The Economics of Ventricular Assist Devices

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Alexander Iribarne, Kimberly N. Hong, and Mark J. Russo

Introduction

"Disruptive technology," a phrase coined by economist Clayton M. Christensen approximately 10 years ago, describes a new technology that unexpectedly displaces an established technology. Whereas sustained technology applies incremental improvements to an established approach, disruptive technology, often lacking in refinement, has the ability to transform common practice. Such has been the case with ventricular assist devices (VADs), which have rapidly transformed the management of end stage heart failure from sole pharmacologic therapy to enhancement with mechanical circulatory support.

As with most forms of disruptive technology, however, VADs are not without a significant burden on healthcare costs in a patient population already consuming healthcare resources at the extreme. Today, nearly five million Americans are diagnosed with heart failure, with an incidence approaching 10 per 1,000 of the population after the age of 65 [1]. The 5 year mortality rate remains at 50 % despite improvements in medical and surgical therapies, with the number of deaths and hospitalizations continuing to rise. In 2001, the estimated cost of heart failure in the US was $21 billion. Heart failure represents a significant public health burden, but also represents an area of intense healthcare resource consumption in an era where there is growing attention, and greater constraints, on healthcare spending. With increasing interests and necessity in comparative effectiveness research, novel therapeutics must be studied not only from the perspective of safety and efficacy but also with respect to their relative cost effectiveness. In this chapter, we briefly discuss the history and landmark trials of ventricular assist devices and focus on the innovations and futures challenges of these devices from a medical economics perspective.

A. Iribarne, MD, MS
Section of Cardiac Surgery, Dartmouth-Hitchcock Medical Center, Lebanon, NH, USA
e-mail: airibarne@gmail.com

K.N. Hong, MD, MHSA
Department of Internal Medicine, Mount Sinai Hospital, New York, NY, USA
e-mail: kimberly.hong@mountsinai.org

M.J. Russo, MD, MS (✉)
Department of Cardiothoracic Surgery, Barnabas Heart Hospital, Newark, NJ, USA
e-mail: mr2143@gmail.com

VADs in Historical Context

In 1964, the National Institutes of Health established the Artificial Heart Program [2]. There was significant early enthusiasm for the development of a total artificial heart. However, in the 1970s, failures in this arena combined with challenges in transplantation secondary to the lack of modern immunosuppression, led to the

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development of the National Heart, Lung, and Blood Institute clinical ventricular assist device program in 1975. This program initially focused on mechanical circulatory support for patients who had recently undergone cardiac surgery [3], but ultimately expanded to focus on support for patients requiring mechanical assistance as a bridge to transplantation (BTT).

Throughout the 1970s and 1980s several VADs were developed, characterized by their large size and use of pulsatile flow and positive displacement. These devices, now commonly referred to as "first generation" VADs, underwent significant evolution, and three devices ultimately received Food and Drug Administration (FDA) approval for use in BTT support – the Thoratec paracorporeal VAD (PVAD)/implantable VAD (IVAD), the Heartmate IP/VE/XVE, and the Novacor LVAS, which is no longer marketed in the United States [4–8].

Much of the early focus on mechanical circulatory support involved use of VADs for temporary support after cardiac surgery or as BTT in critically ill patients on the wait list. Given the early success of VADs, attention turned to investigating an indication for use in destination therapy (DT) among end-stage heart failure patients who were not eligible for transplantation. The results of the landmark Randomized Evaluation of Mechanical Assistance for the Treatment of Congestive Heart Failure (REMATCH) were published in 2001 [9]. The HeartMate XVE was introduced in 2001 with structural modifications, and received FDA approval for a BTT indication in 2001 and for destination therapy in 2003 based on the results of REMATCH.

