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RESEARCH ARTICLE

An updated review of cardiac devices in heart failure

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Abstract
Background Heart failure has the highest rates of adult hospitalisations, the highest mortality rates and significant costs associated with its care. The cost of heart failure is expected continue to grow on a global scale, with $108 billion spent on heart failure in 2012. Mortality rates are high, with incident cases of heart failure resulting in 30% 1-year mortality, and in hospital mortality of acute heart failure, 28%.
Methods and Results This article reviews the devices currently in use for the treatment of heart failure, as well as those that are under investigation. A review of the mechanism of action of devices, the literature supporting their application as therapy, and the cost effectiveness associated with their use are discussed. Conventional techniques discussed herein include the guideline-supported therapies of mechanical circulatory support (MCS) and cardiac resynchronisation therapy (CRT). Novel devices that are discussed include invasive physiological monitoring, neuromodulation, percutaneous ventricular assist devices (VADs) and cardiac contractility modulation (CCM). There has been advancement in mechanical circulatory support devices for the treatment of both acute and chronic heart failure. In addition to MCS, only CRT has resulted in reduced mortality.
Conclusion Due to the clinical and economic arguments, treatment of heart failure is said to be the biggest unmet need in cardiology today. The data reviewed herein support this statement.

Keywords Heart failure · Cardiac devices · Treatment monitoring · Implantable cardioverter-defibrillator (ICD)

Introduction

Heart failure is a complex syndrome with many aetiologies, a broad spectrum of clinical features, and various clinical subsets. It results from impairment in the ability if the heart to pump sufficient amounts of blood into the circulation during systole. An ejection fraction of ≤40% on echocardiography indicates impaired left ventricular systolic function or heart failure with reduced ejection fraction (HFrEF) [1]. Heart failure that occurs with normal left ventricular (LV) systolic function or with en ejection fraction of >50% is known as heart failure with preserved ejection fraction (HFpEF) [2]. Acute heart failure is a heterogeneous set of syndromes. Acute heart failure syndromes (AHFSs) are present in three forms [1]: (1) acute pulmonary oedema, (2) cardiogenic Shock (5–8% of STEMI and 2.5% of non-STEMI) [3], and (3) acute decompensation of CHF. This review presents the current state of the art devices currently in use for the treatment of heart failure, as well as those that are under investigation. The authors have categorized the devices based on their placement within the body and/or the mode of action of the device.

The AHA cites an annual incidence of 670,000 new cases of heart failure annually in the United States with an

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estimated prevalence of 5.8 million or 2.2% of the population [1, 4, 5]. Incidence for the disease approaches 10 per 1000 population after the age of 65. European data on the prevalence of heart failure are provided by the ESC statistics. According to their data on a cohort of 900 million people, prevalence is estimated at 15 Million patients [5]. Therefore, in developed countries, 1–2% of the adult population has a diagnosis of heart failure, with the prevalence rising to >10% in persons 70 and older. The annual incidence is 5–10 per 1000 persons per year [1]. The prevalence of heart failure with a preserved EF (HFpEF) in those with a diagnosis of heart failure is between 30 and 60%, with an incidence of 4.4% [6–8]. The 1-year mortality with incident cases of heart failure is 30%, with 5-year mortality about 50% and at 10 years 10% [9]. Acute heart failure Syndrome has associated with an in-hospital mortality of 28% and cardiogenic shock, the most severe form of acute heart failure, has mortality of 40–80% [10].

Heart failure has the highest rate of adult hospitalizations, highest mortality rates and as a result of this and the costs associated with its care, it has been described as an epidemic [11, 12]. This imposes a significant economic burden on governments and health care organizations.

As an estimate of percentage spending of total health care globally, heart failure spending in 2012 was estimated at $108 billion [11]. The United States has the highest spending on HF per annum, $37 Billion in 2009. The AHA estimates that in the US by 2020, heart failure will cost $57 Billion and by 2030 $77 Billion [13]. The major part of this expenditure is related to hospitalizations, with an estimated cost of $20.1 Billion in 2009 [12]. In Europe, heart failure treatment takes up 1–2% of the European health spending budget, of which 75% are hospital costs [10]. As a result of variety of clinical and economic arguments, it has been said that treatment of HF is the largest unmet clinical need in cardiology today [14]. Figure 1 shows heart failure devices divided by groups (1–11) based on their locations.

