Mechanical circulatory support for infants and small children

Assistance circulatoire mécanique chez le jeune enfant et le nourrisson

Véronique Gournay*, Quentin Hauet

CHU de Nantes, Service de Cardiologie Pédiatrique, Nantes, France

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Summary The number of children in need of mechanical circulatory support has increased substantially over the last two decades, due to the technological progress made in surgery and intensive care, leading to improved survival of patients with congenital heart disease. In addition, primary myocardial dysfunction related to myocarditis or dilated cardiomyopathy may cause end-stage cardiac failure in children or infants, although not as frequently as in adults. The need for mechanical circulatory support may be either temporary until spontaneous myocardial recovery, as in postcardiotomy cardiac failure, or prolonged until heart transplantation in the absence of recovery. Two types of mechanical circulatory devices are suitable for the paediatric population: extracorporeal membrane oxygenation for short-term support; and ventricular assist devices for long-term support as a bridge to transplantation. The aim of this review is to describe the specific issues related to paediatric mechanical circulatory support and the different types of devices available, to report on their rapidly growing use worldwide and on the outcomes for each indication and type of device, and to provide a perspective on the future developments and remaining challenges in this field.

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KEYWORDS
Mechanical circulatory support; End-stage cardiac failure; Childhood; ECMO

Abbreviations: CHD, congenital heart disease; CPR, cardiopulmonary resuscitation; ECMO, extracorporeal membrane oxygenation; ECPR, extracorporeal cardiopulmonary resuscitation; MCS, mechanical circulatory support; VAD, ventricular assist device.

* Corresponding author. Hôpital Mère—Enfant, Service de Cardiologie Pédiatrique, 7, quai Moncousu, 44000 Nantes, France.

E-mail address: veronique.gournay@chu-nantes.fr (V. Gournay).

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Background

The number of children being hospitalized for end-stage heart failure, secondary to congenital heart disease (CHD) or primary myocardial disease, is increasing. This number is expected to rise even higher in the coming years, as the number of patients with CHD reaching adulthood is increasing steadily. While heart transplantation remains the mainstay of treatment for refractory heart failure, with generally good long-term survival approaching 70% 10 years, the mortality rate while awaiting a suitable organ exceeds 20%. Indeed, the number of heart transplantations worldwide has remained stagnant for the last 10 years. Durable mechanical circulatory support (MCS) for the failing heart has been used extensively as a bridge to heart transplantation in adult patients, as numerous ventricular assist devices (VADs) have been available for several decades to provide both temporary and long-term support. Paediatric patients, because of their smaller size and their often complex anatomy and physiology, present a unique set of challenges that has slowed the development of MCS in this population. The use of extracorporeal membrane oxygenation (ECMO), which has long been the sole means of mechanical support for paediatric patients with end-stage cardiac failure, has increased steadily since the 1980s and has contributed to improve survival significantly [1]. However, the short duration of support provided by ECMO (typically 10–20 days) is a major limitation, considering the current waiting times on the transplant list. The use of long-term support with VADs in children as a bridge to transplantation remained sporadic until the early 2000s. However, thanks to the development of suitable devices for infants and small children, mainly the Berlin Heart EXCOR Paediatric VAD (Berlin Heart AG, Berlin, Germany), implantation of VADs in children has grown exponentially in recent years [2].

Paediatric specificities

There are several critical issues to be considered for the successful support of children. The first issue is the miniaturization of the device to make it suitable for a child’s size, requiring a good understanding of the flow devices with regard to haemolysis, thrombogenesis, immuno-activation (activation of an inflammatory cascade) and effective energy transmission (specifically continuous compared with pulsatile). For geometric reasons, miniaturization of the device results in increased surface area per blood volume, which, in combination with lower flow rates than in adults, increases the risk of thrombogenesis. In addition, the narrow size of the openings and canulae causes high shear stress during the passage of red blood cells through the device, promoting haemolysis. Finally, miniaturization of all components of the system reduces energy transmission efficiency. Owing to all these challenges, paediatric patients are more likely to benefit from pulsatile operation mode than adults.

