trend is substantiated by ongoing research endeavors that explore avant-garde techniques such as low-flow extracorporeal CO_2 removal, alongside innovative variations including respiratory dialysis and the development of wearable long-term thoracic artificial lungs [2,3]. While the fundamental tenets of ECMO remain relatively invariant, the constituent elements of an ECMO circuit have evolved to be more integrated, streamlined, and user-friendly, featuring advanced functionalities and heightened safety measures. The assimilation of polymethylpentene (PMP) fiber technology has heralded a new era of efficient and low-resistance artificial gas-exchange membranes [4].

Furthermore, advancements in simulation equipment have contributed to more comprehensive and realistic training experiences for interdisciplinary teams [5]. No-

Received November 14, 2023, **Accepted** December 8, 2023

Correspondence
Kyoung Min Ryu
E-mail: cskmin@naver.com
ORCID: https://orcid.org/0000-0001-8461-6010

© Korean Society for Laser Medicine and Surgery
This is an open access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (http://creativecommons.org/licenses/by-nc/4.0) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Table 1. Overall outcomes by International Summary of Statistics for ECLS (ELSO Registry Report 2023)

	Overall outcomes				
	Total runs	Survived ECLS		Survived to DC or transfer	
Adult					
Pulmonary	51,093	33,932	66%	29,901	58%
Cardiac	47,917	29,012	60%	22,138	46%
ECPR	14,836	6,339	42%	4,571	30%
Pediatric					
Pulmonary	12,885	9,438	73%	7,951	61%
Cardiac	16,598	12,146	73%	9,172	55%
ECPR	6,779	3,954	58%	2,842	41%
Neonatal					
Pulmonary	35,023	30,605	87%	25,552	72%
Cardiac	10,856	7,532	69%	4,882	44%
ECPR	2,636	1,840	69%	1,138	43%
Total	198,623	134,798	67%	108,147	54%
Tuesday, October 17, 2023				© 2023 Extracorporeal Life Support Organization	

Reused from ELSO 2023 [1].
ECLS, extracorporeal life support; ELSO, Extracorporeal Life Support Organization; DC, discharge; ECPR, extracorporeal cardiopulmonary resuscitation.

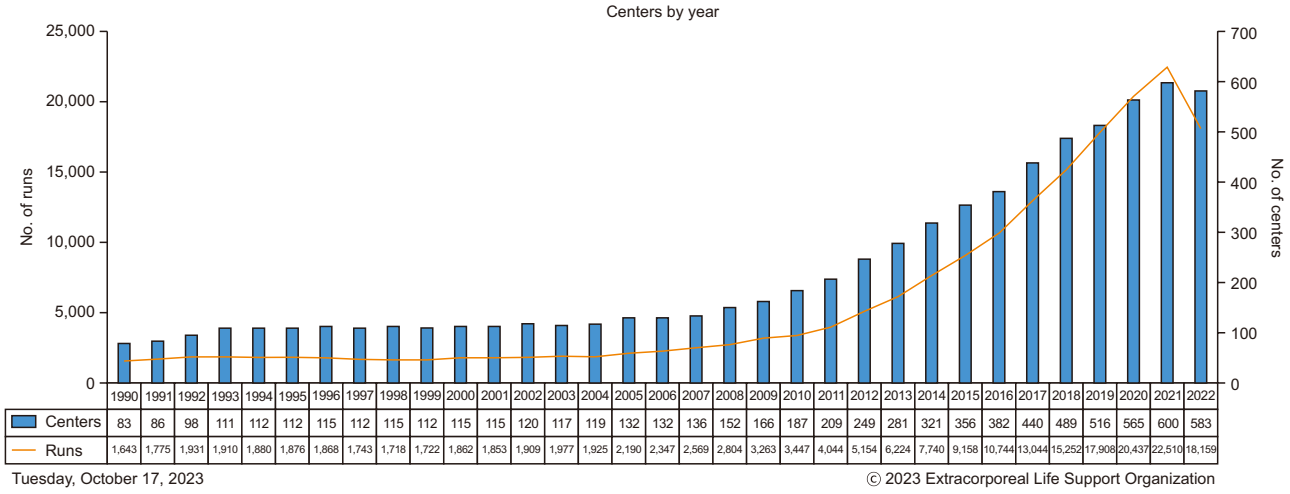


Fig. 1. Number of centers and annual runs by International Summary of Statistics for ECLS (extracorporeal life support). Extracorporeal Life Support Organization (ELSO) Registry Report 2023. Reused from ELSO 2023 [1].

tably, the advent of portable ECMO and the burgeoning demand for wearable ECMO signal a transformative shift in the landscape of ECMO technology.

