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MODERN EXTRACORPOREAL CIRCULATORY SUPPORT SYSTEMS (CENTRIFUGAL PUMPS AND OXYGENATORS). LITERATURE REVIEW

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For more than 70 years, short-term mechanical circulatory support devices, as well as methods and skills for their implantation, have been continuously developed and improved. An in-depth study of each of the existing devices is important not only to optimize patient outcomes, but also to create a safer, more effective, smaller-sized new device. This review considers existing temporary circulatory support devices, as well as oxygenators, that supplement the system to protect lung function. Their main technical characteristics and the peculiarities of their application in clinical practice are given. Based on the literature review, we formulated the main directions of extracorporeal membrane oxygenation evolution in Russia.

Keywords: mechanical circulatory support, centrifugal pump, oxygenator, ECMO.

INTRODUCTION

Modern transplantology has greatly improved the treatment of critically ill patients by using innovative pharmacological therapies and advanced medical devices, allowing for organ support or replacement. Among these technologies, extracorporeal membrane oxygenation (ECMO) systems have emerged as a key intervention [1–3]. Currently, ECMO is a highly effective modality for managing acute cardiac and respiratory failure, serving both as a life-sustaining bridge to heart or lung transplantation.

Originally introduced as an experimental physiological technique, ECMO has evolved into a critical clinical tool. It plays a pivotal role in determining whether organ function can be restored or if definitive treatment through transplantation is necessary [4–10].

ECMO involves the cannulation of major blood vessels to connect the patient to an extracorporeal circuit, which includes essential components necessary for its function: cannulas, an oxygenator, and an extracorporeal pump. Oxygenators serve a dual role – oxygenating the blood and removing carbon dioxide [11–13]. Variations among oxygenators are primarily based on their structural design, priming volume, membrane gas exchange properties, and the pressure required to maintain a blood flow rate of 1–5 L/min to achieve adequate oxygenation. Extracorporeal pumps are responsible for generating the necessary pressure and flow within the circuit. In most modern ECMO systems, centrifugal pumps are employed due to their favorable performance characteristics [14, 15].

This review article highlights key advancements in the development and clinical application of the two primary components of an ECMO system: blood pumps and oxygenators.

EXTRACORPOREAL PUMPS FOR ECMO SYSTEM

Centrifugal pumps are a critical component of the extracorporeal circuit in ECMO systems. They are responsible for maintaining the patient's hemodynamic stability during a procedure by operating at predetermined parameters. These pumps can effectively compensate for circulatory insufficiency or partially substitute the heart's pumping function. They facilitate blood flow through the membrane oxygenator, enabling gas exchange by supplying oxygen and removing carbon dioxide, thus temporarily replacing pulmonary function.

Maquet Rotaflow (Maquet, Getinge Group, Germany)

The Maquet Rotaflow is a centrifugal pump (CP) specifically engineered to deliver continuous blood flow for the purpose of maintaining or replacing the pumping function of the heart (Fig. 1) [16–19]. In addition to

Fig. 1. Appearance of Maquet Rotaflow

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the centrifugal pump, a continuous life support (PLT) system has been developed to provide both cardiac and respiratory support. The system is capable of generating blood flow rates ranging from 0.5 to 7 L/min. The PLT circuit is designed with a minimal number of primary components to reduce shear stress and turbulence.

The system features a 3 mm diameter, precision ball-bearing, low-friction aluminum oxide pump that drives a 4-blade impeller. The pump head is designed to utilize the potential of a radial magnetic drive. The system is automatic but can be manually started in the event of a failure.

The pump fill volume is 32 mL. The inlet and outlet cannulas are 3/8" in diameter; however, the system has been used in neonates and infants using special adapters to fit 1/4" size. The PLS kit includes a highly plasma-resistant polymethylpentene Quadrox iD oxygenator approved for continuous use for 14 days (shown in Fig. 2).

This system integrates an oxygenator and pump to deliver continuous extracorporeal circulatory support for up to 30 days. It features 3/8" inlet and outlet connectors and is capable of providing flow rates up to 7 L/min. These components are coated with biocompatible BIO-LINE or SOFTLINE materials (heparin-free) [20]. The oxygenator is designed with a distinctive membrane fiber arrangement that optimizes interaction with blood flow.