Group 1: Left ventricle

Left ventricular assist devices

Ventricular assist devices (VADs) function as mechanical pumps that take over the function of the ventricle and restore normal haemodynamics and end-organ flow [15]. Cardiac output is improved, thereby decreasing preload, cardiac workload and neurohormonal response with resultant increase in systemic circulation and tissue perfusion. Blood is taken from the left ventricle and exits the pump via a connection to the ascending aorta via surgical anastomosis.

In those patients who are cancer free and not in cardiogenic shock, the 2-year survival of those implanted with a continuous flow left ventricular assist device is 80% [16]. Before 2008, all VADs implanted in the US outside of clinical trials were electrically or pneumatically driven volume displacement pump, i.e. 1st generation pulsatile flow devices.

2nd generation devices are continuous axial flow pumps. In 2009, an RCT demonstrated significantly better survival for those treated with continuous flow device (or 2nd generation pumps) with one and 2-year survival 68 and 58% compared to 55 and 24% with the pulsatile device [17]. Continuous flow pumps have been the dominant technology since 2008 and account for 100% of patients receiving destination therapy since 2010 [18].

3rd generation VADS are continuous flow pumps with non-contact bearings that are currently under investigation and have so far shown non-inferiority to contemporaneously available devices [13, 19].

From 2008 to 2011, 24.8% of patients with a diagnosis of chronic heart failure received a permanent device with resultant survival benefit and improved quality of life [20]. 10% of patients with an LVAD develop significant device malfunctions. Bleeding, right heart failure, stroke, infection and device failure are among the main complications [21].

Uptake of use of VADs in the US remains much higher than Europe: the number of new VAD at >1700/year in the US vs. 430 per year in Europe. Reimbursement within the US for the device and procedures has encouraged this development. Contemporaneous analysis of the REMTACH trial estimated that the IECR was $802700/QOLY. More recently, continuous flow devices were estimated to cost $198,184/QOLY [22]. In a review of use of LVADs within the NHS, LVADS cost £ 80,569 lb by 2011 prices and a review in 2014 estimated a probabilistic incremental cost effectiveness ratio at £53527/QOLY ($84,963) over a lifetime horizon. It concluded that VADs were cost effective comparable to medical management [23].

The mortality advantage of VADs now has a 2-year equivalency to total heart replacement. Iterations of VADs and smaller size of the device continue to address the disadvantages, namely bulky, noisy devices with high complication rates. However, what still remains an issue with VADs is that specialized units are required involving heart failure specialists, infrastructure investment, and reimbursement protocols. The evolution of the LVADs encompassing size (gm) and generation is summarized in Table 1.

Centrimag

Centrimag (Thoratec) is a surgically implanted left ventricular assists device that is designed for short-term extracorporeal support in cardiogenic shock [24]. It is a 3rd generation continuous flow pump that is capable of providing up to 10 L/min of blood flow and has an FDA approval for LV support for up to 6 h [25]. A multicenter