The aim of this paper is to review the technical developments in ECMO technology, including ECMO device circuit and wearable machine.

MAIN TEXT

Innovation of circuit technology; advancing ECMO systems for enhanced patient outcomes

In modern ECMO systems, the incorporation of non-occlusive centrifugal pump technology represents a noteworthy progression (Fig. 2) [6]. This design selection is motivated by multiple advantages, encompassing reduced priming volumes, streamlined circuitry, and a potentially diminished risk of air emboli [7]. Significantly, this type of rotary pump has become prominent in pediatric applications, utilized in around 60% of cases. However, it is essential to acknowledge the persistent debate surrounding its potential for elevated hemolysis compared to the historically employed occlusive roller pumps [6,7].

The present version of centrifugal pump technology incorporates pump heads that pivot on a singular axis. This design alteration is oriented towards friction reduction, engendering a mechanism with increased free-floating

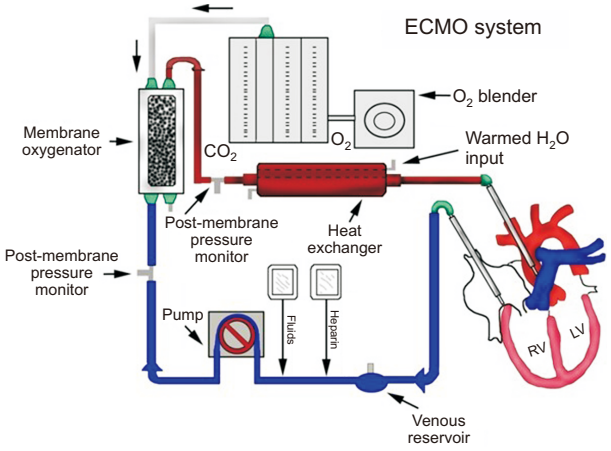


Fig. 2. Schematic view of extracorporeal membrane oxygenation (ECMO) circuit. The main components of ECMO circuit are membrane oxygenator, pump, cannula (access/return), and heat exchanger. RV, right ventricle; LV, left ventricle.



Fig. 3. Cardiohelp, a compact and integrated extracorporeal membrane oxygenation system (Maquet, Rastatt, Germany).

attributes. The enhanced flow characteristics inherent in this design actively contribute to mitigating shear stress on blood components, ostensibly resulting in minimal blood cell damage during ECMO support [8].

A popular example of a standalone centrifugal pump used in ECMO programs is the Rotaflow, made by Maquet. This pump has been regularly chosen in ECMO programs across the United States for over ten years. Its consistent use shows that people trust this technology because it is reliable and effective in supporting blood circulation [8].

As technology progresses, the continuous enhancement of centrifugal pump designs signifies a dedication to optimizing ECMO systems for enhanced patient outcomes. Despite ongoing debates and considerations regarding potential hemolytic effects, the pervasive integration of non-occlusive centrifugal pumps in ECMO underscores their pivotal role as a fundamental component in modern extracorporeal life support technologies.

The Cardiohelp, developed by Maquet, is a pioneering example of miniaturized ECMO systems, signifying an innovative fusion of a distinctively coupled centrifugal pump and PMP membrane, as illustrated in Fig. 3 [9]. This advanced system transcends conventional ECMO configurations, incorporating a spectrum of sophisticated features and functionalities. One of the standout aspects of the Cardiohelp is its comprehensive monitoring capability, facilitated by integrated sensors and transducers. This allows for continuous surveillance of critical parameters such as system pressures, temperature, flow, venous oxygen saturation, hemoglobin levels, and hematocrit. This real-time monitoring ensures precise control and optimization of the extracorporeal circuit, enhancing the overall safety and efficacy of the system. The system is cleverly designed to be small and light, attached to a driver that controls the pump speed. This driver not only helps adjust the pump but also has safety features to keep the patient safe. Plus, it shows doctors and nurses all the important information about the patient's condition in real-time. Introduced in the United States in 2012, the Cardiohelp has become more popular in ECMO programs. More and more people are using it because it works well and helps patients. As technology gets better, the Cardiohelp shows how we keep trying to make ECMO technology better and save more lives.