Despite the significant impact on survival observed in early VAD trials, major opportunity remained for device improvement and innovation. In the REMATCH trial, patients in the device group were more than twice as likely to have a serious adverse event compared to the medical management group. In 1994, the NHLBI issued proposals for "Innovative Ventricular Assist Systems," which sought to improve the durability of ventricular assist systems to at least 5 years and increase reliability to at least 90 %. As an outgrowth of this request for proposals, rotary axial flow devices were developed. These smaller, "second generation" devices differed from their pulsatile counterparts in that they employed rotary axial flow and thus provided continuous flow [10]. The HeartMate II, a continuous flow device first used clinically in 2001, was approved for BTT in 2008 and DT in January 2010 [11].

Since 2008, continued innovation has occurred through the development of third generation, or centrifugal, devices. Through the use of a bearingless design, these devices may have improved durability. Moreover, the smaller size of these devices has important implications for improved quality of life after implantation. The potential for such a device may be reflected by the recent early conclusion of enrollment in the ADVANCE trial, which tests HeartWare's (Framingham, Massachusetts) miniaturized, third-generation VAD in a BTT population. At the 2010 meeting of the American Heart Association, HeartWare reported that 92 % of enrolled patients had achieved the primary endpoint at 180 days [12].

This past year, the NIH issued a request for proposals for the Randomized Evaluation of VAD InterVEntion before Inotropic Therapy (REVIVE-IT) trial [13]. The goal of this study is to explore the potential benefit of mechanical circulatory support in less severe but functionally-impaired heart failure patients, not eligible for transplantation. Largely as a result of an improved durability and safety profile, the REVIVE-IT trial represents a potential paradigm shift in viewing VADs as salvage therapy for the most critically ill heart failure patients, to support for less critically ill patients with impaired functional capacity. The REVIVE-IT trial has yet to begin enrollment, however, the results of this trial have the potential to further expand the role of VADs. The evolution and innovation of VADs over the course of 40 years has not only led to improvements in safety profiles and durability but also expanded the potential clinical indications for mechanical circulatory support.

Early Economic Outcomes with Ventricular Assist Devices

The early focus on mechanical circulatory support was on the safety and efficacy of such devices in the management of end-stage heart failure. As VAD trials completed enrollment and

FDA approval was granted, attention gradually turned toward the challenging issues of insurance coverage and the cost of such devices. Not only were VADs resource intensive due to the cost of the device itself, but they were an added cost in the management of end-stage heart failure patients – an already resource intensive group. Economic evaluation of device therapy includes the costs of operative implantation, post-operative recovery and hospitalization, and management of complications which occur at relatively high rates when compared to most other surgical interventions. Clearly VADs prolonged survival of end-stage heart failure patients, but were these devices cost effective?

Pre-REMATCH In one of the first analyses focused on costs, Moskowitz and colleagues reported on resource utilization among 12 VAD recipients in 1994 and 1995 [14]. The outcomes of this population included two deaths, eight transplants, and two patients on continued support. The average number of LVAD supported days was 177, with a range of 13–481 days, and an initial-implant related hospitalization cost of $141,287 ± 18,513. When hospital costs were broken down, the three most resource-intensive categories were: the device itself (48 % of total cost), professional payments (17 %), and intensive care unit length of stay (10 %). The authors further calculated outpatient costs and the costs of readmission bringing the total cost of LVAD therapy during the first year after implant to $222,460 whereas the cost of cardiac transplantation was estimated to be $176,605.

REMATCH In a follow-up analysis involving the majority of patients enrolled in the REMATCH trial, Oz and colleagues reported a mean and median total hospital cost of $210,187 ± 193,295 and $137,717, respectively, with a wide range of $72,583 to $1,123,565 depending on number of days spent in the intensive care unit [15]. This study was the first to cast light on the potential factors responsible for the high cost of LVADs. Sepsis, pump housing infection, and perioperative bleeding were all significant predictors of the cost of the index hospitalization. When these three factors were all present, the cost of hospitalization was projected at $869,199 and when these factors were all absent the cost was estimated at $119,874. In addition to device-related complications, the study also examined annual readmission costs. Notably, there were approximately 4.5 readmissions per patient, with the annual cost for the entire costing cohort estimated at $309,273. In the 27 patients who survived greater than 1 year, the annual cost decreased to $196,116. This analysis of the REMATCH device cohort demonstrated that improvements in the cost-effectiveness of VADs would require not only device innovation to reduce the frequency of post-operative complications, but also improvements in patient selection given the significant difference in cost between patients who survived greater than 1 year and those that did not.

