Chapter

A Historical Review of Mechanical Circulatory Support

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Abstract

Meaningful and contemporary data regarding the clinical use of mechanical circulatory support (MCS) is founded on the work conducted in the 1950s when a "heart-lung" machine was incorporated to provide support during surgical interventions. Following this milestone, the need to support artificial circulation in patients with heart failure initiated an investigational and legislative collaboration to implement the mission-oriented Artificial Heart Program in the United States during the 1960s. In the subsequent decades, technological discoveries have integrated a series of mechanical systems employed as therapeutic options for short- and long-term artificial circulation in children and adults with advanced heart failure. Since their clinical application, MCS devices have been employed as a bridge to transplantation in over 4000 patients globally. In recent years, the adverse effects and economic burden of MCS have been counterbalanced by the harmonization of therapeutic protocols, the inclusion of multidisciplinary insight, and the allowance of families and patients to participate in shared decision making to address candidacy. In this chapter, we provide a review of the historical aspects of MCS, a therapeutic option for overcoming complexities encountered in reestablishing adequate hemodynamic states and providing a reasonable quality of life.

Keywords: mechanical circulatory support, heart failure, historical aspects, left ventricular assist device

1. Introduction

Heart failure (HF) affects approximately 6 million adults in the United States (US) and is projected to affect over 8 million persons over the age of 18 years by the year 2030 [1]. Of these, it is estimated that the prevalence of advanced heart failure (American College of Cardiology/American Heart Association Stage D) ranges between 250,000 and 300,000 individuals. Between 1988 and 2021, over 83,000 heart transplants were performed in the US. Among those patients, a ventricular assist device (VAD) was used in over 20,000 or approximately 25% of transplantations [2]. Pediatric patients (≤17 years old) comprised 31% of total transplantations, and approximately 9% of children required a VAD as a bridge to transplantation (BTT) [2].

A description of noteworthy milestones in the history of cardiac surgery and mechanical support must include the meaningful advances led by Dr. John H. Gibbon in the 1950s. These advances laid the foundation for the use of cardiopulmonary bypass (CPB) and circulatory assist devices to support patients with perioperative complications and prolonged hemodynamic recovery [3, 4]. Since the early days of mechanical circulatory support (MCS), VADs have become a standardized alternative strategy to bridge to hemodynamic recovery, destination therapy, a bridge during decision-making for the next steps in management, or as a BTT [5].

The first clinical use of a LVAD was reported by Liotta *et al*. in 1963, in a patient with cardiac arrest the morning after aortic valve replacement. The intrathoracic pump was still functioning 4 days postoperatively when the patient died due to brain damage, a complication of cardiac arrest they experienced prior to LVAD implantation [6]. In 1964, The National Institutes of Health (NIH) became actively involved in the development of mechanical assist devices with the inception of the Artificial Heart Program [7]. By 1966, the first successful pneumatically driven paracorporeal left ventricular assist device (LVAD) was employed by DeBakey et al. to support a patient following cardiac surgery. The first human heart transplant was performed by Dr. Christiaan Barnard in 1967, and shortly afterward the use of artificial ventricle technology was initiated as a bridge to support patients until a donor heart could be found [8–10]. Concurrently, the idea of replacing the entire organ using an "artificial pump" came to clinical practice in 1969 by Cooley *et al*. who reported the first use of a total artificial heart (TAH) as a BTT. However, this device was only able to be retained for a few days due to adverse events such as infection, thrombosis, and hemolysis [11].

The establishment of the National Heart, Lung, and Blood Institute (NHLBI) by the NIH in the 1970s promoted the development of implantable devices intending to provide longer mechanical support [7]. In 1978, the first LVAD was used by Norman et al. for nearly 6 days as a BTT [12]. The first TAH intended for permanent support was implanted in 1984 by DeVries et al. with the patient being supported for 112 days before succumbing to sepsis [13].

The first successful BTT case using a VAD was reported by Portner *et al.* in 1984 using the Novacor (Baxter Healthcare Corporation, Oakland, CA) implantable electrical LVAD in a patient with ischemic end-stage heart disease [14]. By the mid-1990s, the FDA approved multiple pulsatile devices allowing patients to recover from hemodynamic compromise [15] (**Figure 1**). Subsequently, in the Randomized Evaluation of Mechanical Assistance for the Treatment of Congestive Heart Failure (REMATCH) trial, a new indication for mechanical support was explored and the trial revealed