Another aspect of paediatric MCS is that the pathophysiology of heart failure is different in children than in adults. Isolated left ventricular dysfunction is rare in children, in whom the need for circulatory support is often due to a combination of right ventricular failure, hypoxaemia and pulmonary hypertension. In this setting, ECMO is the preferable option. Left VAD is used in patients with predominantly left ventricular failure and normal lung function. Biventricular support is more commonly necessary in children with heart failure secondary to CHD. Children with CHD also have intrinsic anatomical variations that can pose significant difficulty in cannulation for MCS (e.g. single ventricle, abnormal systemic venous return, etc.). From a physiological standpoint, previous surgery may further jeopardize the application of MCS (e.g. systemic-pulmonary shunts, disconnected vena cavae in Glenn or Fontan circulations, etc.).

Indications

The two main indications for MCS in children are cardiac medical failure and postcardiotomy (post-surgical) cardiac dysfunction.

Medical indications

Although not as common in children as in adults, dilated cardiomyopathies are the leading cause of heart failure
in children without CHD and are the most common indication for non-surgical MCS. According to the Paediatric Cardiomyopathy Registry, the annual incidence of dilated cardiomyopathies in children aged <18 years is 0.57 cases per 100,000 per year overall, with a much higher incidence in infants than in children (4.40 vs 0.34 cases per 100,000) [3]. The majority of children have idiopathic disease. The most common known cause is myocarditis (46%). As the myocardium may fully recover from viral injury, the presence of myocarditis has been described to be a predictive factor of better outcome in several studies. Indeed, the Paediatric Cardiomyopathy Registry reported a 5-year transplantation-free rate as high as 81% in individuals with myocarditis. In these patients, ECMO can be initiated to rest and unload the heart, allowing the myocardium to recover from injury, as a bridge to recovery, with excellent results. Other factors indicating better prognosis in dilated cardiomyopathy are younger age at diagnosis and higher left ventricular ejection fraction. If the myocardium does not recover, ECMO may then be switched to a long-term means of MCS until heart transplantation.

The optimal timing for initiating MCS is before circulatory collapse, avoiding end-organ injury, particularly neurological damage. As experience with this therapy has increased, the threshold for initiating MCS has been lowered. Currently, MCS should be considered in patients in heart failure requiring a progressive increase in inotropic support (e.g. epinephrine > 0.3 \( \mu g/kg/min \) or requirement of a second inotrope), cardiac index < 2.0 L/min/m\(^2\), decreased mixed venous saturation (< 40%), lactic acidosis, poor end-organ perfusion evidenced by oliguria (< 1 mL/kg/h), altered mental status, mechanical ventilation requirement, inability to tolerate enteral feeding, rising liver enzymes, rising creatinine, immobility or extreme fatigue. A promising alternative strategy in these potential candidates for MCS has been proposed by some centres, consisting of the use of levosimendan combined with milrinone and nesiritide, while minimizing catecholamine use as much as possible and keeping MCS as back-up. MCS was delayed or avoided in a small series of seven patients managed with this strategy [4].

ECMO is also used as a rescue therapy during cardiac arrest refractory to conventional cardiopulmonary resuscitation (CPR). In this indication, ECMO is referred to as extracorporeal cardiopulmonary resuscitation (ECPR). The current American Heart Association paediatric advanced life support guidelines recommend consideration of ECPR for inhospital paediatric cardiac arrest patients failing to respond to initial resuscitation attempts "if the condition leading to cardiac arrest is reversible or amenable to heart transplantation" [5].

The other indications for ECMO are intoxications with cardiodepressive drugs, life-threatening arrhythmias and hypothermic cardiac arrest, usually due to cold-water drowning.