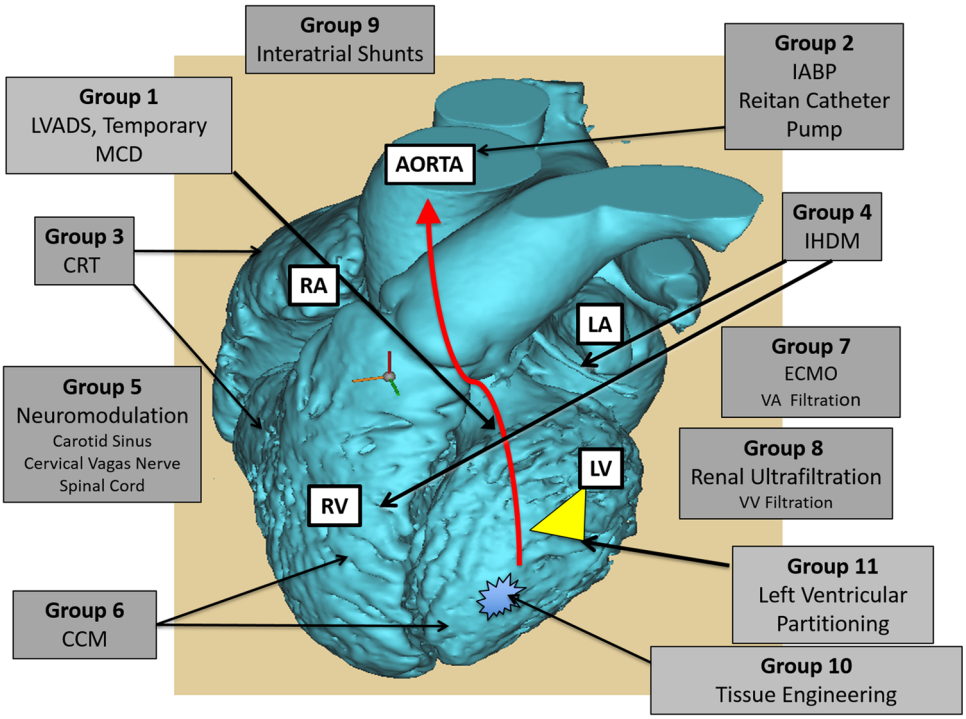

Fig. 1 Heart failure devices divided by groups (1–11) based on their locations. *RA* right atrium, *LA* left atrium, *RV* right ventricle, *LV* left ventricle, *LVAD* left ventricular assist device, *MCD* mechanical circulatory device, *IABP* intra-aortic balloon pump, *CRT* cardiac resynchronization therapy, *IHDM* implantable haemodynamic monitoring device, *ECMO* extracorporeal membrane oxygenation, *CCM* cardiac contractility modulation, *VA* veno-arterial, *VV* veno-venous

Table 1 Evolution of LVADs

Mechanical circulatory support	Devices	Weight (g)	Flow rate (l/min)	Use
First generation VAD	Heartmate XVE (Thoratec)	1150	10	FDA
Second generation VAD	Heartmate II (Thoractec)	280	10	CE
				FDA
	HVAD (HeartWare)	160	10	CE
				FDA
Third generation VAD	Heartmate III	200	10	CE
	INCOR (Berlin Heart)	200	8	CE
Mixed flow	MVAD (HeartWare)	78	10	CE
	Circulite synergy micropump (HeartWare)	25	3	CE

study provided evidence of its ability to provide short-term circulatory support for left, right or biventricular support, with a 30-day mortality of 47% [26].

Temporary mechanical circulatory support

Temporary mechanical circulatory support (MCS) devices are an effective means of providing support in the acute setting of cardiogenic shock or during high-risk procedures such as (percutaneous intervention) PCI. The aims of temporary MCS are to decrease preload and afterload and augment cardiac output with a goal of achieving adequate organ perfusion and oxygen delivery. To do this, they can be used to mechanically unload the left ventricle and right ventricle or provide biventricular support. Use of temporary non-percutaneous devices increased 101% from 2007 to 2011. Percutaneous devices showed the fastest growth of MCS from 2007 to 2011, with a 1511% increase in use [20]. A meta-analysis of percutaneous LVAD compared to IABP did not show any trends towards a reduced 30 mortality rate; however, superior haemodynamic support was observed with percutaneous LVAD over IABP during acute cardiogenic shock [27]. The AHA/ACC assigns a class IIb/C recommendation for LV assist devices in refractory cardiogenic shock and in the European guidelines; a class IIB recommendation is given [28].

TandemHeart™ device

The TandemHeart (CardiacAssist, Inc.) consists of venous transeptal inflow cannula, an extracorporeal continuous flow centrifugal pump that draws blood from a catheter that has been placed through the venous system across the interatrial

septum and into the left atrium. The oxygenated blood from the left atrium is then pumped to the system circulation via a femoral artery catheter [29]. With its use in those with cardiogenic shock, it has been shown to improve cardiac output, increase MAP and reduce pulmonary wedge pressure [30]. TandemHeart has similar 30-day mortality rates when compared to IABP [31]. TandemHeart right VAD (RVAD) has implanted successfully both surgically and percutaneously with acute haemodynamic improvements in a broad range of clinical scenarios [32].