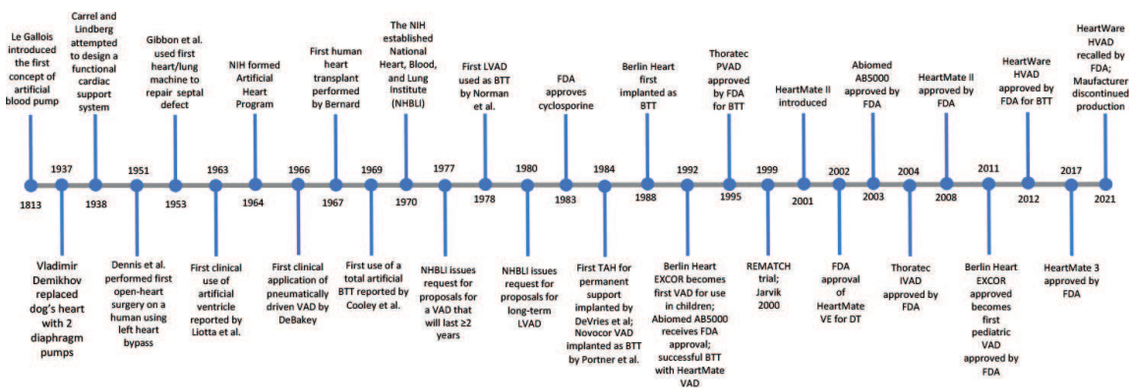

Figure 1.
Important milestones in the history of mechanical circulatory support.

that patients supported by a LVAD exhibited an 81% improvement in 2-year survival compared to medical therapy in patients with advanced heart failure who were not candidates for heart transplantation [5, 16]. The results of this trial led to the approval of the HeartMate VE LVAD device for destination therapy in 2003.

As the prevalence of advanced heart failure increased over the past decades, utilization of LVADs became essential to improve pre-transplant illnesses, improve quality of life, and enhance survivorship—a phenomenon primarily driven by advances in device design, patient characteristics, implantation techniques, and long-term management of adverse effects [17, 18].

2. Ventricular assist devices

2.1 First generation

The earliest VADs incorporated a diaphragm and unidirectional artificial valves to replicate the pulsatile cardiac cycle with a diastolic filling time and a systolic emptying of the devices, mimicking that of the native heart [19]. These devices are pumps designed to mechanically assist a failing Left Ventricle (LV) by removing blood from the LV and returning it into the circulatory system *via* the aorta. While LV dysfunction is more common, VADs can also be used to treat right ventricular failure or both. These first-generation VADs were either pneumatically or electrically driven, included the Thoratec HeartMate IP ("Implantable Pneumatic"), VE ("Vented Electric"), XVE ("Extended Vented Electric") (Abbott Laboratories, formerly Thoratec, Pleasanton, CA), and the Berlin Heart EXCOR (Berlin Heart, Berlin, Germany) [1]. These early devices were used to support patients as a BTT and could be used as left-, right-, and biventricular devices (LVAD, RVAD, and BiVAD). The first-generation devices introduced electromechanical actuation, which allowed some to be powered by a battery worn on the waist, affording better mobility, and allowing patients to be discharged from the hospital waiting for a new heart [20]. Anecdotally, these first devices had several disadvantages including large size, noise emission, infectious diseases, malfunctioning, mechanical tears, or valve degradation.

First-generation LVADs were known as volume displacement pumps and generated flow *via* a pulse generator [15, 21]. The goal of the first-generation LVADs was to provide long-term circulatory support, such that these devices could be used as a bridge to transplant [20, 22].

The HeartMate systems were housed within a titanium shell and situated beneath the patient's diaphragm on the left side. Within the housing, a polyurethane diaphragm divided the blood-contacting chamber and the chamber housing the motor. A sintered titanium microsphere layer was applied to the titanium blood-contacting surfaces of the pump and a fibrillar texture was on the polyurethane diaphragm. These surface modifications allowed circulating cells to adhere and form an intima-like tissue layer [20, 22]. The HeartMate IP (Abbott Laboratories, formerly Thoratec, Pleasanton, CA, USA) was the first LVAD to receive FDA approval for use in patients as a BTT in 1994. Clinical trials of the HeartMate VE began in 1992. Following the positive outcomes from the REMATCH trial, the HeartMate VE was approved by the FDA as destination therapy in 2003. This VAD was later updated to the HeartMate XVE device and served as the device to which the next generation of LVAD was compared. The Heartmate VE and XVE systems were driven by an electric motor. The REMATCH results propelled widespread use of LVADs in the clinical setting and led

to FDA approval of the HeartMate VE (HeartMate I) and the inclusion of other first-generation LVADs such as the Thoratec Implantable VAD (IVAD), an intracorporeal device, as well as the Thoratec PVAD, a paracorporeal device. Both devices provide the option of being used as left, right, or biventricular support and are both approved for use as BTTs. They were pulsatile flow devices comprising a 65-mL blood chamber with unidirectional flow achieved by tilting disk mechanical valves [23].