**Surgical indications**

The most common indication for ECMO is failure to wean from cardiopulmonary bypass after repair or palliation of CHD. The reported frequency of ECMO use after cardiopulmonary bypass in children is 3–5%. Left VAD may be used as an alternative to ECMO for circulatory support after failure to wean from cardiopulmonary bypass in patients suspected to need circulatory support for a long duration (> 2 weeks), if they do not have pulmonary hypertension or respiratory dysfunction. Patients with anomalous origin of the left coronary artery from the pulmonary artery are a typical example, as the recovery of left ventricular function may be delayed for months after coronary artery surgical reimplantation.

**Contraindications**

Contraindications to MCS include extreme prematurity, very low birth weight (< 1.5 kg), significant neurological injury and extracardiac malformations with poor prognosis. Relative contraindications are multisystem organ failure, as organ function may be expected to improve with restoration of haemodynamic stability, and chromosomal aberrations. Decisions about the initiation of MCS are made on a case-by-case basis in such patients.

**Devices**

**Extracorporeal membrane oxygenation**

ECMO circuits are composed of a centrifugal or roller pump with a hollow-fibre or membrane oxygenator, an oxygen blender, a pump console, a heat exchanger and a pump cart. The site of cannulation varies with the indication for ECMO. Patients requiring support in the immediate post-operative period are cannulated through a sternotomy, via aortic, right atrial and often left atrial cannulae, the last being for decompression of the left ventricle. Peripheral cannulation, via the neck in infants and small children or femoral vessels in older children, is preferred in non-surgical patients. The circuit may be primed with crystalloids or blood products, keeping the prime volume to an absolute minimum to decrease the effect of haemodilution. After initiation, ECMO flow is increased to achieve a goal of 100–150 mL/kg/min. Anticoagulation is provided using heparin infusion to maintain an activated clotting time of 180–240 seconds. Mechanical ventilation support should be continued with low settings while on ECMO to prevent atelectasis. Regarding the duration of support, ECMO provides only short-term support, with a maximum duration of 15–21 days.

**Ventricular assist devices**

VADs are composed of inflow and outflow cannulae, a pump system, a power source and a system controller. The inflow cannula is attached to the left atrium (short-term devices) or to the apex of the left ventricle (long-term devices) and blood is pumped by the device into the outflow cannula, which is sutured to the ascending aorta. When a right VAD is indicated, the inflow cannula is attached to the right atrium and the outflow cannula into the main pulmonary artery. In contrast to ECMO, the implantation of VAD devices requires central cannulation via sternotomy and, in the case of long-term devices, cardiopulmonary bypass. The VAD devices can be classified as short- or long-term, with 2 weeks being the usual limit for short-term VADs. The ejection can be achieved with centrifugal, pneumatic pusher
plate or axial flow pumps (Fig. 1). In centrifugal pumps, blood enters in the centre of a rotor and has direct contact with the motor parts (Fig. 1A). In the pneumatic pusher plate systems, blood runs through a closed polyurethane pouch with an inlet and an outlet valve (Fig. 1C). The blood-filled pouch is separated from an air-filled chamber by a thin membrane. Compressed air drives the blood out of the pouch in systole, and negative pressure drives the blood into the pouch in diastole. The resulting flow is pulsatile. In the axial design, a rotating impeller is suspended in a narrow housing and driven by an electrical motor (Fig. 1B). As blood flows through the narrow chamber, it is continuously accelerated by the blades of the impeller. These devices have a low profile and may be implanted in a large blood vessel.

Short-term devices

Short-term devices are usually used for acute processes such as myocarditis, postoperative ventricular dysfunction or acute graft rejection, with a hope of bridging to recovery. Another emerging indication for short-term devices is ‘bridge to decision’, when a patient clearly needs MCS, but has significant end-organ dysfunction with uncertain prognosis that may affect transplantation eligibility.