Despite the significant cost associated with LVAD therapy, it is essential when considering the cost effectiveness of LVADs, to understand the cost of alternative treatments – heart transplantation in the BTT population, and optimal medical management (OMM) in the DT population. DiGiorgi and colleagues examined the costs of patients bridged with the HeartMate XVE versus those receiving a heart transplant [16]. Their results demonstrated that overall, total actual hospital costs of LVADs exceed that of transplantation, with total hospital costs post-LVAD estimated at $197,957 and total hospital costs for transplanted patients estimated at $151,646. The overall net revenue for transplantation was $29,916 whereas for LVADs, net revenue was – $53,201. Importantly, there were a significantly greater number of readmissions among the LVAD group, with readmission costs in the device group estimated at $16,596 and only $6,356 in the transplantation group. In addition to the difference in number of readmissions, the authors also highlight the importance of length of stay which was 36.8 days in the sicker device group and 18.2 days in the healthier transplant group.

Russo and colleagues examined the costs of medical management in the final 2 years of life among the optimal medical management cohort in the REMATCH trial [17]. The mean total cost per patient in the final 2 years of life was $156,168, with more than half of the total cost

incurred during the final 6 months of life. Approximately 75 % of the inpatient costs in the last 6 months were related to hospitalizations for heart failure exacerbations. Notably, during the final 6 months of life, patients spent approximately 1 out of every 4 days of life as hospital inpatients. The results of the analyses by DiGiorgi and Russo demonstrate that although the costs of VADs is great, the costs of alternative strategies for end-stage heart disease, such as transplantation and intensive medical management, are not without a significant cost burden. Thus, early data demonstrated that there existed an opportunity for mechanical circulatory support to compete with the currently available alternatives from a cost-effectiveness standpoint, but improvements would first be necessary in terms of device innovation, clinician experience, and patient selection.

Innovation, Experience, and Improved Cost Effectiveness

Kenneth Arrow, who received the 1972 Nobel Prize in economics, described in his classic text, "The Economic Implications of Learning By Doing," the process whereby workers improve productivity by repetition of a given action which results in increased productivity through practice and innovation [18]. Unlike pharmaceuticals, a "learning by doing" approach is particularly critical in the innovative process of medical devices and surgical procedures, whereby learning and ultimately innovation occur gradually through use and experience with a device or technique [19]. While innovation clearly occurs in the laboratory, there is a feedback pathway where research and development lead to clinical trials which in turn lead to clinic practice, and then ultimately to experience that informs and feeds back to the research and development process [20].

Such an innovative process can be seen in the development of LVADs. Experience with the first generation HeartMate device in the REMATCH trial led to several mechanical device innovations. For example, locking screw ring connectors were added to prevent detachment of the blood transport conduits, and outflow graft bend relief was added to prevent kinking and valve flow incompetence [21]. In addition to changes in the mechanical design of the device, experience in REMATCH gained from clinical practice or "learning by doing" led to refinements in patient selection and management.

As discussed previously in this chapter, early economic evaluation of LVADs highlighted the significant impact of device-related complications, such as sepsis, on total hospital costs. As such, institutions have developed specific guidelines on surgical infection prophylaxis for LVAD recipients. In addition, early economic analysis demonstrated the significant difference in cost of total hospitalization between LVAD recipients who survived the first year of implantation versus those who did not. Work by Leitz and colleagues demonstrated that use of a pre-operative risk score could be used to stratify LVAD recipients into low, medium, high, and very high risk which correlated with 1-year survival rates of 81 %, 62 %, 28 %, and 11 %, respectively [22]. As experience with VADs has grown, several subsequent risk models have been developed to more precisely predict peri-operative morbidity and mortality and aid in patient selection.