The Novacor LVAS (formerly WorldHeart, Oakland, CA, and acquired by HeartWare International, Inc., Framingham, MA) features an implanted pump/drive unit and an external control console. The pump consisted of a polyurethane sac bonded to dual pusher plates contained in a housing that included valve fittings. This device became available in 1984, initially as a console-based unit, but a wearable configuration became available in 1993. This unit was initially intended for destination therapy (DT) in the treatment of individuals with end-stage heart failure, but it was eventually used as a BTT [24]. The first clinical implant for a bridge to transplantation reportedly occurred in 1984 by Portner et al. [25]. Complications associated with the device included cerebral vascular accidents, bleeding, and infection. This device was discontinued by the manufacturer in 2008 with a greater focus on newer-generation VADs.

The Arrow LionHeart LVAD 2000 (Arrow International Inc., Reading, PA) was an implantable pulsatile VAD, designed for use for DT in patients with end-stage heart failure. The system had no percutaneous lines or connections and consisted of a titanium blood pump with inflow and outflow assemblies, a motor, a compliance chamber, and a transcutaneous energy transmission system [26]. The Clinical Utility Baseline Study was performed to establish whether the transcutaneous energy transmission system resulted in fewer infections than the observed during the REMATCH trial and concluded that Lionheart recipients exhibited less sepsis and device-related infection than the REMATCH trial group. The device, however, was discontinued in 2005.

The Berlin Heart EXCOR VAD was developed in Berlin, Germany, by Berlin Heart and is a pneumatically driven paracorporeal support device that can be used to provide left, right, or biventricular support. Its size ranges from pediatric to adult sizes. The device was first used as a BTT in 1988 [27, 28]. In 1992, the Berlin Heart became the first commercially available pulsatile assist device for children. This device received the CE mark in Europe in 2000 but was granted FDA approval for pediatric use only in the USA in 2011. This device is specifically designed for infants and children with stroke volumes of 10, 25, and 30 mL [29]. It is a pneumatic, compressor-operated diaphragm pump with polyurethane valves. Larger pumps (50, 60, and 80 mL) are equipped with mechanical valves.

BiVADs may be useful in patients with total heart failure and support both sides of the heart by balancing left and right pump flows. First-generation BiVADs included Abiomed BVS5000 and AB5000 (AbioMed Inc., Danvers, MA, USA), Thoratec PVAD and IVAD (Thoratec), Berlin Heart EXCOR (Berlin Heart, Berlin, Germany), and Medos HIA-VAD (MEDOS Medizintechnic GmbH, Stolberg, Germany) [2].

The Abiomed BVS5000 (AbioMed) was clinically introduced in 1987 and approved for use by the FDA in 1992. The device is an extracorporeal, dual-chambered BiVAD. The advantages of this device include simplicity and low cost, making it one of the most frequently used BiVADs worldwide [30]. The BVS5000 has two separate pumping and filling bladders driven by a pulsatile drive console. The device has demonstrated reasonable success in bridging patients to recovery from cardiogenic shock; however, issues with portability and thrombus incidence present limitations

should long-term VAD support be required [31]. The Abiomed AB5000 (AbioMed) gained FDA approval in 2003 and is very similar to the BVS5000, as it is a pneumatically driven volume displacement pump. Unlike the BVS5000, its paracorporeal location means that this device can be used as a VAD treatment or as a replacement, allowing the patient greater mobility [32].

The Thoratec PVAD (Thoratec) was approved by the FDA in 1995 for BTT and in 1998 for postcardiotomy support. It is a pneumatically driven paracorporeal VAD suited for left, right, or biventricular assistance, as well as use as a total artificial heart. The Thoratec IVAD (Thoratec) was approved by the FDA in 2004 to support systemic and/or pulmonary circulations in left, right, or biventricular assist configuration. This device is intracorporeal, pneumatically actuated, and pulsatile, operating in a full-to-empty mode utilizing optical infrared sensors to detect the end-systolic and diastolic position of the membrane providing an adequate balance of blood flow [33].

The Medos HIA-VAD is a paracorporeal device with transparent pump chamber sizes to be used in adult, infant, and pediatric cases. Development was initiated in 1982 at Helmholtz Institute for Biomedical Engineering in Aachen, Germany, and was acquired by Medos Medizintechnik GmbH in 1990. It has been used since 1994 and received the CE trademark in Europe in 1997. The system can work either at a fixed rate or with an electrocardiogram trigger and is pneumatically actuated, providing left, right, or biventricular support [15, 19].