Short-term VADs are centrifugal pumps. The devices in general use nowadays are the Biomedicus Biopump (Medtronic, Minneapolis, MN, USA) (Fig. 1A), the Rotaflow (Maquet Cardiovascular, Wayne, NJ, USA) and the Thoratec PediMag (formerly Levitronix PediMag/CentiMag; Thoratec Co., Pleasanton, CA, USA), designed for small infants weighing as little as 3 kg. Central cannulation via sternotomy in the left atrium and the aorta without going into cardiopulmonary bypass is recommended to provide optimal circuit flow. Compared with an ECMO circuit, these VADs have the advantage of a lower priming volume, and, due to the absence of oxygenator or venous reservoirs, lower heparin requirements and reduced trauma to red blood cells. Limitations of the centrifugal pumps are that only short-term support is provided, requiring a conversion to a long-term VAD if recovery is not successful after 2–3 weeks. In addition, sedation and mechanical ventilation have to be continued.

Long-term devices

The Berlin Heart VAD or EXCOR is a paracorporeal pneumatically driven pulsatile-flow VAD. It is the only device suitable for all paediatric patients, including neonates, and is capable of providing both left VAD and biventricular VAD support. It is available with five pumping chamber sizes (10–60 mL). The blood pump is transparent, allowing visual control of filling, emptying and thrombus formation (Fig. 1C). The blood-contacting surfaces of the pump are heparin-coated, reducing anticoagulation requirements. Patients implanted with a Berlin Heart no longer need mechanical ventilation, can resume enteral feeding and, although they have to remain hospitalized, are ambulatory (Fig. 2). The duration of support may extend up to 400 days.

The Thoratec VAD is another paracorporeal pneumatic VAD, implantable in children aged ≥7 years of age with a body surface area > 0.7 m².

Apart from the EXCOR and Thoratec VADs, long-term devices suitable for school-age children (body surface area 0.7–1.5 m²) are the MicroMed DeBakey VAD Child and the Abiomed BVS 5000, both of which are axial flow pumps. These devices allow ambulation and rehabilitation during support, but are capable of providing left-sided support only.

The main differences between ECMO and the Berlin Heart EXCOR (the VAD most commonly used in children) are summarized in Table 1.

Outcomes

Extracorporeal membrane oxygenation

Information on outcomes after ECMO has been collected by the international Extracorporeal Life Support Organization Registry since 1989. This registry has collected data on over 37,000 patients so far, analysed with a specific focus on neonatal and paediatric cardiac patients, accounting for 19% of all cases recorded [6]. The main complications of ECMO are intracranial or surgical site bleeding, thromboembolic events, haemolysis, infections and renal failure, all of which have a significant impact on survival. A significant limitation of the registry is the absence of functional assessment and long-term neurological follow-up. Fortunately,
several publications have addressed the issue of long-term neurological outcome after ECMO, particularly after ECPR.

Post-surgical extracorporeal membrane oxygenation

Three large series have reported outcomes of children with postcardiotomy myocardial dysfunction requiring ECMO, in 180 patients (median age 109 days), 66 patients (mean age 5.2 years) and 58 patients (mean age 12 days), respectively [7–9]. Failure to wean from cardiopulmonary bypass, followed by low cardiac output and pulmonary hypertension, were the main indications for ECMO. The duration of ECMO support ranged from 5 to 6 days. Survival to hospital discharge ranged from 38% to 45%. Overall, 26 out of 244 (10.6%) survivors of ECMO required heart transplantation, with no heart transplantation being a predictor of mortality. The major complication of postcardiotomy ECMO was haemorrhage, frequently requiring reintervention. Prolonged ECMO duration and renal failure were consistent predictors of mortality in the three studies. Complete operative repair tended to be associated with improved survival compared with palliative surgery. One should also keep in mind that any significant residual lesion has to be ruled out when a patient remains dependent on support after surgery.