Fig. 2. Oxygenator Quadrox iD

Fig. 3. Extracorporeal head for the Medos Deltastream DP3 pump

Medos Deltastream DP3 Pump (XENIOS AG, Germany)

The Medos Deltastream DP3 is an ECMO pump approved for medium-term use of up to 14 days [21–24]. It is a diagonal flow pump that combines features of both centrifugal and axial pumps (Fig. 3). The DP3 is equipped with 3/8" and 1/4" inlet and outlet connectors, has a priming volume of 16 mL, and can generate flow rates of up to 8 L/min.

Flow rates vary by cannula size: up to 8 L/min with a 3/8" outlet and up to 2.4 L/min with a 1/4" outlet. The pump speed is adjustable between 100 and 10,000 rpm. A zero flow mode enables rapid shutdown by reducing the speed to prevent backflow. The system incorporates a ceramic bearing and magnetic clutch, and includes an optional pulsation mode adjustable between 40 and 90 wpm. The DP3 cannot be manually restarted; however, in the event of a failure, the portable console (weighing up to 10 pounds) is equipped with two 90-minute power batteries, ensuring temporary support during power or system failures. Additionally, the manufacturer offers a range of compatible adult and pediatric oxygenators.

CentriMag/PediVas (Abbott, USA)

The CentriMag and PediVAS are magnetically levitated centrifugal pumps designed to provide extracorporeal support for adult and pediatric patients, respectively [25–30]. The PediVAS system is suitable for use in both neonates and infants. It has a low priming volume of 14 mL, in contrast to the CentriMag's 31 mL (Fig. 4).

The inlet and outlet cannula diameters are 1/4" for the PediVAS and 3/8" for the CentriMag. Owing to differences in impeller design, the PediVAS can deliver flow rates of up to 1.7 L/min at 5500 rpm, while the CentriMag can reach up to 9.9 L/min at the same speed. This corresponds to a maximum working pressure of 540 mmHg for the PediVAS and 600 mmHg for the CentriMag.

Both devices are FDA-approved for up to 30 days of use for ECMO and ventricular assist applications. The PediVAS and CentriMag pump heads are compatible with the same console and system components (Fig. 5).

These CPs are magnetically levitated and operate without bearings, eliminating contact between the impeller and the housing. This design minimizes friction and heat generation, thereby reducing the risk of hemolysis and thrombosis. The motor is passively cooled through ambient-temperature convective airflow.

Medtronic Pumps (Medtronic Inc., USA)

Medtronic centrifugal pumps – specifically the Adult BPX-80 and Pediatric BP-50 – have been extensively used in open-heart surgery procedures [31–35]. These

Fig. 4. a, CentriMag centrifugal pump; b, PediVas centrifugal pump

Fig. 5. CentriMag drive system

pumps are available in two configurations: the BPX-80, with a priming volume of 80 mL for adult use, and the BP-50, with a 48 mL priming volume for pediatric patients. Both models feature a smooth vortex cone design (Fig. 6).

Both pumps are intended for short-term use. The BPX-80 features 3/8” inlet and outlet cannulae and can deliver flow rates of up to 8 L/min. The pediatric BP-50 pump provides flow rates of up to 1.5 L/min. These pumps are compatible with the Carmeda heparin-coated extracorporeal circuit (Carmeda AB, Sweden), which is designed to enhance biocompatibility.