The NIPRO-VAD (National Cardiovascular Center/Toyobo ventricular assist system) is an extracorporeal pneumatically driven diaphragm pump. It was reportedly first implanted in 1982 at the Saitama University Medical School and the Osaka University Hospital. While the device has been used long term, up to 1264 days, patients supported by this system have limited mobility and therefore the device has been exchanged for second- and third-generation devices [22].

The Zeon VAD is a pneumatically driven extracorporeal pump, first implanted in 1980. The pump was used for left, right, and biventricular support as BTT in Japan. The pump was discontinued in 2005 [22].

2.2 Second generation

Since first-generation pumps were limited by their large size, high noise emissions, decreased patient mobility, and durability issues, research to develop smaller, more reliable devices was initiated [15]. Some of the features that characterize the second-generation LVADs from the first are that they are continuous, rather than pulsatile pumps, and that they produce axial blood motion using a rotor [34]. The second- and third-generation VADs replace or support only the ventricular function. There is no direct attempt made to imitate the modality of the native, ventricular function [20, 34].

The first reported device that falls in the second-generation category is the Biomedicus Bio-Pump (Medtronic Inc., Eden Praire, MN, USA). It has been used since the mid-1980s. Is a centrifugal pump that provides extracorporeal left and/or right ventricular assistance for short-term bridge-to-bridge, bridge-to-recovery, and bridge-to-transplant support [34, 35].

The HemoPump was the first implantable rotary blood pump with an extracorporeal drive. It required continuous infusion of a purge fluid. It was only used within clinical trials in the USA and the first in man use was in 1988, marking the beginning of the era of implantable, less invasive, rotary ventricular assist devices [36].

A few years later in Europe, in 1999, the ROTAFLOW (Maquet, Hirrlingen, Germany) was approved for pulmonary and/or ventricular support, including cardiopulmonary bypass, or used in the framework of extracorporeal membrane oxygenation (ECMO) procedures [34].

The first clinical use in a human of the DeBakey VAD, which later evolved to the HeartAssist 5, was in November 1998, and this marks the beginning of a new era of long-term second-generation LVADs. The VAD itself consists of a miniaturized axial flow pump system, an external controller system, and a clinical data acquisition system [37, 38]. This is the only rotary LVAD where the flow is measured directly at the outflow prosthesis with an ultrasonic transducer, thereby producing reliable system monitoring [38].

After a decade of pioneering work achieved with the HemoPump, the Impella product family evolved into a platform technology. In 1999, the Impella device was approved for use in Europe. The Impella RP (AbioMed Inc., Danvers, MA, USA) is a minimally invasive temporary microaxial pump for the percutaneous treatment of RV failure in pediatric or adult patients for up to 14 days. The device is exclusively inserted percutaneously through the femoral vein and advanced in an antegrade fashion across the pulmonary valve into the pulmonary artery under fluoroscopy. The pump aspirates blood from the inferior vena cava and ejects it into the pulmonary artery. This action provides forward flow in the pulmonary circulation and unloading of the RV [39]. The Impella 2.5, CP, 5.0, 5.5, and LD have also been designed and approved for use in High-Risk Percutaneous Coronary Interventions (HRPCI) and cardiogenic shock [34].

The Impella 2.5 and CP are percutaneous microaxial circulatory support pumps. The Impella 2.5 can deliver up to 2.5 l/min of systemic flow augmentation by pumping directly from the left ventricle into the ascending aorta [40]. The Impella CP can deliver flows up to 3.7 l/min. The Impella 2.5 and CP are used for HRPCI. The Impella 2.5 showed better results in patients undergoing HRPCI than the intra-aortic balloon pump [41]. In addition, the Impella CP due to easy placement access through the femoral artery, can be used in cases of acute decompensated heart failure or worsening cardiogenic shock driven by the left ventricle.

The Impella 5.0 and 5.5 are larger microaxial pumps implanted through a conduit sutured to the axillary artery [42] or directly sutured to the aorta through a graft either through a full sternotomy or through partial upper one in cases of small axillary artery [43] and can provide flows, 5.0 and 5.5 l/min, respectively, like that of durable LVADs [44]. They also promote patient mobilization and therefore give patients the ability to participate in physical therapy. They can also be used when other smaller microaxial pumps result in refractory hemolysis, resulting in better outcomes [45]. The Impella 5.5 can be used in cardiogenic shock as a bridge to recovery, a bridge to transplant, a bridge to a decision, or a durable LVAD [46].

The Jarvik 2000 FlowMaker (Jarvik Heart, Inc., New York, NY) is an axial flow LVAD that has been used in patients since the year 2000 as a bridge to recovery (BTR), BTT, and DT. This device uses alternative outflow connections and can also be used to support right ventricular function in humans. The pump is equipped with five speeds that can be manually set [47]. It is one of the smallest clinically available LVADs as well as having the longest period of left ventricular support with 9.5 years of uninterrupted support [16].