The efficacy of the Cardiohelp in managing respiratory failure within a cohort of 22 adults was evidenced by its ability to rectify blood gas-exchange abnormalities, enhance hemodynamics, and improve overall subject stability [10]. This favorable outcome aligns with the anticipated reduction in thromboembolic complications and diminished reliance on blood-product repletion attributable to the biocompatibility of the circuit. Nevertheless, the study observed that, in 9 out of the 22 cases, device replacement was necessitated due to clot accumulation in the circuit. The integral design of the Cardiohelp, housing all elements within a single component, mandates a complete circuit exchange, potentially resulting in augmented program expenses. Moreover, the reported cost of the Cardiohelp device surpasses that of conventional, less integrated ECMO systems.

The Cardiohelp has notably demonstrated its substantial influence in the realm of inter-facility ECMO transport [11]. With a weight of approximately 9 kg and compact dimensions, it possesses a distinct advantage in terms of portability. Its ease of maneuverability further enhances its practical utility across diverse clinical settings. The commendation of improved monitoring and safety features during both ground and air transport underscores the Cardiohelp's adaptability across various transportation modalities. In a retrospective comparative analysis with a less integrated ECMO system, Alwardt and collaborators delineated various advantages of the Cardiohelp system [9]. These encompassed a diminished requirement for adjunct equipment, streamlined circuitry, an interface characterized by user-friendliness, and straightforward preparation and deployment procedures. The confluence of these attributes substantially enhances the system's attractiveness and acceptance among users, facilitating its seamless integration into clinical practice.

The field of rotational pump design has experienced significant progress, with diagonal pumps such as the Deltastream DP3 emerging prominently [12-14]. Boasting a low prime volume of 16 ml, a compact design, high revolutions per minute (up to 10,000), and versatile flow capabilities supporting a range up to 8 L/min, the DP3 has demonstrated both safety and efficacy in a case series involving 16 pediatric ECMO subjects. Its lightweight and compact design further establish it as a suitable device for inter-facility ECMO transport by helicopter (Fig. 4). These innovations underscore the ongoing endeavors to refine ECMO technology, enhancing its adaptability and efficacy across diverse clinical scenarios.



Fig. 4. .The Deltrastream DP3 pump and driver with Medos Hilite LT hollow-fiber membrane (Medos Medizintechnik AG, Stolberg, Germany).

The extensive cohort study involving 233 pediatric subjects across 7 centers exemplified the versatility and multifunctional utility of the Deltastream DP3 system [15]. The DP3 demonstrated remarkable adaptability in diverse mechanical circulatory support applications, encompassing venous-venous ECMO, venous-arterial ECMO, and its utilization as a ventricular assist device. Significantly, indications for DP3 support were uniformly distributed between cardiac and respiratory support, emphasizing its efficacy across a broad spectrum of clinical scenarios. Within the comprehensive investigation, a 26% rate of equipment exchanges, whether membrane or complete system, was observed across the 7 centers. The reasons for these exchanges varied from routine maintenance to emergent situations. Despite these occurrences, the DP3 consistently upheld its multifunctional utility, ease of preparation and handling, and demonstrated proficiency in accommodating the entire spectrum of mechanical circulatory support indications. An additional noteworthy attribute augmenting the appeal of the DP3 is its incorporation of a pulsatile mode [16]. In vitro studies have substantiated its capacity to generate sufficient pulsatile flow through small-bore cannulas, particularly those employed in neonates. Despite the additional resistance posed by a membrane and circuitry, the DP3 consistently exhibited ample pulsatility across a wide range of flows [17]. This pulsatile feature, synchronized with the patient's electrocardiogram, mirrors the mechanisms of an aortic balloon pump. The evaluation of this option suggests that the DP3 can produce satisfactory pulsatile flow under various simulated heart rates, ratios, and arrhythmias [18,19].

