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REVIEW

Heart Transplantation: Is It Still the Gold Standard?

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Abstract

Patients with advanced heart failure (AHF) have a poor prognosis. Significant advancements have been made in the surgical treatment of AHF with the use of mechanical circulatory support (MCS) and heart transplantation (HT). In carefully selected patients with AHF, HT remains the gold standard treatment, but left ventricular assist device (LVAD) therapy has become an important alternative. The 5-year survival post HT is 72% compared to 58–63% with contemporary LVADs. While HT provides a better quality of life and freedom from device-related complications, it is limited by the availability of donor organs. In the future, fully implantable LVAD systems and expanded donor strategies are expected to further optimise treatment options for patients with AHF.

Key words: heart failure; heart transplantation; left ventricular assist device

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Introduction

Advanced heart failure (AHF) is associated with extremely low survival rates, and treatment options remain a significant challenge, with 1-year mortality reaching 50% (Egbe et al, 2022; Subramaniam et al, 2022). For carefully selected patients with AHF who have exhausted guideline-directed medical and device therapy, heart transplantation (HT) may be a treatment of choice (McDonagh et al, 2021).

However, the availability of donor organs remains limited, and the list of patients waiting for a suitable match continues to increase, with a waiting list mortality of 14.5% (NHS Blood and Transplant, 2024). Additionally, many patients with AHF have comorbidities that contraindicate transplantation as a treatment option (Mehra et al, 2016). These challenges have driven developments in the field of mechanical circulatory support (MCS) devices.

This review aims to explore the current status of HT as the gold standard treatment and the progress and challenges of left ventricular assist devices (LVAD) as a treatment alternative. Particular attention will be given to the strengths, weaknesses, and future developments of both therapeutic options with a focus on the 3rd generation fully magnetically levitated centrifugal flow HeartMate 3 (HM3, Abbott, Chicago, IL, USA) LVAD. The device provides continuous blood flow and uses magnetic fields to suspend and rotate the pump's rotor, thus reducing the risk of complications by minimising damage to blood components.

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Background

Heart Transplantation

The first successful HT was in the 1960s. Early HT outcomes were poor with most patients surviving only weeks or months due to infections and rejection, leading surgeons across most of the world to stop attempting the operation. However, advancements in surgical techniques, organ preservation and immunosuppression have made HT a well-established practice, and over 157,000 heart transplants have been performed worldwide.

Left Ventricular Assist Devices

LVADs are mechanical pumps that assist the left ventricle to improve systemic perfusion. Since their inception in 1963, when the first LVAD was implanted in Houston, USA, they have undergone significant evolution. This has led to Food and Drug Administration (FDA) approvals for both bridge-to-transplant (where the intention at LVAD implant is for the patient to have a HT after a period of stabilisation or reversal of barrier to HT on the device) and destination therapy (where eventual HT was not the intent at LVAD implant) indications (U.S. Food and Drug Administration, 2017). Currently, in the UK, the National Health Service (NHS) funds the use of LVADs as a bridge-to-transplant only (National Health Service (NHS) England , 2018).

LVADs have progressed from large, bulky pulsatile devices in the 1990s to smaller, lighter, continuous-flow pumps in the 2000s that are also more reliable and less invasive. The HM3 LVAD is a third-generation device, designed to improve hemocompatibility and reduce shear stress on blood components, leading to fewer complications and improved outcomes. Following the withdrawal of its main competitor in the market, it has become the most widely implanted LVAD (Jorde et al, 2024).

An LVAD has five main components: an inflow cannula, a mechanical pump, an outflow cannula, a percutaneous driveline, and an external controller. The inflow cannula is surgically implanted into the left ventricular (LV) apex, with the outflow cannula being anastomosed to the aorta (Fig. 1). This configuration allows blood from the LV to flow into the pump through the inflow cannula and then to be diverted to the aorta. The driveline, a surgically tunnelled cable, connects the pump to an external control unit which operates and monitors the device. It typically exits the body through the anterior abdominal wall.