In 2001, Thoratec introduced the most successful LVAD, with respect to implantation numbers and studies, the HeartMate II VAD which was smaller and lighter than the original HeartMate XVE [3] (**Figure 2**). The development was initiated in

1991 with research collaboration between the McGowan Center of the University of Pittsburgh and Nimbus Company [20, 34]. It was approved for use in 2005 in Europe and the USA, the FDA approved it as a BTT device in 2008 and as a DT device in 2010. It is an axial-flow device composed of a blood pump, percutaneous lead, an external power source, and a system driver. The pump rotor and blood tube are made of smooth titanium, while the stators, inlet and outlet elbows, and intraventricular cannula are textured with titanium microsphere coatings. This design reduced prothrombotic sites and minimized wear and tear associated with multiple moving parts. Surfaces contacted by blood were designed with a textured titanium lining as an antithrombotic measure. Initially, the pump was placed in the intra-abdominal position but was then switched to a preperitoneal position where the body of the pump can then be easily accessed for pump exchange through a left subcostal approach [48]. From 2009 to 2017, the HeartMate 2 was the main LVAD being implanted worldwide. Although the improvement of survival over time has led to widespread adoption of this therapy, adverse events persist including, infection, bleeding, and pump thrombosis [49]. The rate of pump thrombosis has been reported as high as 10% after the first-year post-implantation, with a rate of 13% of pump exchange secondary to pump thrombosis [50]. One cause of driveline failure in the HeartMate II is damage to the wiring insulation of the percutaneous lead resulting in an electrical short to ground, referred to as a short-to-shield (STS). The percutaneous lead has six electrical wires attached to six motor stators to power a three-phase pump. There are three stranded primary wires and three backup wires for each of the phases. An STS occurs when there is an inappropriate electrical connection between one of the stranded wires and the shield, disrupting the normal flow of power [51]. A phase-to-phase short occurs when there is a loss of insulation between the three redundant motor coils (i.e., phases) of the driveline. When present, phase-to-phase short is particularly troublesome in that pump stoppages are likely and unpredictable. The manufacturer, therefore, recommended against controller exchange due to concern over the possibility that the pump would not restart, and instead recommended driveline repair, followed by surgical pump exchange should the problem persist [52]. Currently, there are still thousands of patients supported with the HeartMate 2 pump, **Figure 2**.

The CircuLite Synergy Micro-Pump, unlike the HemoPump and the Impella, was approved as a long-term LVAD and was implanted for the first time in a human in 2007. This pump was mainly used as a partial support device and sits in a pacemaker-like pocket [34].

The EVAHEART is the only implantable, centrifugal second-generation LVAD. The first-in-human use was in 2005 and was approved in Japan in 2010. It requires continuous insertion of cool seal fluid (purified water) [34].

The Heartmate X was announced in 2012 as an axial LVAD and leverages HeartMate 2 core bearing technology and is still under development in the animal stage [34]. It is a smaller pump and potentially allows for a less invasive implantation technique and could be used for smaller patients [53].

The Thoratec PHP was approved in Europe in 2015, which was the last approval of the second-generation LVADs, consisting of a shaft-driven axial pump with a foldable impeller. The device is inserted through the femoral artery and advanced to the aortic valve.

The MERA HCF-MP23 (Senki Medical Instrument Manufacturing Co. Ltd., Tokyo, Japan) is a centrifugal pump used for short-term extracorporeal circulatory support. The use is aimed at open heart surgery circulatory support and for bridge-to-decision