Early experience with LVADs clearly led to refinements in device technology and patient selection, which ultimately led to improvements in clinical outcomes. However, have refinements in devices themselves and the selection of device recipients ultimately led to improvements in the cost-effectiveness of VADs?

Initial economic evaluation of VADs focused largely on reporting of costs rather than cost-effective analysis. However, even a cursory examination of the reported hospital costs from the REMATCH trial, driven largely by the costs of the index hospitalization, hospital readmissions, and the need for device replacement, demonstrated that VADs would far exceed the generally accepted incremental cost effectiveness ratio (ICER) threshold of $50,000–$100,000 per quality adjusted life year (QALY). In fact, economic modeling by Clegg and colleagues demonstrated that LVADs offered an additional 0.6 QALYs per patient over the 5-year duration of their model at

an additional cost of £102,000 or an ICER of £170,616, approximately $341,232 using a currency conversion adjusted for the time of publication [23]. One-way sensitivity analysis showed that the results were not sensitive to variations in cost, discount rate, or utility. Similarly, in 2002 the Technology Evaluation Center of Blue Cross and Blue Shield performed an independent cost-effectiveness analysis of LVADs using parameter estimates from published sources at the time. The results demonstrated that use of LVADs led to an increase in cost of $802,700 per one QALY gained, compared with optimal medical management. The calculated ICER was stable despite sensitivity analysis on the utility of New York Heart Association Category III/IV, cost of outpatient care, cost discount rate, cost of rehospitalization, and probability of rehospitalization for LVAD. Russo and colleagues calculated the ICER of patients enrolled in REMATCH to be $602,361/QALY [24].

Early American and European estimates of the cost-effectiveness of VADs were bleak. Not only were calculated ICERs far outside the range of medical therapies that would be considered cost-effective, sensitivity analyses demonstrated that acceptable ICER thresholds could be achieved only at the extremes of clinical variables that composed the economic models.

Measuring Device Technologies

With growing constraints in healthcare funding, there is increasing demand for objective clinical and economic evidence to demonstrate that a particular intervention will be safe and effective while providing improved quality of life at an acceptable cost. However, given the rate of technological change, evidence to support the use of new technologies frequently lags behind their application. The need to evaluate device-based therapies has increased exponentially, particularly in cardiovascular disease.

Historically, tools to evaluate clinical therapies were developed for the evaluation of drug-based therapies. However, devices and drugs are inherently different – drugs are "discrete technologies." That is, drugs are singular and driven by a fixed active agent. Research and development occurs at the benchtop, and they do not undergo significant evolution after introduction to the market. Application in clinical practice signals the end of the development process. Although doses and delivery mechanisms may change, the active chemical agent remains fixed. Therefore, the life-cycle of a drug is linear, and advances in therapy are discrete and discontinuous.

Devices, in contrast, are "complex technologies," consisting of a number of modular components where changes in any component may impact outcomes. Application does not signal the end of the development process. Significant research and development continues to occur in the clinical setting. Outcomes are operator dependent, and operators learn by doing and, in addition, incremental advances may occur continuously. Clinical experience with devices can feed back to the research and development stages resulting in design refinements and further innovation. This may be ongoing even in a randomized clinical trial setting.

As a result, traditional methods of evaluation suffer from inherent limitations. Specifically, while innovation is dynamic and medical technologies change over time, evidence is static with findings from a fixed time period. Therefore, while clinical decision makers demand information from today, and policy makers require data for the future, frequently evidence from clinical trials is limited to the past.

The dynamic nature of surgically implantable devices and their application complicates the ability of policy makers to obtain rigorous and timely evidence to guide decisions on the adoption and use of a new technology. Quantifying uncertainties regarding emerging technologies is challenging. In order to overcome these challenges, economic modeling needs to incorporate the dynamics of technological change and learning into analysis as it may alter conclusions. This includes use of advance analytical techniques to account for potential changes in the technology, operator experience, patient management, and target populations over the study period. These include patient risk stratification, volume-outcome

analysis, learning analysis, assessment of temporal trends, and incorporation of data collected beyond the close of the study period. Sensitivity analyses and Markov modeling offer analytical means to control for uncertainty and changes over time. In addition, post-marketing surveillance, including capturing outcomes in everyday practice and revisiting payment decisions, is also crucial to assessing and reassessing the clinical and cost effectiveness of rapidly evolving technologies.