The long-term effects of a pulsatile feature on ECMO outcomes remain uncertain; however, its potential advantages during extracorporeal cardiopulmonary resuscitation (ECPR) are noteworthy. The pulsatile mode holds promise in enhancing coronary perfusion during ECPR initiation and attenuating the dampening effect on pulsatility induced by the native cardiac output, thereby augmenting perfusion to vital organs. This underscores the DP3's dedication to delivering innovative solutions tailored to specific clinical requirements, with the potential to enhance patient outcomes [17].

Innovations in wearable systems: advancements in miniaturized technologies and pumpless devices for extended support and ambulatory care

The progression of ECMO systems, characterized by compact designs and integrated components, along with the introduction of a bi-caval dual-lumen cannula, has broadened the utilization of ECMO to encompass patients awaiting lung transplantation [20]. This pivotal shift towards extended support durations has compelled an innovative approach to the clinical care of these patients, involving liberation from mechanical ventilation, ambulation, and rehabilitative strategies. Encouraging outcomes observed in the implementation of this approach have generated interest in the exploration and development of miniaturized systems capable of facilitating ambulation and movement. This heightened interest holds the potential to extend the applicability of ECMO to address various chronic respiratory conditions beyond its conventional usage [21,22].

A noteworthy advancement in this context is the portable pediatric pump-lung, a compact and integrated system comprising a microporous hollow-fiber membrane oxygenator and a centrifugal pump. Weighing approximately 280 g, with a blood surface area of 0.3 m^2 and a priming volume slightly exceeding 100 mm, this device signifies a substantial stride in reducing the size and weight of ECMO systems. In a pioneering study utilizing a juvenile sheep model, the pediatric pump-lung demonstrated the capacity to provide sustained support for 30 days, exhibiting minimal impact on hematologic and blood chemistry parameters [23]. This accomplishment presents a promising avenue for advancing long-term mechanical circulatory support for infants and children experiencing severe cardiorespiratory failure, potentially offering an alternative for those awaiting organ transplantation. Additional investigations utilizing the pediatric pump-lung in a sheep model experiencing acute respiratory failure further demonstrated its efficacy in rectifying blood gas abnormalities, stabilizing hemodynamics, and alleviating right ventricular workload [24]. These findings not only substantiate the device's viability for chronic conditions but also accentuate its effectiveness in scenarios involving acute respiratory failure. Using hollow-fiber membranes along with centrifugal pumps has made ECMO systems much smaller. A cool thing happening in this area is the paracorporeal ambulatory assist lung. It's a small device, only 1.8 kg, and about 13 × 13 × 13 cm in size as illustrated in Fig. 5 [25]. This little gadget uses special fiber bundles and impellers with magnets inside, making it compact. Tests, both in labs and with real patients, show that this lung device can push out 3.5 liters of air per minute at a speed of 2,100 revolutions per minute. This new idea could change how we use ECMO, making it easier to help people with breathing problems in different places.

Two pumpless devices designed for long-term use are currently under development at the University of Michigan: the M-lung and a compliant thoracic artificial lung [26]. The M-lung features blood and gas paths passing through a series of fiber-bundle compartments, arranged to enable perpendicular flow of blood and gas. Computational flow dynamics and in vivo testing of this low-resistance device have illustrated that the mixing of blood within the gated compartments enhances O_2 transfer and effectively eliminates CO_2 at a rated flow of 2 L/min. The innovative design of the M-lung, with its gated compartments for improved mixing, signifies a forward-thinking approach to optimizing gas exchange in a pumpless system. In contrast, the compliant thoracic artificial lung adopts a different design, comprising a flexible chamber housing a mat of hollow-fiber bundles [27]. Blood is directed through these bundles via inlet and outlet conduits, while fresh gas flows adjacent to them. Preliminary animal experiments have yielded promising results, suggesting that positioning the device between the pulmonary artery and left atrium reduces the load on the right ventricle, achieving flows exceeding 7 L/min. Subsequent studies have further demonstrated that the compliant thoracic artificial lung can be sustained for an impressive 14 days without a notable increase in resistance. Significantly, this prolonged support duration was