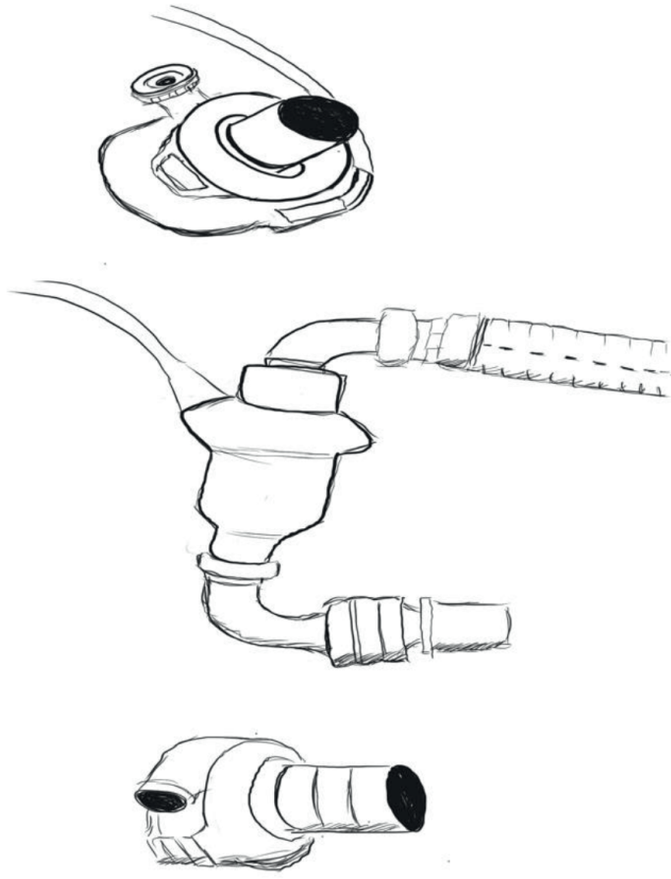

Figure 2.
Schematic representation of the HeartMate II (Abbott Laboratories, Abbott Park, IL). A successful continuous-flow pump with axial design.

use for up to 4 weeks. However, it was successfully used as an RVAD in a patient with right heart failure post-LVAD implantation for up to 17 weeks [54].

2.3 Third generation

Third-generation LVADs are continuous-flow centrifugal pumps designed with magnetic and/or hydrodynamic levitation of the impeller with non-contact bearings and outflow directed perpendicular to the axis of rotation [15, 19, 20, 55]. Fully magnetically levitated implantable blood pumps were proposed in patients by Olsen and Bramm in 1986 and Moise in 1987 [55]. Currently, continuous flow LVADs (CF-LVADs) are used in 99% of patients requiring an LVAD [30]. The development of third-generation devices aimed to improve durability and hemocompatibility. The two main LVADs discussed in this chapter are HeartMate III and HeartWare. Other examples include the TandemHeart (CardiacAssist Inc., Pittsburgh, PA, USA), Levacor (World Heart Inc., Salt Lake City, UT), and the DuraHeart (Teruma Heart, Inc., Ann Arbor, MI).

The HeartWare HVAD (Medtronic Inc., FL, USA) was approved by the FDA for BTT in 2012 and its implantation is completely intrapericardial; a smaller pump size eliminates the need for an abdominal pocket [30, 55]. From 2012 to 2017 was the pump of choice as BTT and for an additional year was the pump most commonly implanted as destination therapy. This device has magnetic and hydrodynamic levitation of the internal rotor and is connected directly to the heart at the base of the

left ventricle. This device had the advantage that could be implanted without cardiopulmonary bypass easily due to the design of the coring knife [56]. The FDA recalled this device and Medtronic halted distribution and sale in June 2021 due to increased risk of neurological events and mortality associated with the internal pump, and the ability to restart if the internal pump stops [57].

The HeartMate III (Abbott Laboratories, formerly Thoratec Corporation, Pleasanton, CA, USA) was initially approved by the FDA for adults awaiting a heart transplant in 2017 and approved for long-term use in 2018. Its initial development started in 1998, using the same technology as the CentriMag, but modified to be fully implantable [55]. The first in human use was in June 2014. This device is implanted directly into the left ventricle and is fully magnetically levitated. It is designed to pass an inflow cannula through the apex of the heart and is directed toward the mitral valve to optimally drain blood from the left ventricle through the outflow graft and into the systemic circulation. The implications of this technology are substantial. Data from the MOMENTUM three randomized trial and subsequent publications (including the 5-year follow-up) have demonstrated the superiority of the centrifugal-flow LVAD to the HeartMate II with respect to survival to transplant, recovery, or LVAD support free of debilitating stroke or reoperation [58]. The superior performance of the HM3 at 6 months was due to 0% of the HM3 patients experiencing pump thrombosis, whereas 10.1% of patients with HM2 experienced pump thrombosis. Significant differences were not appreciated when comparing HM3 and HM2 with respect to bleeding, sepsis, driveline infection, right heart failure, arrhythmia, respiratory failure, renal dysfunction, hepatic dysfunction, or hemolysis not associated with pump thrombosis.

The HeartMate 6, an off-label use of two HeartMate 3 devices for biventricular support as a total artificial heart, has been reported in a patient as a successful bridge to transplant [59].

The Abbott CentriMag was the first available third-generation blood pump that was fully magnetically levitated. Originally developed and commercialized by Levitronix in 1995, the medical arm of Levitronix was then acquired by Thoratec in 2011 and Thoratec was later acquired by Abbott in January 2017 [55]. It is an extracorporeal centrifugal pump and is approved for use as an RVAD for up to 30 days in patients with cardiogenic shock. The magnetic levitation and motor principles are identical to those of the HeartMate 3, described above. Cannulation configuration differs depending on the support needed, i.e., LVAD, RVAD, or BiVAD. The CentriMag can also be used as a pump in the ECMO circuit [55].