Impella device

The Impella (Abiomed) is an axial flow, rotary blood pump that is inserted through the arterial system and placed into the left ventricle by means of a retrograde fashion across the aortic valve. It provides non-pulsatile forward blood from the left ventricular outflow tract and results in unloading of the left ventricle with expulsion into the aorta. Impella has demonstrated haemodynamic benefits with use in the acute setting. It has proven to be equivalent to the IAPB with respect to mean adverse outcomes [33]. (Mortality)There are no RCTs on the higher functioning Impella device as of yet (Impella 5.0). Impella is indicated for use in acute cardiogenic shock and high-risk PCI [33].

HeartMate percutaneous heart pump (PHP)

The PHP (St. Jude Medical) works as a left ventricular unloading device, similar the Impella, with a flow rate of 5 L/min through a 14F sheath. It has a collapsible impellar blade that crosses the aortic valve, which is connected to an extracorporeal motor via a cable. Its efficacy and safety for use during high-risk PCI were established in SHIELD I RCT. (Presented at Transcatheter Cardiovascular Therapeutics in 2015).

Whilst there have been innovations with respect to percutaneous mechanical circulatory support, they have not resulted in improved mortality rates. The large increase in their use possibly reflects their relative ease of use, minimal invasiveness, and the improved haemodynamic profile associated with their use. It is the author's opinion that a need still exists to treat acute heart failure that will result in statistically significant and reproducible improved mortality rates, an endpoint that has not yet been achieved.

Group 2: Aorta

Intra-aortic balloon pump (IABP)

The IABP is placed into the descending aorta via arterial access. It is inflated during diastole and deflated during systole. The result is an augmented diastolic pressure and improved coronary perfusion with reduced afterload and enhanced ventricular contraction [25]. Its use in clinical practice has shown equivocal benefit, with a meta-analysis not supporting its use for MI complicated by cardiogenic shock. The IABP-SHOCK II trial revealed no improvement of 30-day mortality rates in those with acute cardiogenic shock [34]. One analysis associated the use of IABP with a 25.2% increase in the cost of hospital stay [20]. Despite these data, it continues to be used and are frequently used as a comparison in the investigation of novel devices.

Reitan catheter pump

This is an axial flow pump similar to the Impella. However, it is placed in the descending Aorta, as opposed to the left ventricle. It functions to create a pressure gradient within the aorta that results in decreased afterload and increased organ perfusion. There are no RCTs demonstrating its efficacy in heart failure but its use in high-risk PCI has been shown to be safe and efficacious [35].

Group 3: Cardiac resynchronization therapy

When the left ventricle contracts synchronously, it results in efficient ejection of blood. However, if electrical disturbances of the heart result in sites of premature stimulation, such as LBBB, regions of early and delayed contraction can occur. This results in a decline in cardiac out and efficiency with a decrease in systolic function by 20% [24, 25].

With CRT, a left ventricular lead is placed in a tributary of the coronary sinus in addition to a right ventricular and atrial lead enabling pacing and subsequent resynchronization of the impaired mechanical contraction patterns to improve myocardial efficiency [22].

With CRT therapy in heart failure, all-cause mortality is reduced by 22% [21, 22]. CRT has also been shown to reduce heart failure hospitalizations as well as improvements in NYHA class, QOL scores, exercise capacity and LV function [36, 37].

International guidelines including ESC [37] and the ACC/AHA/HRS [38] recommended CRT for patients with EF $\leq$35%, NYHA III or IV with symptoms despite treatment wide QRS duration (>120 ms) and Sinus Rhythm. With the prevalence of QRS prolongation at around a third of the cohort of heart failure patients and with the current guideline criteria in mind, it is estimated that between 5 and 10% of the HF population are indicated for CRT [39]. Careful selection of patients who are likely to respond to CRT, remains an issue [40]. 20–30% of patients in major trials did not have a response to CRT [41]. Significant

attention has been placed on the implant procedure with adverse events related to device implantation 12.7% in one meta-analysis [42]. Cost-effectiveness analysis of the major trials with substantial follow-up periods reports the incremental cost per Quality adjusted life-year gained as: $19,600 for Companion [43] $38,202 in the analysis of CARE-HF data, $32,822 in analysis of data from the longest CRT RCTs [44]. Furthermore, analysis from the CARE HF trial confirmed that CRT alone was cost effective in all age groups [45].