VADs as an Evolving Technology

One might have expected innovations in VADs to occur in a protracted manner; however, as discussed previously, innovation and improvements in clinical outcomes with VADs occurred relatively quickly through experience. In fact, such improvements in clinical outcomes could already be observed during the REMACH trial. Park and colleagues demonstrated that there was a 15 % improvement in overall survival among patients randomized during the second half of the trial when compared to those randomized during the first half [25]. In addition, there were significantly fewer adverse events when the two trial time periods were compared with improvements in sepsis, pump housing inflow and outflow graft infections, bleeding, and renal failure in patients enrolled in the second half of the trial.

Such observed improvements in clinical outcomes during the REMATCH trial appear to have translated into significant improvements in cost-effectiveness during the course of the trial. While the mean ICER of device therapy was $602,361/QALY over the entire study period, there was a significant decrease in the ICER from the first to the second half of the trial with estimated ICERs of $898,666/QALY and $505,286/QALY, respectively [24].

REMATCH

During the REMATCH trial, several changes to the device technology were implemented, including modification of the driveline, introduction of a locking screw ring to prevent detachment of the blood-transport conduits to and from the pump/inflow valve reinforcement, and bend relief of outflow graft [26]. Meanwhile, clinicians improved their management of LVAD patients by modifying the operative procedure [27], developing clinical protocol to prevent and manage driveline infections with antimicrobial agents [28–30], and changing anticoagulation regimens, which reduced the adverse event profile associated with the therapy [31, 32]. As previously noted, even within the study period, measurable improvements in outcomes were evident, including decreased costs, improved survival, and decreased ICER [25].

Post-REMATCH

Approval of the HeartMate XVE by the FDA, Medicare, and a number of private insurers, allowed for expanding experience. In the 2 years following Medicare approval for reimbursement, an analysis of a post-marketing registry showed that the overall survival rate of LVAD patients remained similar to that seen in the trial [22]. However, over time, the length of stay for the implant hospitalization, the most costly part of the care process, fell by 25 % from an average of 44 days in the pivotal FDA trial (with a mean cost of $210,187) to 33 days within 3 years of dissemination [33]. This is important, because the cost of index hospitalization accounted for the majority of the mean total costs in the VAD group. Furthermore, the implementation of new protocols has reduced the incidence of adverse events, specifically in driveline infections and thrombosis [28–32]. The modeled ICER of the Heartmate XVE during the post-REMATCH time period was less than half of the overall REMATCH ICER. This ICER reflects improvements in device reliability and a reduction in the cost of the index hospitalization in the VAD group, and an increase in survival and costs in the OMM arm to account for the application of biventricular pacing and implantable cardiac defibrillators [24].

Second Generation Devices

Despite early evidence demonstrating the potential importance of patient selection and risk stratification using variables such as end-organ dysfunction and right ventricular failure, malnutrition, or infection; the acuity of patients implanted during the early post-REMATCH period did not differ significantly from the original REMATCH study population [22]. In the current era, with growing evidence of the importance of risk stratification in patient selection, there has been a gradual shift away from viewing LVADs as a salvage therapy for patients who are sliding on inotropes or progressing to multisystem organ failure. Instead, LVADs now form an important potential component of heart failure management in the functionally impaired as well as the less severe heart failure population. A multivariable regression analysis of the larger population captured by the registry (n = 262) showed that baseline risk factors, such as poor nutrition, hematological abnormalities, and markers of end-organ dysfunction, distinguish patient risk groups. Stratification of destination therapy candidates into low, medium, high, and very high risk on the basis of a risk score corresponded with dramatically different 1-year survival rates (81 %, 62 %, 28 %, and 11 %, respectively) [34].