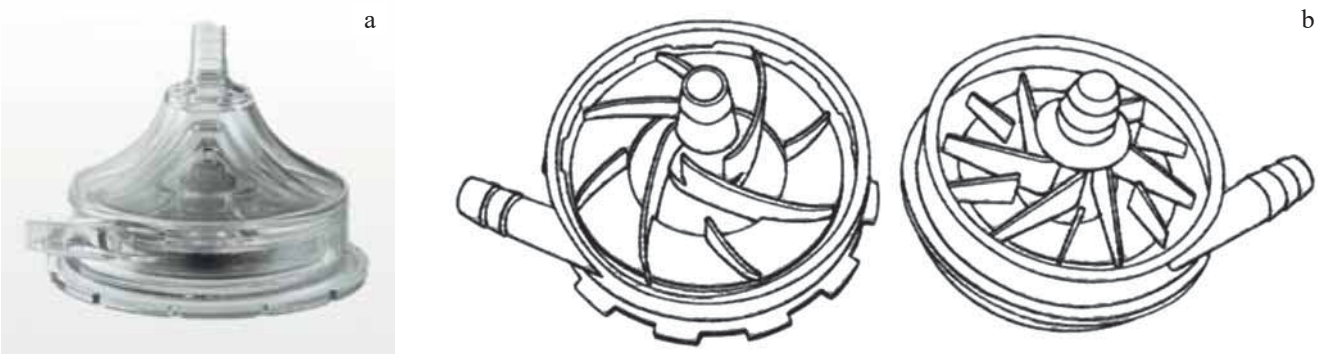

Fig. 6. a, BPX-80 centrifugal pump for adult patients; b, BP-50 centrifugal pump for pediatric patients

Fig. 7. a, Affinity centrifugal blood pump; b, Medtronic Bio-Console for pump control

The Affinity centrifugal blood pump (AP40), a second-generation model of the BPX-80, offers a reduced priming volume of 40 mL. It incorporates a smooth cone and low-profile fins optimized for minimizing hemolysis (Fig. 7, a). This pump is compatible with the Medtronic Bio-Console and includes a new remote actuator for impeller speed control (Fig. 7, b).

The Affinity centrifugal pump provides blood flow rates of up to 10 L/min at lower rotational speeds compared to earlier Medtronic models. Its design minimizes heat generation by reducing friction from moving components and ceramic spherical bearings. This pump

has shown low hemolysis, with less than 0.1 grams of hemoglobin released per 100 L of blood at a flow rate of 5 L/min [36].

Fig. 8. a, LivaNova Revolution centrifugal blood pump; b, Specialized pump control console

LivaNova Revolution (Sorin Group, UK)

The LivaNova Revolution is another centrifugal pump, featuring a priming volume of 57 mL and 3/8" inlet and outlet connectors (Fig. 8, a) [37]. It is operated via a specialized console and is fully integrated with the Sorin LivaNova control system (Fig. 8, b).

The open impeller design of the LivaNova Revolution pump facilitates easy priming and de-airing. Its housing features an injection-molded nylon magnet impregnated with ferromagnetic particles, enhancing the pump's durability. The LivaNova system can deliver flow rates of up to 8 L/min. The Revolution 5 centrifugal pump received FDA approval for use in ECMO systems for durations of up to 5 days.

Oxygenators for the ECMO system

A variety of oxygenators are currently available for both adult and pediatric ECMO systems. The key performance parameters of these devices have been analyzed and are summarized in Table 1 [38–44].

Table 1

Main technical specifications of oxygenators for an ECMO system

	Filling volume (mL)	Maximum blood flow rate (rpm)	Gas exchange surface area (m^2)	Heat exchange surface area (m^2)	Surface coating	Maximum usage time
Medos HILITE 800 (for pediatric patients)	55	0.8	0.32	0.074	Heparin coating	Long-term use
Medos HILITE 2400 (for adult patients)	95	2.4	0.65	0.16	Heparin coating	Long-term use
Medos HILITE 7000 (for adult patients)	275	7	1.9	0.45	Heparin coating	Long-term use
Getinge QUADROX iD (for adult patients)	250	7	1.8	–	Bioline coating	30 days
Getinge QUADROX iD (for pediatric patients)	81	2.8	0.8	0.15	Bioline coating	30 days
Eurosets ECMO (for adult patients)	225	7	1.81	0.08	Phosphorylcholine	14 days
Eurosets ECMO (for pediatric patients)	190	4	1.35	0.08	Phosphorylcholine	14 days
Paragon Pediatric (for pediatric patients)	175	4	1.23	0.2	Rheopak Albumin coating	15 days
Paragon Mini (for pediatric patients)	225	5	1.78	0.2	Rheopak Albumin coating	15 days
Paragon Midi (for adult patients)	250	7	1.95	0.4	Rheopak Albumin coating	15 days
Paragon Maxi (for adult patients)	290	9	2.44	0.4	Rheopak Albumin coating	15 days
LivaNova EOS (for adult patients)	150	5	12	0.14	Phosphorylcholine	5 days
LivaNova Lilliput II (for pediatric patients)	90	2.3	0.67	0.02	Phosphorylcholine	5 days
Novalung Minilung (for pediatric patients)	95	2.4	0.65	0.074	Heparin coating	29 days
Novalung iLA Membrane (for adult patients)	225	4.5	1.3	–	Heparin coating	29 days
Novalung XLung (for adult patients)	275	7	1.9	0.45	Heparin coating	29 days