CRT has been deemed to be one of the most successful heart failure therapies to emerge in the last quarter of a century with applicability to 25–30% of patents [46]. Clinical trials demonstrating the improved mortality, reduced hospital admissions and improved quality of life, along with repeated demonstrable cost effectiveness for the use of CRT in the treatment of heart failure, should be enough to alleviate payers' concerns with respect to use of the CRT device and justify the former statement.

Group 4: Implantable haemodynamic monitoring devices (IHMD)

The increases in intracardiac and pulmonary arterial pressures that occur as a result of decompensated heart failure are apparent weeks before the onset of symptoms [47, 48]. Studies of implantable haemodynamic monitoring systems have suggested clinical benefit [49, 50], and ongoing hypothesis being assessed in clinical trials is whether implantable haemodynamic monitoring devices could reduce heart failure hospitalizations [51].

An innovative means of assessing physiological parameters are implantable devices to collect hemodynamic data. Clinically, they are indicated for ambulatory HF patients. It is hoped by monitoring these physiological parameters, assessment of which would be by patient and or/doctor/nurse practitioners, medication changes could prevent acute decompensation and hospitalizations [52].

Right ventricular pressure monitoring

Right heart pressures can provide diagnostic, therapeutic and prognostic information with respect to heart failure. The Chronicle (Medtonic Inc) is an implantable continuous heamodynamic device that consists of an implanted memory system which is inserted subcutaneously in the pectoral area. It has a specialized transvenous lead sensor that measures intracardiac pressure at the right ventricle, which can be viewed remotely [53]. A single-blinded RCT, COMPASS HF, of 277 patients showed a non-significant reduction of all HF events [51].

Left atrial pressure monitoring device

The common pathway for acute heart failure results in an increase in left atrial pressure. This rise of LAP is gradual and precedes symptom onset [54]. Therefore, the potential exists to curb acute decompensations by accurate monitoring of LAP with resultants titration of medications [55].

The Heartpod Device (St. Jude Medical) consists of a sensor that is fixed onto the interatrial septum via cardiac catheterization and transeptal puncture; this is coupled to a coil antenna positioned in the subcutaneous tissue. It is capable of recording of left atrial pressures, an intracardiac electrogram and body temperatures. A handheld patient advisory module powers the device. The Heartpod Device was proved to be safe and feasible by means of measuring LAP [56].

The HOMEOSTASIS trial showed favourable outcomes with respect to LAP control and symptom reduction [57]. An RCT is going currently with safety and efficacy endpoints that aims to show a reduction in worsening heart failure and hospitalizations [58].

Pulmonary arterial pressure monitoring

The Cardiomems device (St. Jude Medical) is a permanently implanted wireless pulmonary artery pressure sensor. The device consists of a pressure sensitive capacitor that is inserted via catheter into the femoral vein to the deployment site in the pulmonary artery. The CHAMPION RCT randomized patients post-insertion of the device to treatment and non-treatment. The primary efficacy endpoint of reduced hospitalizations for heart failure at 6 months was achieved with a reduction of HFH of 28% ($p < 0.0002$) [59].

The economic cost of heart failure treatment has been discussed in "Group 2: Aorta". With respect to this and the notoriously high hospital admission and readmission rates, interest in innovating in IHMDs is justified. However, the ideal parameter(s) to adjudge definite decompensation has not yet been identified. Once achieved and reciprocal treatment identified, IHMD could treat the clinical and economic need of treating heart failure effectively.