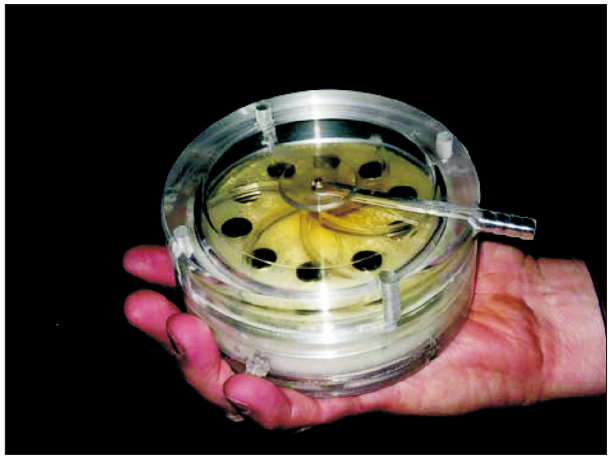


Fig. 5. The paracorporeal ambulatory assist lung prototype created for novel integrated wearable artificial lung (University of Pittsburgh, USA).

achieved while maintaining normal physiologic function and minimizing thrombus formation.

The advancements with the M-lung and the compliant thoracic artificial lung hold substantial promise for the future of long-term ECMO support. With ongoing refinements and extended evaluations, these pumpless devices may emerge as viable alternatives for supporting patients awaiting lung transplantation. The University of Michigan's commitment to innovative solutions represents a pivotal stride toward expanding the capabilities of ECMO technology for extended and sustainable use across diverse clinical scenarios [26,27].

CONCLUSION

The continuous progression of ECMO technology, marked by innovations in centrifugal pump design, the advent of miniaturized systems like Cardiohelp, and the introduction of inventive pumpless devices, underscores a steadfast dedication to advancing patient outcomes and broadening the scope of extracorporeal life support applications across diverse clinical scenarios. These developments represent a collective effort within the scientific community to refine and expand ECMO capabilities, contributing to a more nuanced and effective approach to life support interventions for critically ill patients.

ORCID

Kyoung Min Ryu, https://orcid.org/0000-0001-8461-6010

AUTHOR CONTRIBUTIONS

All work was done by KMR.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

FUNDING

None.

DATA AVAILABILITY

None.

ACKNOWLEDGMENTS

None.

SUPPLEMENTARY MATERIALS

None.

REFERENCES

1. ECLS International Summary of Statistics [Internet]. Extracorporeal Life Support Organization; 2023. [cited 2023 Oct 17]. Available from: https://www.elso.org/registry/internationalsummaryandreports/internationalsummary.aspx
2. Betit P. Technical advances in the field of ECMO. Respir Care 2018;63:1162-73.
3. Abrams D, Brodie D. Extracorporeal membrane oxygenation for adult respiratory failure: 2017 update. Chest 2017;152:639-49.
4. Müller T, Bein T, Philipp A, Graf B, Schmid C, Riegger G. Extracorporeal pulmonary support in severe pulmonary failure in adults: a treatment rediscovered. Dtsch Arztebl Int 2013;110:159-66.
5. Weems MF, Friedlich PS, Nelson LP, Rake AJ, Klee L, Stein JE, et al. The role of extracorporeal membrane oxygenation simulation training at extracorporeal life support organization centers in the United States. Simul Healthc 2017;12:233-9.
6. O'Brien C, Monteagudo J, Schad C, Cheung E, Middlesworth W. Centrifugal pumps and hemolysis in pediatric extracorporeal membrane oxygenation (ECMO) patients: an analysis of Extracorporeal Life Support Organization (ELSO) registry data. J Pediatr Surg 2017;52:975-8.
7. Park Y, Drucker NA, Gray BW. Device updates in pediatric and neonatal ECMO. Semin Pediatr Surg 2023;32:151334.
8. Lawson DS, Lawson AF, Walczak R, McRobb C, McDermott P, Shearer IR, et al. North American neonatal extracorporeal membrane oxygenation (ECMO) devices and team roles: 2008 survey results of Extracorporeal Life Support Organization (ELSO) centers. J Extra Corpor Technol 2008;40:166-74.
9. Alwardt CM, Wilson DS, Alore ML, Lanza LA, Devaleria PA, Pajaro OE. Performance and safety of an integrated portable extracorporeal life support system for adults. J Extra Corpor Technol 2015;47:38-43.
10. Haneya A, Philipp A, Foltan M, Camboni D, Müeller T, Bein T, et al. First experience with the new portable extracorporeal membrane oxygenation system Cardiohelp for severe respiratory failure in adults. Perfusion 2012;27:150-5.
11. Philipp A, Arlt M, Amann M, Lunz D, Müller T, Hilker M, et al. First experience with the ultra compact mobile extracorporeal membrane oxygenation system Cardiohelp in interhospital