Consistent with these observations, recent studies have demonstrated that less acutely ill but functionally impaired heart failure patients receiving continuous flow LVADs as BTT or DT experienced shorter lengths of stay and greater short- and long-term survival compared to non LVAD patients [35]. Furthermore, significant improvements in device durability have been demonstrated in recent years [10, 11]. The device used during REMATCH, the Heartmate VE, was known to have limited durability even prior to its clinical application. Engineers projected that the lifetime of the device was between 18 and 24 months. With mean cost of hospitalizations related to device replacement exceeding $180,000, 5 % of total costs were related to hospital readmissions in which a device replacement occurred. Currently, a number of second generation devices have completed various trial phases. The devices, which are smaller, axial flow pumps with blood-immersed or pivotal bearings, possess a life expectancy of up to 15 years. More recently, third generation devices have entered clinical trials. These devices, which are further miniaturized and eliminate the mechanical bearing, may potentially have a nearly unlimited life.

Collectively these important advances have led to further improvements in the ICER related to long-term use of LVADs. For the second generation era, assuming improvements in survival during index hospitalization and further improvements in reliability with no further changes in OMM, the ICER improved, approaching the important $100,000 threshold [24].

Similarly, Slaughter and colleagues recently compared costs and clinical outcomes data from patients enrolled in the HeartMate II DT trial who received a continuous flow LVAD with patients from the LVAD arm of the REMATCH trial [36]. The results demonstrated that inflation-adjusted costs were significantly lower in the continuous flow group, estimated at $193,812, as compared to the pulsatile flow group, estimated at $384,260. In addition, the authors report a significant decrease in mean length of stay from 44.7 to 27.2 days and a reduction in in-hospital mortality from 31 % to 8 % among continuous flow patients. Moreover, Rogers and colleagues recently demonstrated that the ICER of continuous flow devices was $198,184 per QALY which equates to a 75 % reduction in ICER compared to the $802,700 per QALY for pulsatile flow devices.

Despite improvements in clinical outcomes and cost effectiveness, however, current research demonstrates that there is room for continued improvement in reducing the economic burden of complications. Iribarne and colleagues studied the effect of post-operative complications on total hospital costs of LVAD recipients over a 7-year time period [37]. The results demonstrated that the most common complications included renal failure requiring dialysis, pneumonia, and unplanned return to the operating room, resulting in an average median increase in hospital costs of $123,966. Importantly, infections were among the most costly complications, with sternal

wound infection, LVAD pocket infection, and sepsis resulting in an average median increase in hospital costs of $250,227 and an average median increase in length of stay of 43.1 days.

Over a relatively short time, LVADs demonstrated significant improvements in clinical outcomes which have been largely the result of improvements in patient selection and device innovation resulting from clinical experience. Although initial estimates demonstrated that VADs were clearly far outside the range of what is generally considered cost-effective, improvements in outcomes correlate with reductions in cost, which has gradually led to more reasonable ICERs. Room for continued improvement does remain however. Inasmuch as VADs demonstrate the rapidity in which a given technology can improve, these devices also highlight the challenges of assessing a dynamic technology, where device innovation often outpaces clinical trials and a "learning by doing" approach affords future innovation. Such challenges not only face clinicians and clinical trialists in their assessment and implementation of medical devices, but also policy makers who must often make policy decisions on rapidly evolving technology.

Health Policy and Coverage Decisions

Different healthcare systems approach the evaluation and application of new technologies in different ways. European nations tend to put a greater emphasis on planning laws and payment policies to help shape diffusion than the US does. Planning laws target the dissemination of expensive, high technology device therapies, such as nuclear medicine imaging and open-heart surgery units, and reimbursement systems affect demand for all types of technology. Recently, the United Kingdom's National Health Systems have strengthened their analytical enterprise by creating the National Institute for Health and Clinical Evidence (NICE) to advise National Health Service (NHS) clinicians and administrators about the clinical and cost effectiveness of interventions by issuing clinical guidelines for specific medical conditions or individual technology appraisals [38]. About 140 of such appraisals were published by May 2008, of which 19 focused on medical devices. If technologies are found to be cost-effective, purchasers within the NHS are obligated to fund them. NICE elected not to support LVADs for destination therapy patients based on findings from their own cost-effectiveness analysis [23].