Patient Selection

The choice between HT and LVAD therapy relies on careful consideration of patient characteristics. Understanding these factors is crucial for optimal patient outcomes.

HT candidates are typically under 70 years of age, with end-stage heart failure, and have exhausted all other therapeutic options. These patients have single organ failure and acceptable pulmonary haemodynamics. They need to be free of active infections or malignancies. Adequate social support and concordance with

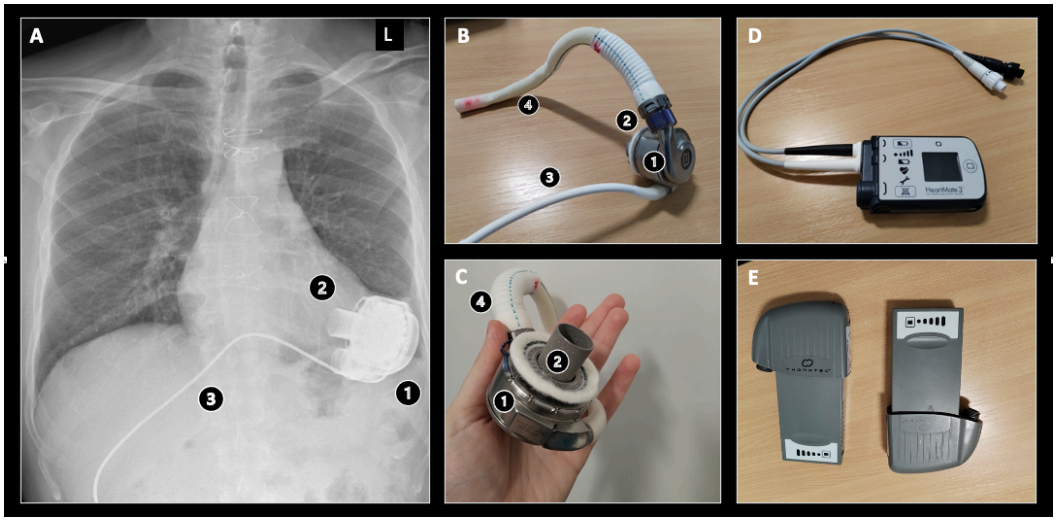

Fig. 1. Components of a left ventricular assist device (LVAD) system. (A–C) demonstrate the implanted hardware: (1) the HeartMate 3 LVAD pump, (2) inflow cannula positioned in the left ventricular apex, (3) percutaneous driveline that exits through the anterior abdominal wall, and (4) outflow cannula anastomosed to the ascending aorta. (D) shows the external controller unit that manages the pump function, while (E) displays the portable battery units that power the system. Source: Original photographs taken at our institution using our own equipment. L, Left.

medical therapy are also essential to success (Mehra et al, 2016). Several conditions may contraindicate HT, including active substance abuse, severe psychiatric illness, significant cerebral and peripheral vascular disease, irreversible end-organ dysfunction, severe obesity (body mass index >35 kg/m^2), and fixed pulmonary hypertension (Mehra et al, 2016).

LVADs, unlike donor hearts, are readily available. When used as a bridge-to-transplant, they allow patients to avoid clinical deterioration while awaiting a suitable organ. LVAD therapy may be appropriate for patients with relative contraindications to transplantation. Key considerations include adequate LV size to accommodate the device (Molina et al, 2022), absence of severe right ventricular failure, commitment to managing device care and dedicated caregiver support.

Outcomes

Heart Transplantation

HT offers excellent long-term survival rates. According to data from the International Society for Heart and Lung Transplantation (ISHLT), the median survival following HT is approximately 12.1 years for patients who received transplants between 2001 and 2009, with many individuals today living 15 years or more (Hsich et al, 2022). Short-term outcomes are good, with one-year survival rates exceeding 86%, three-year survival rates typically between 79% and 86%, and five-year survival at 72% (Colvin et al, 2024; Suarez-Pierre et al, 2021). These improvements in survival can be explained by advances in surgical techniques, novel organ preservation methods and better post-operative care.