Group 5: Neuromodulation

Sympathetic overactivity as well as withdrawal of parasympathetic activity contribute to the development of heart failure [60]. The targeting of the sympathetic nervous system via pharmacological beta blockade in the treatment of HF reduced mortality by 35% [61]. Neurostimulatory approaches currently under investigation with respect to heart failure are also known as neuromodulation. There are

currently innovative devices attempting to therapeutically increase the parasympathetic tone via afferent stimulation in the form of spinal cord stimulation and carotid sinus. Inhibiting sympathetic tone via efferent parasympathetic stimulation via cervical vagal stimulation is also under investigation [62].

Cervical vagal nerve stimulation

Stimulation of the vagus nerve in humans has been shown to be safe and tolerable [63]. A system for Cervical Vagal Nerve Stimulation (VNS) consists of a stimulator unit implanted under the skin of the chest, which is tunnelled under the skin to join an intracardiac sensing electrode that is positioned at the right ventricular apex and an electrode that is placed on the vagus nerve 3 cm below the carotid artery bifurcation [64]. Implantation of this device requires a surgeon with knowledge of head and neck, along with the cardiologist. The recently published RCT, INNOVATE-HF, compared VNS with continued medical therapy. The efficacy endpoints of death from any cause or first event for worsening heart failure were not reached. VNS did show improvements to QOL measures and NYHA class [65].

Spinal cord stimulation

Spinal cord stimulation (SCS) is aimed at reversing the sympathovagal imbalance that develops in heart failure [66]. SCS (Eon Mini Neurostimulation system, St. Jude) is delivered by inserting electrodes into the epidural space and placed to encompass various thoracic levels. The electrodes are connected to a subcutaneously implanted pulse generator. Larger trials in humans to date have had conflicting results. A pilot multicenter study, which provided SCS at T1-T3, showed improvements in NYHA class, symptoms and functional capacity that were observed in a statistically significant manner compared to non-treated patients [67]. However, a single-blinded multicenter RCT with 81 patients targeting T2–T4 showed no statistically significant changes in Left Ventricular ejection volume index, peak VO_2 or ntBNP at 6 months [66].

Carotid sinus nerve stimulation

Electrical stimulation of carotid sinus nerve fibres or baroreceptor fibres causes parasympathetic efferent activation and sympathetic withdrawal [68]. To achieve carotid sinus nerve stimulation, a patch electrode is implanted on the carotid sinus, CVRx (Rheos). The electrode wire is tunneled subcutaneously to a battery powered implantable pulse generator that is implanted subcutaneously in the pectoral region. The impulse generator delivers programmable chronic activation energy to the right carotid sinus [62]. Limited clinical data exist, but subsets from hypertension studies indicate the potential for patient with heart failure [69, 70].

There remains no uncertainty that the use of pharmacological beta blockade to treat heart failure resulted in decreased mortality. With respect to neurostimulation, the early evidence has not provided any indicators so far that such substantial benefits could be obtained. The complexity of the nervous system cannot be overstated. If and once an ideal target area for neurostimulation is identified, existing and emerging devices could be tailored for treatment at these areas.

Group 6: Cardiac contractility modulation (CCM)

CCM is an electrical device-based approach that enhances failing myocardium by strengthening the contraction of left ventricular contraction. High-frequency biphasic electrical impulses are delivered to the myocardium during the absolute refractory period. This causes an increase in calcium release into the myocardial cells, thereby strengthening contraction.

CCM signals are provided by a pacemaker like impulse generator (Optimizer III, IMPULSE dynamics) that connects to the heart via two leads that are placed endocardially on the right ventricular septum. A third lead is placed in the right atrium to detect the timing of atrial activation. An algorithm is employed to detect atrial activation to ensure appropriate timing of CCM signal delivery, thereby ensuring delivery of impulse delivery without risk of inducing ventricular arrhythmias [52].