In the US, it is approved for 6-hour acute extracorporeal circulatory support during cardiac surgery or humanitarian use device for RVAD support in cardiogenic shock as a result of right-sided heart failure. It is the surgical temporary ventricular assist device of choice. In Europe, it is approved for 30 days of extracorporeal VAD support [55].

The Levacor LVAD (WorldHeart has ceased trading) development was originally started by Medquest in 1996 and then was later acquired by WorldHeart. The first in human use was in March 2006. It is a radial flow pump employing a hybrid active and passive bearing to suspend a centrifugal impeller. In 2011, World Heart discontinued efforts to commercialize this device as a result of large device size and technical issues [60].

The Terumo DuraHeart LVAD (Terumo Corporation, Tokyo, Japan) was developed in 1991 with its first human use in January 2014. It is an implantable radial flow pump incorporating an axial magnetic bearing providing long-term left ventricular

assistance with a contact-free impeller suspension system. The US SUSTAIN trial (A Study Evaluating Safety and Effectiveness of the DuraHeart Left Ventricular Assist System in Bridge to Transplant Patients) began in 2008 but was prematurely terminated in December 2011, due to slow recruitment based on the size of the device and the difficult configuration of the inflow cannula [61].

The HeartWare MVAD (Medtronic Inc., FL, USA) is a miniaturized implantable VAD that uses a passive maglev and hydrodynamic bearing system to levitate the rotor once it is rotating. It was developed in 2004 with the first in human use in July 2015. Its clinical trial was suspended 2 months later and has not been restarted [55].

The TandemHeart (CardiacAssist Inc., Pittsburgh, PA, USA) uses a paracorporeal, continuous flow, centrifugal pump originally developed for left atrial-to-femoral artery bypass to provide hemodynamic support during high-risk coronary interventions and post-cardiotomy cardiac failure. It was first used in a human in the year 2000 The use of this device has been reported in several conditions and with a change in cannulae configuration it can be used in acute myocardial infarction, post-LVAD implantation, pulmonary hypertension, severe acute mitral regurgitation, and cardiac rejections after heart transplantation [34, 62]. This device has also been successfully used for post-myocardial infarction interventricular septum defect, allowing time for left ventricular recovery and definitive surgical repair [63].

The Berlin Heart INCOR (Berlin Heart GmbH., Berlin, Germany) is an implantable VAD that has an active magnetically levitated rotor. It is implanted below the diaphragm in an abdominal pump pocket and due to the size, it is not viewed as being suitable for less invasive implantation methods. Despite its designs, the initial results were undermined due to issues with the design of the inflow cannula causing high rates of embolic complications. The first in human use was in 2002. However, recent results with new designs have shown improved results with respect to GI bleeding and *de novo* pump thrombosis [64].

The Ventracor (is no longer trading) was developed in 1997 with the first in human use in 2003. Approximately 450 devices were implanted before the company ceased trading in 2009 [55].

The Arrow CorAide left ventricular assist system (LVAS) (Arrow International, Reading, PA, USA) is a continuous flow left ventricular assist device, as a bridge to transplantation or recovery as well as destination therapy in patients with New York Heart Association (NYHA) class IV heart failure. Its use has been limited to clinical trials and was originally developed at the Cleveland Clinic. The first patient was implanted in May 2003. It was the first third-generation magnetically levitated pump to be included in a clinical trial [65].

3. Temporary and durable mechanical circulatory support

With the progress in comprehensive evaluation, and diagnostic and therapeutic approaches in patients with heart failure, device selection has become the cornerstone for improving outcomes. Guidelines in the acute and chronic management of cardiovascular failure have incorporated importance to categorize individuals based on the severity and acuity of the disease. Therefore, the Interagency Registry for Mechanically Assisted Circulatory Support (INTERMACS) was founded in 2005 to summarize the clinical outcome profiles of patients with advanced stage HF who receive a MCS device. This classification encompasses seven progressive clinical profiles within the NYHA class III and IV functional status. Short-term or temporary

devices are generally recommended to provide uni- or bi-ventricular assistance to patients with cardiogenic shock, decompensated heart failure, cardiac arrest, or high-risk percutaneous coronary interventions. Therefore, these devices are typically employed for bridging patients to transplantation, recovery, or bridge-to-decision. Models of temporary support have included the intra-aortic balloon pump, the Impella devices (AbioMed, Danvers, MA, USA), the TandemHeart (LivaNova, London, England, UK), the Rotaflow (Maquet), the CentriMag/PediMag (Abbott), and the veno-arterial extracorporeal membrane oxygenation. Durable devices have been divided as previously described, first-, second-, and third-generation devices based on the flow mechanics. Many of these devices have evolved to provide better features such a smaller size, improved biological compatibility, and an overall reduction in costs and adversity.