Left Ventricular Assist Devices

Survival rates for LVADs have improved significantly with each generation of device. Recent data from the Multicenter Study of MagLev Technology in Patients Undergoing Mechanical Circulatory Support Therapy With HeartMate 3 (MOMENTUM-3) trial, which compared HM3 with HeartMate 2 (HM2) LVAD, showed early and mid-term survival rates comparable to HT with a 3-year survival 83% and 5-year survival of 58% (Mehra et al, 2022) (Table 1). Additionally, the ELEVATE registry, a prospective, predominantly European registry of consecutive HM3 LVAD implants with real-world data, demonstrated an even higher five-year survival rate of 63.3% (Schmitto et al, 2024), suggesting that outcomes in clinical practice may be even better than those observed in controlled trials. Overall, the HM3 LVAD showed improved outcomes compared to previous generation devices, with better survival rates, lower adverse event rates, and improvements in quality of life (Mehra et al, 2018). However, long-term data beyond five years are still limited, due to the relatively recent introduction of HM3 in clinical practice.

Adverse Events

Heart Transplantation

Acute Rejection

Acute allograft rejection is one of the most feared complications following HT. There are three types of rejection: hyperacute, acute cellular rejection (ACR) and antibody-mediated (AMR). ACR, the most common, is primarily T-cell mediated, while AMR involves a B-cell immunologic release of antibodies against antigens expressed on the donor organ cells. Hyperacute rejection is due to ABO incompatibility, and although common when transplantation was first introduced, nowadays this is very rare. Despite advances in immunosuppression, the risk of rejection remains significant, particularly within the first year of transplantation (Khush et al, 2019). These patients have a higher risk of developing a further complication of cardiac allograft vasculopathy (CAV) and also increased mortality (Nelson et al, 2020). The clinical presentation varies from asymptomatic cases, which are often only detected by surveillance biopsy, which is the current gold standard for diagnosis of rejection, to patients in cardiogenic shock.

Primary Graft Dysfunction

Primary graft dysfunction (PGD) is a serious complication that can occur within the first 24 hours post-transplant and is a leading cause of early mortality (Nicoara et al, 2018; Sabatino et al, 2017). PGD involves severe impairment of the donor heart's function, affecting the left or right ventricle, or both. While its exact pathophysiology remains unclear, PGD is thought to result from a combination of donor- and recipient-related factors (Nicoara et al, 2018). It requires aggressive management, including inotropic support and MCS (Marasco et al, 2010).

Table 1. Long-term outcomes and major complications: HeartMate 3 LVAD versus heart transplantation.

Outcome/Adverse event	LVAD (HM3)	Heart transplantation
Survival		
1-year	85%[1]	>86%[2]
3-year	83%[1]	79–86%[2]
5-year	58–63.3%*[1,3]	72%[2]
10-year	Not yet available†	50–53%[2]
Major adverse events		
Stroke	15.0% at 2 years[3]	2–3%[2]
GI bleeding	10.2% at 2 years[3]	-
Major infections	56.4% at 2 years[3]	-
Right heart failure	15.3% at 2 years[3]	-
Device thrombosis	1.1% overall[3]	
Device malfunction		-
-Internal components	6.9% overall[3]	
-External components	9.5% overall[3]	
Acute rejection	-	32.9% at 1 year[4]
Primary graft dysfunction	-	13.9% at 24–72 hours[5]
Cardiac allograft vasculopathy	-	33% at 5 years[6]
Malignancy	-	22% of deaths at 5 years[7]
Infections	Device-specific	30–60% at 1 year[8]
Renal dysfunction	-	45% at 1 year[9]

CNI, Calcineurin inhibitor; GI, gastrointestinal; LVAD, left ventricular assist device; HM3, HeartMate 3.
*ELEVATE registry showed higher survival (63.3%) than the Multicenter Study of MagLev Technology in Patients Undergoing Mechanical Circulatory Support Therapy With HeartMate 3 (MOMENTUM-3) trial (58%).
†Long-term data beyond 5 years are not yet available for HeartMate 3.
Data taken from:
[1]Mehra et al, 2022;
[2]Hsich et al, 2022;
[3]Schmitto et al, 2024;
[4]Sabatino et al, 2017;
[5]Khush et al, 2019;
[6]Chih et al, 2016;
[7]Merola et al, 2017;
[8]Youn et al, 2018;
[9]Hamour et al, 2009.