Extracorporeal cardiopulmonary resuscitation

Fourteen studies have reported on 762 patients treated with ECPR from 1990 to 2008, with cumulative hospital survival in 371 (49%), ranging in individual reports from 33% to 79% [1,10,11]. The most consistent predictors of mortality found in several studies were non-cardiac disease, renal dysfunction on ECMO, neurological complications on ECMO and lowest pH on ECMO. Unexpectedly, conventional CPR duration before ECPR initiation was not a predictor of mortality in nine of the studies. Survival without gross neurological impairment has even been reported in patients after prolonged chest compression for up to 176 minutes, so a maximum duration of CPR beyond which ECPR is not beneficial cannot be determined. Furthermore, in a review of the Extracorporeal Life Support Organization database, although pre-ECMO arterial pH was strongly associated with outcome, 12% of children of the survivors had a pre-ECMO pH < 6.9 [11]. The quality of CPR, as well as the delay between the cardiac arrest and CPR initiation, are more likely to influence mortality than CPR duration. Another factor is the underlying pathological condition, which may affect the quality of resuscitation. For example, patients with complex cardiac anatomy precluding effective blood flow supply and oxygen delivery to the brain during CPR,

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Characteristics of the two main types of paediatric mechanical circulatory support.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient size</td>
<td>ECMO</td>
</tr>
<tr>
<td>Experience</td>
<td>Any</td>
</tr>
<tr>
<td>Thousands of paediatric cases since 1975</td>
<td>Hundreds of paediatric cases since the early 1990s in Europe and the early 2000s in the USA</td>
</tr>
<tr>
<td>Setting</td>
<td>Intensive care unit, mechanical ventilation</td>
</tr>
<tr>
<td>Anticoagulation</td>
<td>Strictly required</td>
</tr>
<tr>
<td>Maximum duration of support</td>
<td>15–21 days</td>
</tr>
<tr>
<td>Respiratory support</td>
<td>Yes</td>
</tr>
<tr>
<td>Biventricular support</td>
<td>Always</td>
</tr>
<tr>
<td>Flow type</td>
<td>Non-pulsatile</td>
</tr>
<tr>
<td>Complications (neurological injury)</td>
<td>High</td>
</tr>
</tbody>
</table>

ECMO: extracorporeal membrane oxygenation; EXCOR: paediatric ventricular assist device.

Figure 2. Eight-year-old patient 1 month after surgical implantation of an EXCOR left ventricular assist device; she was feeding correctly and was able to walk around within the ward.
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such as blocked aortopulmonary shunts, are more likely to suffer fatal ischaemic brain injury.

Neurological outcome in ECPR survivors was mostly assessed by the Paediatric Cerebral Performance Category score, which rates disability from 1 (normal) to 6 (brain death). In the nine studies in which this information was available, the Paediatric Cerebral Performance Category score was ≤ 2 (indicating no or only mild dysfunction) in 161 out of 204 survivors (79%).

Thus, acceptable survival and neurological outcome can be achieved with ECPR in children after a prolonged witnessed cardiac arrest refractory to conventional resuscitation measures. However, these results can not be generalized to ECPR rewarming protocols after hypothermic arrest, usually due to cold-water drowning, initiated after an ill-defined delay in patients found pulseless, in whom a survival of only 22% was reported recently [12].

Early and adequate CPR, as well as rapid ECMO deployment requiring immediate staff and resource availability, are of utmost importance to ensure good results with this technique.

Myocarditis

An analysis of data from the Extracorporeal Life Support Organization registry focused on ECMO in patients with acute myocarditis [13]. Of 19,348 reported paediatric ECMO uses from 1995 to 2006, 260 runs were for 255 patients with myocarditis. Of these, 155 (61%) survived to hospital discharge, with rates of 96% for recovery and 4% for heart transplantation. Female sex, arrhythmia on ECMO and need for dialysis during ECMO were independent risk factors for in-hospital mortality. Strokes occurred in 8.2% of patients and brain death occurred in 6% of patients.

Bridge to transplantation

A few retrospective studies have reported the outcomes of patients supported by ECMO while awaiting transplantation [14—17]. The size of the series ranged from 21 to 47 patients. The average duration of support varied from 6 to 20 days, with extremes going up to 85 days. Mortality on waiting list was around 35% and survival to discharge, after either successful weaning or transplantation, ranged from 45% to 55%. Patients with cardiomyopathies and myocarditis had better chances of favourable outcome than those with CHD, whereas older age and renal insufficiency were risk factors for poor outcome.