By contrast, Medicare, lacking cost-effectiveness as a criterion for coverage decisions, approved the LVAD for coverage. In addition, Blue Cross and Blue Shield Association (BC/BS), a private US insurer, approved reimbursement for VAD implantation. BC/BS has a well-established coverage decision-making process, and its Technology Evaluation Center (TEC) assesses about 15–20 technologies annually to provide guidance to health plans [39]. TEC not only calculated an exceedingly high ICER ($802,700/QALY) but found that "within the range of values used in this analysis, the ICER was fairly stable amid changes in these variables".

These observations highlight that while rigorous evidence is needed to guide clinical application and adoption decisions related to the introduction of new technologies, coverage decisions should not be binary "go/no go" decisions. Health care systems may need some flexibility to allow for short-term inefficiencies to garner long-term value. Among the criteria affecting coverage, cost effectiveness analyses can provide important guidance, but these ratios should not entirely drive the decision making process. Other considerations, such as equity concerns, if a clinical condition is life threatening or if the device is an emerging technology with serious prospects of improvement within a realistic period of time, should play a role as well. Approval of LVADs by the FDA, Medicare, and a number of private insurers, despite a widely recognized unfavorable ICER, allowed for expanding experience and improved clinical and economic outcomes.

BTT and DT

Most current VAD studies define patients as bridge-to-transplantation or destination therapy, with eligibility for transplantation being the distinction between the two. These are, however,

artificial labels devised for regulatory purposes and not exclusive categories of patients. The clinical characteristics that make a patient ineligible for transplant are dynamic. Similarly, with the adoption of alternate list criteria, even the clinical contraindications to transplantation are not fixed. For these reasons it is often difficult to clinically differentiate between DT and BTT patients.

Discussion to this point has focused on implantable VADs as DT, however, it should be pointed out that VADs in the BTT setting have been shown to be cost-effective [40] and comparable to other end-stage heart failure therapies such as biventricular pacers and ICDs. Future studies should avoid this classification system, and focus on all implantable VAD patients. Twenty-five percent of DT patients are ultimately transplanted [41] and therefore achieve prolonged survival after transplant, and a small number of patients are recovered with subsequent explanation. It is likely that if cost-effectiveness studies looked at all VAD patients (BTT, DT and recovery) results would be more generalizable and thus offer more clinically relevant data to guide the application of these devices.

Future Directions

VADs represent a rapidly evolving, "disruptive" technology that have and continue to have a significant impact on the management of patients with end stage heart failure awaiting transplantation as well as those with severe heart failure who are ineligible for transplantation. As with most forms of disruptive technology, VADs were introduced in a somewhat unrefined form, but quickly evolved through a "learning by doing" approach where clinicians directly involved with such devices in clinical trials helped inform the mechanics of future innovation and the medicine of optimal patient selection. Improvements in survival and morbidity over the past decade have translated into observed improvements in length of hospitalization, complications, total hospital costs, and ultimately cost-effectiveness. However, inasmuch as LVADs have evolved, they still represent a technology that is resource intensive in a heart failure population consuming healthcare resources at the extreme. Economic modeling suggests that LVADs have the potential to represent a cost-effective therapy, perhaps even in a functionally impaired, but less severe heart failure population. Continued assessment, however, is necessary. Assessing rapidly evolving technology is challenging as technological advancement often outpaces the clinical trials that establish a technology's safety and efficacy. Policy makers must understand the implications of such rapid technologic evolution when making coverage decisions, and more importantly understand that only through use of devices can innovation and improved clinical practice be realized. Investigators, likewise, must continue to refine patient selection to improve survival and reduce post-operative complications which continue to serve as significant predictors of total hospital costs. Just as LVADs continue to evolve with greater refinement, so too must our methods of economic evaluation evolve to encompass the dynamics and uncertainties of this rapidly evolving technology.

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