Thus far, CCM has been used in patients with a normal QRS, with an EF <35%, not indicated for CRT and an NYHA II and NYHA III [71]. To date, two RCTs [34, 35] have been performed using CCM as a treatment for heart failure. Its efficacy with respect to improving mortality and hospitalization has not been proven, but it has been shown to improve functional capacity, exercise capacity estimated by peak VO_2 and QOL [72], along with NYHA classification. The cost per application of CCM was €17,278 in one Austrian study in 2008 which also suggested that the overall effectiveness and safety of use of CCM in heart failure patients are low [73]. In addressing the clinical need for treating heart failure, CCM identifies and seeks treats one of the problems of myocardial dysfunction, resulting in enhanced strength of cardiac muscle contraction. However, the clinical results and economic assessment have not justified this as a means to treat heart failure. It is the author's opinion that it would be plausible to theorize that in conjunction with another therapy that would address other significant physiological problems associated with heart failure, CCM could potentially provide worthy clinical results.

Table 2 Heart failure devices based on mode of action

Physiological mode of action	Device	Placement of device	Connections	FDA/ CE	Clinical guidelines/ off label use
Left ventricular pressure unloading	IABP	Aorta	Percutaneous arterial insertion	Exempt	Cardiogenic shock
	Reiten catheter pump (Cardiobridge)	Aorta	Percutaneous	–	High-risk PCI ADHF
Left ventricular volume unloading	Impella (Abiomed)	Left ventricle crossing the aortic valve	Percutaneous cardiac catheterisation left ventricle across aortic valve	FDA 2012 CE 2004	Cardiogenic shock High-risk PCI
	HeartMate percutaneous heart pump (Thoratec)	Left ventricle	Percutaneous cardiac catheterisation femoral artery left ventricle across aortic valve	CE 2015	Cardiogenic shock High-risk PCI
Left atrial to femoral bypass	TandemHeart (TandemLife)	Left atrium	Percutaneous venous access interatrial septum puncture left atrium to femoral artery bypass	FDA 2011 CE 2006	Cardiogenic shock
Implantable haemodynamic monitoring devices	Chronicle (Medtronic)	Right ventricle	Device-subcutaneously lead-percutaneous transvenously to RV outflow tract	FDA-N/A	Prevention of decompensation in chronic heart failure
	Heartpod (St. Jude Medical)	Left atrial	Percutaneous cardiac catheterisation transeptal puncture		Prevention of decompensation in chronic heart failure
	CardioMems (St. Jude Medical)	Pulmonary artery	Percutaneous venous access	FDA-N/A CE-2014	Heart failure reduced ejection fraction
Cardiac contractility modulation	Optimizer III (impulse dynamics)	Right ventricular septum right atrium	Percutaneous cardiac catheterisation subcutaneously	–	Chronic heart failure Normal QRS EF < 35%
Neuromodulation-on	Precision pulse generator (Boston Scientific)	Vagus nerve percutaneous pectoral region	Surgical percutaneous	–	Chronic heart failure EF < 40%
	Demipulse (Cyberonics)	Vagus nerve percutaneous pectoral region	Surgical percutaneous	–	Chronic Heart Failure EF < 35%
	CVRx (Rheos)	Carotid sinus subcutaneous pectoral region	Percutaneous	FDA CE 2014	Chronic heart failure
	Eon Mini Neurostimulation system (St. Jude)	Spinal cord subcutaneous lateral abdominal region	Epidural subcutaneous	–	Chronic heart failure
	PrimeADVANCED (Medtronic)	Spinal cord subcutaneous lateral abdominal region		–	Chronic heart failure
	BioControl (CardioFit)	Right vagus nerve right ventricle	Surgical percutaneous cardiac catheterization		Chronic heart failure EF < 40%
Left ventricular partitioning	Parachute	Left ventricle	Percutaneous to left ventricle	CE 2013	Symptomatic dilated ischaemic cardiomyopathy

Table 2 continued

Physiological mode of action	Device	Placement of device	Connections	FDA/ CE	Clinical guidelines/ off label use
Interatrial shunts	Interatrial Shunt Device (Corvia)	Interatrial septum	Percutaneous	CE 2016	HFpEF HFrEF
	V-Wave (V-Wave Ltd)	Interatrial septum	Percutaneous	–	HFpEF HFrEF
Left ventricular modification	Algisyl- LVR (LoneStar Heart)	Left ventricle	Surgical	CE-2014	Dilated cardiomyopathy
Renal vein unloading/ ultrafiltration	Magenta	Renal veins	Percutaneous	CE-2014	Acute heart failure
	Aquadex (Sunshine Heart)	Renal veins	Percutaneous venous access		Acute heart failure