Cardiac Allograft Vasculopathy

CAV is the Achilles' heel of HT and a major cause for long-term graft failure. It is a progressive condition and represents a form of accelerated coronary artery disease triggered by complex pathophysiology involving both immune and non-immune insults (Chih et al, 2016). Angina is rarely present, as the graft is

denervated. The incidence and severity of CAV increase with time post-transplant. Approximately one-third of patients within 5 years post-transplant are affected by CAV, with around half having CAV at 10 years (Merola et al, 2017). Early use of mammalian target of rapamycin inhibitor (mTORI) has been shown to attenuate the progression of CAV (Matsuo et al, 2013). Additional treatment primarily focuses on controlling hypertension and hyperlipidaemia, with some single-centre studies supporting the use of aspirin to delay disease progression and graft failure (Asleh et al, 2021).

Immunosuppression-Related Complications

(a) Infection

The use of lifelong immunosuppression to prevent rejection leaves transplant recipients vulnerable to infections, especially in the early post-operative period. Opportunistic infections, such as cytomegalovirus, fungal infections, and bacterial infections, are common (Velleca et al, 2023). The risk is highest early post-transplant while patients are on high doses of immunosuppressants, but typically decreases after the first year when doses are reduced.

(b) Malignancy

Long-term immunosuppression leading to reduced host immunosurveillance increases the influence of oncogenic viruses in carcinogenesis (Mudigonda et al, 2022). Viruses such as Epstein-Barr virus (EBV), human herpesvirus 8, human papillomavirus (HPV), and hepatitis B and C contribute to an increased risk of malignancies. Skin cancers are most common in particularly basal cell and cutaneous squamous cell carcinomas, as well as post-transplant lymphoproliferative disorders. Risk factors for malignancy include male gender, older recipient age, re-transplantation and prior malignancy (Awad et al, 2022). These account for an estimated 22% of deaths annually after 5 years post-transplant (Youn et al, 2018).

(c) Renal Dysfunction

Calcineurin inhibitors (CNIs) such as tacrolimus and cyclosporine, used for immunosuppression, are nephrotoxic and can result in chronic renal failure, a major cause of long-term morbidity (Barten et al, 2018; Groetzner et al, 2009; Hamour et al, 2009). In some cases, haemodialysis and kidney transplantation may be required. Changing the immunosuppression regimen, such as switching CNI to mTORI or reducing drug target levels, is one way to address these issues (Zuckermann et al, 2012).

Left Ventricular Assist Devices

Although the newest generation of LVADs has shown improved survival rates and safety compared to their predecessors, they are not without issues. These adverse events can significantly impact quality of life and survival (Table 1).

Haemocompatibility-Related Adverse Events

Haemocompatibility-related adverse events (HRAEs), including pump thrombosis, ischaemic and haemorrhagic stroke, and spontaneous nonsurgical bleeding, remain important adverse events of LVAD therapy. With current LVADs, patients

are typically anticoagulated with warfarin. An analysis of the 5-year MOMENTUM 3 trial data reveals a reduction in the rates of late HRAEs with HM3 compared to HM2 (Mehra et al, 2022), due to advancements in pump design and transition to continuous-flow technology.

(a) Stroke

Stroke is a serious complication. It can be caused by thrombus formation in the device, debris in the outflow graft, or embolism from the left atrium, left ventricle, or aortic arch. The risk of stroke is highest immediately after LVAD implantation and increases again around 9 to 12 months (Samura et al, 2019). The incidence is 10–15% at 2 years and is significantly reduced compared to earlier LVADs (Mehra et al, 2022).