In addition, an analysis of the United Network for Organ Sharing database reported the outcome of 2532 transplantations in children, 171 (6.8%) of whom were supported by ECMO while awaiting transplantation [18]. Patients receiving ECMO had a higher incidence of posttransplantation complications (cardiac reoperation, need for dialysis, infection, stroke) before discharge than those with VADs, resulting in a higher 30-day posttransplantation mortality.

Ventricular assist devices

The largest single-centre experience with the EXCOR (94 children) has been reported recently by Hetzer et al. from the Berlin Heart Institute [2]. In this report, the authors divided their nearly 20-year period into two time periods; they showed significant improvements in survival over the years, as the success rate (transplantation or successful weaning) increased from 49% in the first decade (1990—2001) to 69% in the later era (2002—2011). The improvement was even more marked in infants. The authors attributed these improvements to earlier implantations of VADs and modifications in the management of anticoagulation. Indeed, the incidence of thrombotic adverse events decreased significantly.

In North America, the EXCOR only became available in 2004, initially as a result of compassionate appeals to the Food and Drug Administration. Since that date, its use has grown exponentially, as more than 200 children have been implanted in North America. Extensive data regarding the outcome of these children have been reported in two large multicentre studies [19,20]. The first study was the Berlin Heart Investigation Device Exemption trial, referred to as the IDE trial, which was conducted in 17 centres between 2007 and 2010, comparing the safety and effectiveness of the EXCOR in a carefully selected cohort of children, with a historical control population supported with ECMO as a bridge to transplantation [20]. The 48 study subjects were divided into two groups based on body surface area (< 0.7 m² and > 0.7 m²). In both groups, survival time on support was significantly longer in patients supported with the EXCOR than in those on ECMO. Overall, approximately 90% of the patients in both groups achieved a favourable outcome, mostly with heart transplantation. Upon successful completion of this trial, the EXCOR was granted approval in the USA in late 2011. The 90% survival of the IDE trial is seemingly very high compared with the European experience and pre IDE trial results in the USA. However, the data from the IDE trial do not necessarily reflect real-world experience. Indeed, they do not capture the experience of > 75% of all children in the USA implanted with the EXCOR on compassionate-use access during the same period, who were not enrolled in the IDE trial because they met one or more exclusion criteria or because they were implanted at one of the 27 non-IDE study sites. Hence, the second large multicentre North American study was conducted in order to characterize the performance of the EXCOR in unselected patients [19]. In this study, Almond et al. analysed the larger compassionate-use cohort (156 subjects) combined with the 48 original IDE trial subjects. The median duration of support was 40 days (range 1—435 days). As expected, 12-month survival in this unselected population was lower than that in the IDE trial (75%, comprising 64% who reached transplantation, 6% who recovered and 5% who were alive on the device). Neurological dysfunction (mostly from thromboembolic events) occurred in 29% and was the leading cause of death. Other serious adverse events were major bleeding (44%), major infection (46%) and respiratory failure (29%). Multivariable analysis identified lower weight, end-organ dysfunction reflected by renal and hepatic dysfunction, and biventricular support as risk factors for mortality. In contrast to other studies, ECMO before EXCOR implantation was not a risk factor in this model. It is possible that ECMO, when used strictly for short-term resuscitative support to normalize end-organ function before VAD implantation, may improve VAD candidacy in selected patients. This duality of effect for ECMO may account for its absence in the final multivariable model.
The absence of influence of ECMO on in-hospital mortality was also reported in a retrospective cohort study performed between 2004 and 2011 in all children listed for heart transplantation requiring EXCOR implantation in the two UK paediatric heart transplantation centres [21]. During this 7-year period, 102 children required EXCOR support. Of these, 86 (84%) survived to transplantation (n = 74) or EXCOR explantation (n = 12) and 81% survived to discharge. Neither age, ECMO use nor duration of support influenced outcome. Stroke, ongoing requirement for ventilation while on EXCOR and diagnosis other than dilated cardiomyopathy were the only independent mortality risk factors. The proportion of children undergoing heart transplantation bridged with an EXCOR has increased over time from 12.3% in 2004 to 59% in 2011.