Group 7: Extracorporeal membrane oxygenation (ECMO)

This uses a centrifugal pump to drive deoxygenated blood from the patient's venous system, through an externalized membrane oxygenator system that results in carbon dioxide and oxygen exchange before returning to the patients arterial system. With respect to its in use in heart failure, it has similar outcomes to contemporaneous percutaneous VADs [74]. There are no RCTs demonstrating its efficacy however. ECMO-assisted PCI in the setting of cardiogenic shock as a result of AMI has been shown to improve survival [75, 76]

Group 8: Renal filtration (renal vein offloading)

Ultrafiltration is a means of removing sodium and water to improve haemodynamics in heart failure patients. The Aquadex system was inserted peripherally and provides veno-venous haeomfiltration extracorporally. The UNLOAD trial using the Aquadex system demonstrated superior efficacy over medial diuresis in reducing weight and fluid loss and a decrease in the rate and length of hospital admissions [47]. However, a meta-analysis of trials using various ultrafiltration devices reported no benefits to all-cause mortality or rehospitalizations [48]. Magenta is a percutaneous system that is placed into the renal veins to reduce venous pressure within the renal vein relative to the central venous pressure as a treatment for acute heart failure (Presented at EuroPCR Innovators day).

Group 9: Interatrial shunts

Elevation of left atrial pressures, causing pulmonary congestion, is reported in 90% of patients presenting with acute heart failure. Interatrial shunts are designed to relieve left atrial excess volume [49]. Blood flow is observed being shunted from the left to right atrium. Corvia Medical received CE approval for its InterAtrial Shunt Device (IASD) (Fig. 7) for the treatment of HFpEF. A non-randomized open label trial reported improvements left atrial pressures, functional capacity and QOL after 6 months [50]. V-Wave device (V-Wave Ltd) described a first-in-man case study of a 70-year-old man with HFrEF. The results demonstrated functional improvement, QOL improvement, 3-month post interatrial shunt placement [77].

Group 10: Tissue engineering

The increased volume of the left ventricle along with the stiffening of the myocardium that occurs with ischaemic cardiomyopathy results decreased cardiac output. Alginate-Hydrogels (Algysil-LoneStar, Inc.) are an inert implant that is being assessed as a means of treating this problem. Surgically inserted via thoracotomy, Algisyl implant has resulted in improved exercise capacity and symptoms in addition to standard medical therapy [78].

Group 11: Left ventricular partitioning

Anterior myocardial infarction results in an acute loss of myocardium in the left ventricle. Remodelling of the left ventricle occurs causing an increase in left ventricular volume, which can result in heart failure [79]. The parachute is a device that is inserted percutaneously. It was developed as a means to isolate damaged myocardium, while creating a new left ventricular apex (Fig. 1). The self-expanding nitinol frame permits contraction of the underlying healthy myocardium, an ePTFE occlusive membrane and an atraumatic foot [80]. The PARACHUTE trial showed significant improvement in left ventricular

volumes, with sustained improvements in NYHA class and QOL scores. The device is CE marked since 2011. A pivotal trial is currently underway in the US [81]. Table 2 summarizes heart failure devices based on the mode of action.

Conclusions

Contemporaneous clinical, economic and epidemiological evidence highlights the epidemic that is heart failure. Morbidity and mortality remain high with cost constraining the uptake of effective treatment with device therapies such as VADs, certainly in Europe. The need to treat heart failure is a validated need. Within heart failure, there exist a number of more filtered needs with both broad and narrow scopes. The need to reduce mortality in particular with respect to acute cardiogenic shock, the need to improve patients quality of life, the need to develop smaller and more durable VADs are amongst a few. New devices continue to be produced; however, efficacy and mortality improvements have not been effectively proven in clinical trials. Cost effective analysis of current and future therapies should be incorporated in clinical reviews to improve the possibility of implantation for heart failure.

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Compliance with ethical standards

Conflict of interest We declare that there is no conflict of interest for any authors.

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