(b) Device Thrombosis

Pump thrombosis, although less common, is a potentially catastrophic complication (Scandroglio et al, 2016). It can result from device-related factors, such as outflow graft kinking, extrinsic compression, low pump speed, and patient-related factors such as subtherapeutic international normalised ratios (INRs). The ideal strategy for treating thrombosis in contemporary devices has yet to be defined. Treatment options vary and include unfractionated heparin, thrombolysis, pump replacement and urgent HT.

(c) Non-Surgical Bleeding

Non-surgical bleeding, mainly from the gastrointestinal tract, is another complication of LVADs and can cause frequent hospitalisations (Aggarwal et al, 2012). Gastrointestinal bleeding is often linked to the formation of arteriovenous malformations, especially in the proximal small bowel, in combination with the presence of anticoagulation therapy. Continuous-flow pumps have been associated with a reduction in von Willebrand factor (vWF), contributing to the bleeding risk (Meyer et al, 2014; Uriel et al, 2010). However, the newer magnetically levitated centrifugal pumps do not degrade high-molecular-weight multimers of vWF to the extent seen with other devices (Mehra et al, 2019).

Haemodynamic-Related Events

Long-term continuous flow with LVADs predisposes patients to aortic regurgitation (AR) and right-sided heart failure (HF), either in isolation or concurrently. These events are classified as haemodynamic-related events and occur more frequently with increasing duration of LVAD support (Grinstein et al, 2023).

(a) Right Heart Failure

Despite careful evaluation of the right ventricular (RV) status prior to implantation, de novo right heart failure (RHF) post LVAD is common (Kirklin et al, 2017). LVADs promote LV unloading and reduce RV afterload; however, this can cause a leftward shift of the intraventricular septum, which subsequently alters septal and RV geometry and ultimately RV contraction (Houston et al, 2017). LVADs also increase RV preload, which can further increase right-sided filling pressures and RV wall stress. RHF post-LVAD may need additional therapies, such as inotropes or temporary MCS.

(b) Aortic Regurgitation

The mechanism of AR development is multifactorial and is linked to reduced aortic valve opening, which promotes valve stasis and commissural fusion. It is also linked to LV unloading with increased transvalvular pressure gradients transmitted across the aortic valve and altered aortic root biomechanics (Rubinstein et al, 2024). AR creates a substantial regurgitant flow loop and can lead to impaired LVAD effectiveness and reduced cardiac output.

Driveline Infections

One of the unique complications of LVADs is the risk of driveline infections. These are the most common types of LVAD-associated infections and can cause serious complications, including bacteraemia and sepsis if not treated properly (O'Horo et al, 2018). The driveline exits the body through the skin, providing an entry point for bacteria. Many strategies to minimise the risk of driveline-related infection have been tested, but the optimal solution would be to remove the driveline completely and design fully internalised power sources (Mehra and Gustafsson, 2021).

Quality of Life Considerations

Heart transplant recipients generally experience superior long-term quality of life compared to LVAD patients, and they have better outcomes in terms of their mental health (Heilmann et al, 2016). The main advantages of HT include freedom from external devices, the ability to participate in most physical activities, and improved exercise capacity. However, these benefits come with challenges, such as lifelong immunosuppression and risk of malignancy, which are not necessarily predictors of poor quality of life (Albert et al, 2024).

LVADs also provide a significant improvement in quality of life compared to medical management. This can be seen as early as 1–3 months after LVAD implantation, with patients achieving adequate aerobic capacity for normal daily activities (MacIver and Ross, 2012). Several key factors affect quality of life, including self-care ability, social support availability and emotional adjustment (Levelink and Brütt, 2021; MacIver and Ross, 2012). However, patients with LVADs often need to manage the physical and psychological burden of living with a device, including the constant need for a power supply and the limitations on physical activities such as swimming. Psychological distress remains a serious concern in some patients (Adams and Wrightson, 2018).

Developments

Heart Transplantation

Ongoing research and innovation in HT aim to address many of the current challenges and improve patient outcomes.