transport. Interact Cardiovasc Thorac Surg 2011;12:978-81.
12. Lunz D, Philipp A, Judemann K, Amann M, Foltan M, Schmid C, et al. First experience with the deltastream® DP3 in venovenous extracorporeal membrane oxygenation and air-supported inter-hospital transport. Interact Cardiovasc Thorac Surg 2013;17:773-7.
13. Speth M, Münch F, Purbojo A, Glöckler M, Toka O, Cesnjevar RA, et al. Pediatric extracorporeal life support using a third generation diagonal pump. ASAIO J 2016;62:482-90.
14. Fleck T, Benk C, Klemm R, Kroll J, Siepe M, Grohmann J, et al. First serial in vivo results of mechanical circulatory support in children with a new diagonal pump. Eur J Cardiothorac Surg 2013;44:828-35.
15. Stiller B, Houmes RJ, Rüffer A, Kumpf M, Müller A, Kipfmüller F, et al. Multicenter experience with mechanical circulatory support using a new diagonal pump in 233 children. Artif Organs 2018;42:377-85.
16. Evenson A, Wang S, Kunselman AR, Ündar A. Use of a novel diagonal pump in an in vitro neonatal pulsatile extracorporeal life support circuit. Artif Organs 2014;38:E1-9.
17. Wang S, Kunselman AR, Clark JB, Ündar A. In vitro hemodynamic evaluation of a novel pulsatile extracorporeal life support system: impact of perfusion modes and circuit components on energy loss. Artif Organs 2015;39:59-66.
18. Patel S, Wang S, Pauliks L, Chang D, Clark JB, Kunselman AR, et al. Evaluation of a novel pulsatile extracorporeal life support system synchronized to the cardiac cycle: effect of rhythm changes on hemodynamic performance. Artif Organs 2015;39:67-76.
19. Wang S, Kunselman AR, Ündar A. Novel pulsatile diagonal pump for pediatric extracorporeal life support system. Artif Organs 2013;37:37-47.
20. Rehder KJ, Turner DA, Hartwig MG, Williford WL, Bonadonna D, Walczak RJ Jr, et al. Active rehabilitation during extracorporeal membrane oxygenation as a bridge to lung transplantation. Respir Care 2013;58:1291-8.
21. Bain JC, Turner DA, Rehder KJ, Eisenstein EL, Davis RD, Cheifetz IM, et al. Economic outcomes of extracorporeal membrane oxygenation with and without ambulation as a bridge to lung transplantation. Respir Care 2016;61:1-7.
22. Spinelli E, Protti A. Get fit for lung transplant with ambulatory extracorporeal membrane oxygenation! Respir Care 2016;61:117-8.
23. Liu Y, Sanchez PG, Wei X, Watkins AC, Niu S, Wu ZJ, et al. Effects of cardiopulmonary support with a novel pediatric pump-lung in a 30-day ovine animal model. Artif Organs 2015;39:989-97.
24. Wei X, Sanchez PG, Liu Y, Claire Watkins A, Li T, Griffith BP, et al. Extracorporeal respiratory support with a miniature integrated pediatric pump-lung device in an acute ovine respiratory failure model. Artif Organs 2016;40:1046-53.
25. Madhani SP, Frankowski BJ, Burgreen GW, Antaki JF, Kormos R, D'Cunha J, et al. In vitro and in vivo evaluation of a novel integrated wearable artificial lung. J Heart Lung Transplant 2017;36:806-11. Erratum in: J Heart Lung Transplant 2017;36:1025.
26. Skoog DJ, Pohlmann JR, Demos DS, Scipione CN, Iyengar A, Schewe RE, et al. Fourteen day in vivo testing of a compliant thoracic artificial lung. ASAIO J 2017;63:644-9.
27. Fernando UP, Thompson AJ, Potkay J, Cheriyan H, Toomasian J, Kaesler A, et al. A membrane lung design based on circular blood flow paths. ASAIO J 2017;63:637-43.

How to cite this article: Ryu KM. Advances in extracorporeal membrane oxygenation (ECMO) technology: navigating toward a wearable solution. Med Lasers 2023;12:205-211. https://doi.org/10.25289/ML.23.039