Potential consequences of the development of mechanical circulatory support

An important issue is that the average waiting time on the transplant list is doomed to increase in the current setting of static organ supply as the number of children supported with a VAD before heart transplantation increases. This was indeed one of the conclusions drawn from the UK experience [21]. Given the high risk of thromboembolic strokes and bleeding while on EXCOR, the likelihood of successful outcome may decrease as support duration extends. This should be taken in consideration when determining the optimal timing of EXCOR implantation. The dilemma for clinicians is the fact that the appropriate time for implantation between ‘too early’ and ‘too late’ for this device is difficult to determine.

Another potential drawback of MCS could be a higher risk of rejection after transplantation due to human leukocyte antigen sensitization, induced by exposure to blood products while supported. However, based on the above-mentioned analysis (the United Network for Organ Sharing database of 2332 paediatric transplantations, 17% of whom were supported at the time of transplantation [either VAD, ECMO, or intra-aortic balloon pump]), the use of a VAD does not predict higher posttransplantation mortality in paediatric patients [18]. Ten-year posttransplantation survival for all patients was approximately 57%. In this population, the need for ECMO, but not the need for a VAD, was a strong predictor of 30-day mortality, reflecting poor clinical and functional status. ECMO ceased to be a predictor of poor outcome among patients surviving the initial 30 days, and the survival curves were parallel in ECMO, VAD and non-assisted patients. Thus, those patients who reach transplantation with adequate end-organ function and survive the perioperative period appear to have similar long-term outcomes, regardless of the need for MCS. These findings suggest that MCS does not increase the risk of rejection after transplantation.

Future developments

In the mid 2000s, the growing recognition of increasing numbers of children with heart failure prompted the National Heart, Lung and Blood Institute in the USA to launch a programme with the aim of developing a novel circulatory support device for children weighing 2–25 kg. The technical requirements for these devices were: rapid deployment (< 1 hour after decision to initiate support); minimal priming volume and blood product exposure; flexible cannulation to accommodate anatomical variants; minimize risk of complications, including infection, bleeding, haemolysis and thrombosis; long-term support up to 6 months after insertion.

The Pumps For Kids, Infants and Neonates (PumpKIN) programme provided financial support for the preclinical testing of four promising devices [22,23]. One of the programmes (PediaFlow Pediatric, Pittsburgh) has ended secondary to a lack of industry partner, but three are currently in the in-vitro or early stages of in-vivo testing in animal models. Clinical trials are anticipated in the next few years.

Jarvik Heart, in collaboration with the University of Maryland, is redesigning the Jarvik 2000 axial flow pump for paediatric use in infants. It is extremely small with a priming volume of 1 mL and sits inside the ventricle wall.

Both the Paediatric Cardiopulmonary Assist System (Enson) and the Pedi Pump Lung (Levitrionix in collaboration with the University of Maryland) will be self-contained devices capable of pumping and oxygenating blood simultaneously.

Conclusion

With the number of children in end-stage heart failure growing disproportionately to the stagnant organ supply in transplantation programmes, the need for development of MCS devices that are safe and sustainable for the paediatric population is becoming more pressing. Considerable progress has been achieved in this field over the last two decades. The use of ECMO first and then VADs, mostly the EXCOR, has grown exponentially worldwide to offer children and infants life-saving support. This support can be either temporary as a bridge to recovery after a cardiac arrest or postcardiotomy failure, or prolonged for several months as a bridge to transplantation in the absence of recovery. However, the high rate of complications, particularly thromboembolic strokes and bleeding, remains a concern. Further research to develop safer miniaturized devices and improve anticoagulation management is thus warranted. Indeed, the optimal timing for implantation remains a major issue for clinicians, considering the high risk of life-threatening adverse events, as the average waiting time for transplantation on VAD support is steadily extending.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.

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