Donation After Circulatory Death

Donation after circulatory death (DCD) represents a significant advancement in addressing the critical shortage of donor hearts, leading to an increase of transplant volumes of nearly 50% (Messer et al, 2020). Historically, HT has been per-

formed using hearts retrieved from brain-dead patients. DCD, originally called non-heart-beating donation, refers to the use of organs from donors with irreversible neurologic injuries, who are ventilator dependent but do not meet criteria for brain death. In DCD, medical support is withdrawn, typically in an intensive care unit, and death is declared following cessation of circulation. Organ retrieval begins once death is confirmed. Evaluating the quality of the DCD heart is challenging, as its assessment takes place after circulatory arrest; optimising preservation methods to minimise ischemic injury is crucial. Currently, DCD heart transplants account for 30–40% of heart transplant activity in centres with established DCD protocols. DCD cardiac allografts have comparable outcomes to those of donors after brain death (Chew et al, 2019; Messer et al, 2020).

Novel Organ Preservation Methods

Traditionally, donor heart preservation involved storing the heart in an ice cooler. However, this organ preservation modality has several limitations, including ischemia and cold-induced graft injuries, especially with longer travel times. Newer methods, such as the SherpaPak Cardiac Transport System, the hypothermic oxygenated machine perfusion (HOPE) of the donor heart, and the TransMedics Organ Care System (OCS) *ex-vivo* transfusion, have been developed (Fig. 2). These innovations aim to reduce ischemic injury and improve post-transplant outcomes.

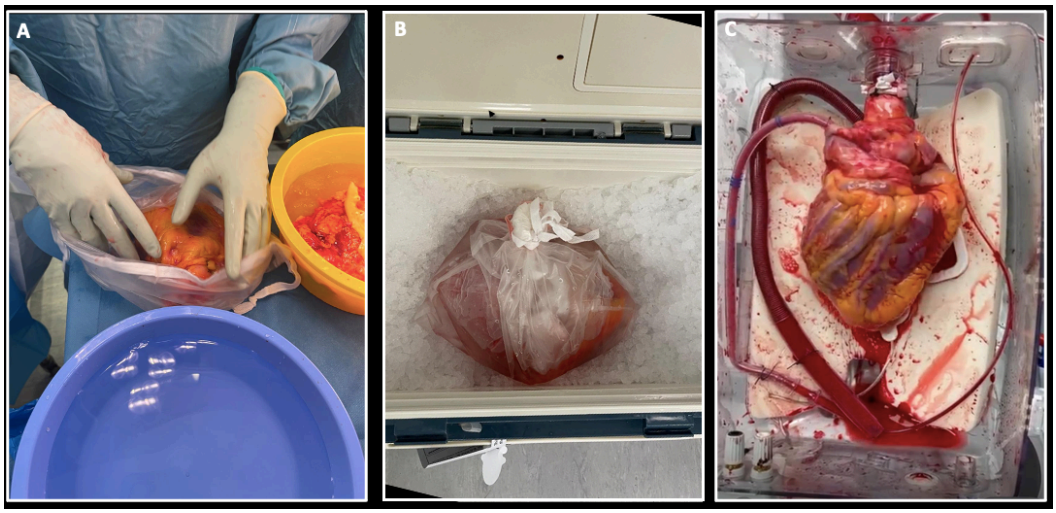

Fig. 2. Traditional and newer methods of donor heart preservation. (A,B) demonstrate the traditional method of donor heart preservation, where the organ is placed in a sterile bag with cold preservation solution and stored in a portable ice cooler. (C) shows the Organ Care System (OCS), a contemporary *ex-vivo* perfusion system that keeps the donor's heart warm and beating during transport and perfused with oxygenated blood. Source: Original photographs with our equipment taken upon arrival at our hospital-recipient centre. These images were taken for training and educational purposes and were stored in accordance with the Trust's policy.