Table 2

Summary data on extracorporeal pump application

	Advantages of extracorporeal pumps	Disadvantages of extracorporeal pumps
Maquet Rotaflow Pump	1. Minimal shear stress inside the pump cavities. 2. There is a switch to manual operation mode. 3. Continuous use for up to 14 days	High hemolysis rates
Medos Delta Stream DP3 Pump	1. Can create an optional pulsing operation mode from 40 to 90 beats/min. 2. Unique zero flow mode that prevents unwanted backflow. 3. A portable (~10 kg) console with two batteries for 90 minutes	No switch to manual operation
CentriMag Pump / PediVas Pump	Magnetic levitation that reduces the risk of hemolysis and thrombosis	No backup power supply
Medtronic BPX-80 / BP-50	1. There is a heparin-coated modification. 2. High preload sensitivity	High hemolysis rates. Short-term use
Medtronic Affinity	1. Low hemolysis rates. 2. High pump efficiency	Short-term use
Revolution LivaNova Pump	1. Low coefficient of friction due to unsealed bearings. 2. Easy filling and venting of pump cavities. 3. Nylon magnet impregnated with ferromagnetic particles, pressure-cast, with characteristics that, in combination with the impeller, increase the longevity of the pump	Only 2 channels for pressure measurement and two flow limits can be set. Short-term use

DISCUSSION

This review summarizes the key characteristics of pumps and oxygenators currently used in modern clinical ECMO practice. Based on the collected data, the main advantages and limitations of various extracorporeal pumps have been identified and are presented in Table 2.

In evaluating CPs for ECMO, considerations extend beyond the performance of oxygenators under varying flow and pressure conditions. Equally important are the pressure and flow requirements within the cannula connected to the patient. In many cases, particularly in patients with low body mass or small vessel diameter, smaller cannulas are required. For instance, at a flow rate of 5 L/min, a 5 mm diameter cannula can produce a pressure drop of up to 150 mmHg. This substantial resistance must be carefully factored into system design and patient management.

The growing number of ECMO procedures performed in intensive care and cardiac intensive care units over recent decades has demonstrated high survival rates among critically ill patients. Currently, the systems in use are predominantly imported, highlighting the need for the development of Russian-made CPs.

The development and implementation of domestically produced CPs is extremely important and essential. It would not only enhance the quality of medical care but also contribute to the creation of locally produced consumables required for clinical procedures.

At this stage, scientific data supporting the selection of specific pump models for further improvement are available. Advancing domestic CPs for clinical use will lay the foundation for the production of locally sourced consumables for ECMO procedures.

CONCLUSION

Based on the collected data, the use of magnetic levitation and centrifugal flow has proven to be both effective and safe for patient treatment. Reducing undesirable postoperative complications and promoting functional recovery are key clinical objectives in the application of ECMO systems in clinical practice.

In alignment with global standards for the development of such systems, medical and technical requirements have been formulated for the first Russian-made extracorporeal pump currently under development for ECMO circuits. Ongoing research will focus on three-dimensional mathematical modeling of the CP design, calculations for the key components, creation of prototypes, and testing them on hydrodynamic test benches to ensure compliance with specified medical and technical criteria.

The authors declare no conflict of interest.

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