4. Current trends in mechanical circulatory support

It has been estimated that survival rates in patients with continuous flow devices are 81% and 70% at 1- and 2-year post-implantation, respectively. Additionally, survival trends showed that outcomes are more satisfactory in VADs used for BTT than those in the DT cohorts. Nevertheless, even in the DT population, which inherently possesses greater comorbidities that contraindicate them for HT, long-term outcomes are still excellent exhibiting 68% overall survival at 2 years [66]. The Heartmate III recently achieved ~80% in the primary composite outcome of survival without disabling stroke or reoperation at 2 years [67]. Beyond implantation and the perioperative risks, this difference primarily resulted from a substantial reduction in the incidence of pump-related thromboembolic phenomena and reoperation due to device malfunctioning. Furthermore, data suggest that proactive implantation of VADs in patients with heart failure (INTERMACS classes 4–7) has excellent outcomes with a survival rate in the 80–95% range 1 year after implantation. Certainly, technological advances have made a significant difference in the last decades. In addition, at many centers, the selection of appropriate candidates for mechanical support has been developed to incorporate multidisciplinary evaluation before implantation. The harmonization of this approach provides meaningful benefits, as some studies have identified numerous comorbidities that are associated with poor outcomes. Such factors include limited life expectancy, active malignancy, multisystemic end-stage organ dysfunction, severe infections, hematologic dyscrasias, and anatomical and psychological components [66].

5. Conclusion

Over the last decades, there have been revolutionary developments in mechanical support. Although patients with chronic heart failure exhibit improved survivorship with the application of evidence-based medical therapies, VADs are superior to medical therapy for improving survival among patients with advanced heart failure with reduced ejection fraction [18]. This topic is important because estimates reveal that over 18 million persons are diagnosed with heart failure in the United States and Europe at present [17]. Furthermore, heart failure is far more prevalent in older age groups, reaching 4.3% among persons aged 65–70 years in 2012, and is projected to increase steadily, reaching 8.5% in the US by the year 2030 [17].

For individuals with refractory heart failure requiring transplantation, it has been estimated that a VAD is used as a bridge to transplantation in approximately 9% of children and 25% of adult patients The shortage of donor organs and the expanding pool of patients with heart failure have led to growing interest in mechanical circulatory support; fortunately, we have observed meaningful and positive trends from the incorporation of MCS over the past five decades. We commend all those individuals who have been at the forefront of these developments and equally acknowledge those with behind-the-scenes contributions to this field.

As of today, this modality has been successfully expanded to employ MCS as bridge-to-transplant, bridge-to-recuperation, or destination therapy. However, following the withdrawal of HVAD from the global market in June of 2021, we are currently left with a reduced armamentarium for managing patients with advanced heart failure with reduced ejection fraction, particularly in the pediatric population. Therefore, shifting the paradigm to advance device miniaturization, improving surgical implantation techniques, and effectively reducing adverse events would be of greatest value in the following decades to further advance the field of mechanical circulation. An integrative alliance among technology companies, healthcare practitioners, and researchers is paramount to promoting education, innovation, and accessibility.

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Conflict of interest

The authors declare no conflict of interest.

Appendices and nomenclature

ACTION	Advanced Cardiac Therapies Improving Outcomes Network
BiVAD	biventricular assist device
BTR	bridge to recovery
BTT	bridge to transplantation
Circulatory support	
CPB	cardiopulmonary bypass
DT	destination therapy
EUROMACS	European Registry for Patients Assisted with Mechanical
FDA	Food and Drug Administration
HF	heart failure
HVAD	HeartWare Ventricular Assist Device
INTERMACS	Interagency Registry for Mechanically Assisted Circulatory Support
LVAD	left ventricular assist device
LVAS	left ventricular assist system
MCS	mechanical circulatory support

MOMENTUM 3	Multicenter Study of MagLev Technology in Patients Undergoing Mechanical Circulatory Support Therapy with HeartMate 3
NHLBI	National Hearts, Lung, and Blood Institute
NIH	National Institutes of Health
RV	right ventricle
RVAD	right ventricular assist device
STS	Society of Thoracic Surgeons
TAH	total artificial heart
US SUSTAIN Trial	A Study Evaluating Safety and Effectiveness of the DuraHeart Left Ventricular Assist System in Bridge to Transplant Patients
VAD	ventricular assist device

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