Xenotransplantation

Xenotransplantation has the potential to significantly expand the donor pool, addressing the organ shortage, while also improving survival outcomes by offer-

ing recipients a rapidly available graft before they deteriorate while on the waiting list. Recent progress in gene editing and immunology has brought this approach closer to reality. Ongoing challenges include immunologic barriers, transmission of zoonosis into the human pool, as well as ethical considerations (DeFilippis et al, 2022a). In January 2022, the first successful xeno-HT was performed, with a genetically modified pig heart transplanted into a 57-year-old patient, who survived for two months (Griffith et al, 2022; Wang et al, 2022).

Immunosuppressive Therapy

Generally, immunosuppression is with a combination of agents such as CNI (tacrolimus, cyclosporin), corticosteroid, antiproliferative drugs (mycophenolate mofetil, azathioprine) and mTOR inhibitors (sirolimus, everolimus). These drugs have their own side effect profile, which impacts post-transplant morbidity. Newer therapies, such as renal-sparing agents like belatacept (Uriel et al, 2022) and interleukin-6 and immunoglobulin G degrading enzyme of Streptococcus pyogenes, are being developed to address the limitations of current immunosuppressive regimens (Jordan et al, 2017).

Non-Invasive Rejection Monitoring

Endomyocardial biopsy is currently the gold standard in monitoring rejection, but these are invasive and can have complications (Giarraputo et al, 2021). Advances in non-invasive blood tests and imaging techniques are being studied to detect rejection earlier and more accurately (Giarraputo et al, 2021; Marco et al, 2023). The use of peripheral blood gene expression profiling and circulating donor-derived cell-free DNA (Dd-cfDNA) is a promising biomarker for non-invasive detection of rejection (Truby et al, 2023; Velleca et al, 2023). Dd-cfDNA can detect allograft injury up to 3–5 months before the appearance of histopathological changes on biopsy, with a negative predictive value of >97% for both ACR and AMR (Holzhauser et al, 2023). The combination of gene expression profiling and Dd-cfDNA has the potential to reduce the requirement for protocolised surveillance endomyocardial biopsies.

Left Ventricular Assist Devices

As durable LVAD technology continues to evolve, extending its use to a broader range of patients with ambulatory HF will require a number of important challenges to be addressed.

Fully Internalised Systems

The future of LVAD is moving towards fully implantable systems. This evolution aims to reduce infections and improve quality of life by removing all external components, including drivelines. Fully implantable devices rely on wireless energy transfer and implantable batteries, without the need for external power cables. To achieve this, several key features are necessary, including long-lasting, rapidly chargeable implantable batteries and miniaturized controllers to reduce complications from abdominal or thoracic wall placement (Shaffer et al, 2021). Wireless energy transfer and transcutaneous energy transmission systems are being developed

to power LVADs. Results from *in vitro* and animal studies have shown promising solutions, such as the use of a coplanar energy transfer system (Pya et al, 2019).

Biocompatible Surface Materials

Research into new materials is ongoing to develop LVADs with improved hemocompatibility to reduce the risk of thrombosis and bleeding. This includes the development of advanced biomaterials that mimic the lining of blood vessels and are designed to reduce derangements in hematologic and inflammatory pathways, ultimately leading to fewer HRAEs (Shaffer et al, 2021). The main advantage is the potential for low-intensity or alternative anticoagulation strategies. This could reduce the risk of bleeding associated with current anticoagulation agents.

Adaptive Flow Autoregulation

Future LVADs are likely to include smart technology with integrated pressure sensors and advanced algorithms that allow the device to automatically adjust its function based on the patient's physiological needs (Varshney et al, 2022). For example, sensors could monitor real-time changes in blood pressure, flow, and oxygenation, allowing the device to adjust its output in response to varying conditions, such as exercise or rest, resulting in a more efficient and patient-friendly device.

Right Ventricular Support and Total Artificial Heart

As MCS technology advances for LV failure, parallel developments are occurring for RV support systems and total artificial heart (TAH) technology. Contemporary RV support options include both percutaneous and surgical options. Percutaneous devices such as Impella RP provide up to 5 L/min flow with a 72.7% survival rate in FDA post-approval studies (DeFilippis et al, 2022b). The development of durable RV assist devices has focused on adapting existing LVAD technology in a right-sided configuration (DeFilippis et al, 2022b). Research is also focused on minimally invasive solutions to support right heart function, such as the percutaneous catheter technology (PERKAT) RV device—a novel system that modifies intra-aortic balloon pump (IABP) technology. This device requires only an 18 Fr sheath for rapid deployment (Kretzschmar et al, 2018).

The TAH represents a complete cardiac replacement solution, with dual polyurethane ventricles to replace the native heart's ventricles and valves. New systems incorporate portable drivers, allowing patients to mobilise and return home while on the waiting list (Melton et al, 2019). A multicentre study showed that critically ill patients can be effectively bridged to transplantation with TAH; 63.5% of recipients were successfully transplanted with post-transplant survival rates of 84% at one year (Carrier et al, 2021). Next-generation devices focus on the development of smaller versions to accommodate more patients, reduced complications related to bleeding and clotting, and the development of fully implantable systems suitable for both temporary and permanent support (Demondion et al, 2013; Sunagawa et al, 2016).

Discussion

For suitable candidates, HT offers the best long-term outcome with significant improvements in quality of life and functional status, along with freedom from device-related complications (Fernandez Valledor et al, 2024; McDonagh et al, 2021). LVADs are becoming increasingly important in the treatment of patients with AHF, particularly those who are ineligible for transplantation or cannot wait for a suitable donor organ (Saeed et al, 2023). Continued technological improvements have led to excellent mid-term survival on HM3 LVAD, which is comparable to that of HT recipients. Efforts to minimise adverse events and the development of totally implantable LVADs will be revolutionary and will enable the broader adoption of this technology.

The future of AHF management lies in technological advancements in both fields. For HT, novel preservation techniques such as *ex-vivo* perfusion systems and hypothermic oxygenated machine perfusion are extending organ preservation times and improving viability. Xenotransplantation may revolutionize donor availability; early results are promising, although challenges regarding long-term survival and risk of zoonotic disease transmission will need to be addressed.

LVAD technology is progressing toward fully implantable systems. The development of transcutaneous energy transmission systems and improved battery technology could eliminate driveline infections, while advanced biomaterials may reduce the need for anticoagulation. Integration of physiologic sensors for flow optimization could better replicate natural cardiac function, potentially improving patient outcomes and experience. It is important to note, however, that while LVADs have demonstrated survival rates approaching those of HT, current analyses in the UK suggest that LVAD therapy exceeds typical National Health Service cost-effectiveness thresholds compared to medical management. Therefore, healthcare systems must balance the clinical benefits and technological advances against economic constraints when implementing these life-saving technologies (Beese et al, 2024).

Conclusion

HT provides the best long-term outcomes and survival for patients eligible for transplantation, while LVAD is an effective alternative for those awaiting transplantation or ineligible for it. The choice between HT and LVAD depends on individual patient factors, including eligibility for transplantation and organ availability. Other considerations, such as quality of life, risk of complications, patient preferences, and lifelong immunosuppression, also play a significant role in determining the best treatment strategy. The future of AHF treatment is certainly an exciting area to watch. The gold standard of tomorrow will be an adaptable approach, not just adding years to life but also improving the quality of life.

Key Points

- Heart transplantation remains the current gold standard treatment for carefully selected patients with advanced heart failure.
- Left ventricular assist devices (LVADs) are an increasingly important alternative for patients who cannot wait for a transplant or for those with contraindications.
- Advances in heart transplantation include efforts to increase the donor pool and improve post-transplant outcomes.
- Advances in LVAD technology are focused on developing fully implantable systems to minimise risks and improve patients' quality of life.

Availability of Data and Materials

All the data of this study are included in this article.

Author Contributions

TK, SA, AK and SB designed the work and drafted the manuscript. All authors contributed to the important editorial changes in the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

According to NHSBT guidance, these images can be used for training and educational purposes. The images are stored in accordance with the Trust policy/information governance. The research was conducted in strict accordance with the ethical principles outlined in the Declaration of Helsinki.

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Conflict of Interest

The authors declare no conflict of interest.

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