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The Status of Failure and Reliability Testing of Artificial Blood Pumps

SONNA M. PATEL,* AMY L. THROCKMORTON,* ALEXANDRINA UNTAROIU,† PAUL E. ALLAIRE,† HOUSTON G. WOOD,† DON B. OLSEN‡

Artificial blood pumps are today’s most promising bridge-to-transplant, bridge-to-recovery, and destination therapy solutions for patients with congestive heart failure. There is a critical need for increased reliability and safety as the next generation of artificial blood pump approaches final development for long-term destination therapy. To date, extensive failure and reliability studies of these devices are considered intellectual property and thus remain unpublished. Presently, the Novacor N100PC, Thoratec VAD, and HeartMate LVAS (IP and XVE) comprise the only four artificial blood pumps commercially available for the treatment of congestive heart failure in the United States. The CardioWest TAH recently received premarket approval from the US Food and Drug Administration. With investigational device exemptions, the AB-180, AbioCor, LionHeart, DeBakey, and Flowmaker are approved for clinical testing. Other blood pumps, such as the American BioMed-Baylor TAH, CorAide, Cleveland Clinic-Nimbus TAH, HeartMate III, Hemadyne, and MagScrew TAH are currently in various stages of mock loop and animal testing, as indicated in published literature. This article extensively reviews in vitro testing, in vivo testing, and the early clinical testing of artificial blood pumps in the United States, as it relates to failure and reliability. This detailed literature review has not been published before and provides a thorough documentation of available data and testing procedures regarding failure and reliability of these various pumps. ASAIO Journal 2005; 51:440–451.

As a viable option for over 40,000 patients each year in dire need of a heart transplant, ventricular assist devices (VAD) or total artificial hearts (TAH) are capable of providing supplemental mechanical circulatory support or complete heart replacement for patients with irreversible congestive heart failure (CHF). Currently, these devices are being used for bridge-to-recovery (BTR), bridge-to-transplant (BTT), and destination therapy support situations. With over 30 years of research and thousands of hours of reported clinical circulatory support time, it is reasonable to expect device failure rates (when used in the BTT application) to be < 1%. However, as with any mechanical or other type of device, blood pumps are also susceptible to failure, and now, because performance expectations are for long-term implantation, failure and reliability studies are critical. Researchers and developers must incorporate a failure and reliability data monitoring and tracking database into the design and testing of every blood pump. This must include a failure modes and effects analysis (FMEA), in vitro (hydraulic and mock loop) and in vivo (animal) experiments, clinical testing, and human factors evaluations.

Failure is defined as the inability of a device to operate within performance specifications over a prescribed period. The numeric value describing the probability that the device will perform its intended function satisfactorily for a particular period is the reliability. Currently, the term “failure” is not specifically defined by the US Food and Drug Administration (FDA), but rather by the individual researchers, designers, and manufacturers. Although the National Institutes of Health (NIH) have published guideline requirements, many manufacturers continue to define their own performance specifications. Although the FDA requires the submission of these data and analyses for investigational device exemptions and premarket approval (PMA), methods of failure and reliability testing with specific endpoints have not been standardized. Nevertheless, evaluation techniques for the design and clinical study of VADs have been recommended by the NIH, FDA, Bethesda Conference, Society of Thoracic Surgeons and American Society for Artificial Internal Organs (STS-ASAIO), and Association for Advancement of Medical Instrumentation (AAMI). Table 1 summarizes the standards set forth by these organizations. Designers, developers, and manufacturers have been completing studies for many years by applying methods and techniques developed by other scientists in the field. Because there are no formal and required testing procedures, each individual pump is tested under protocols varying from internal corporate determinations or those required by the FDA. This article presents a detailed discussion of study data to provide the scientific community with an in-depth perspective of failure and reliability in the field of artificial blood pump technology.

The blood pumps discussed in this article have been separated into three categories: commercially approved and clinically employed pumps, pumps in clinical testing, and pumps currently undergoing laboratory evaluation. We discuss the
Table 1. Device Performance Criteria

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Must not deviate from output flow rate for more than 30 seconds</td>
<td></td>
</tr>
<tr>
<td>Produce and maintain outlet 60 mm Hg</td>
<td></td>
</tr>
<tr>
<td>Maintain preload of 15 mm Hg</td>
<td></td>
</tr>
<tr>
<td>Average pump output 4 l/min</td>
<td></td>
</tr>
<tr>
<td>Two-year durability tests with 12 mock loops</td>
<td></td>
</tr>
<tr>
<td>80% reliability with 60% confidence</td>
<td></td>
</tr>
<tr>
<td>Maximum output flow rate of 8 l/min</td>
<td></td>
</tr>
<tr>
<td>Pressure rise of 110 mm Hg</td>
<td></td>
</tr>
<tr>
<td>Mean pulmonary pressure of 25 mm Hg</td>
<td></td>
</tr>
<tr>
<td>Small overall size, low infection</td>
<td></td>
</tr>
<tr>
<td>Five-year reliable function</td>
<td></td>
</tr>
<tr>
<td>Operate for 40–80 million cycles/year without replacement</td>
<td></td>
</tr>
<tr>
<td>Operational requirement of 90% reliability over 5 years</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Device</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIH (1986)</td>
<td>Device Readiness Testing Program for Blood Pumps</td>
</tr>
<tr>
<td>National Heart, Lung, and Blood Institute (1986)</td>
<td>Request for Proposal TAH</td>
</tr>
<tr>
<td>NIH (1994)</td>
<td>Request for Proposals for Implantable Ventricular Assist Systems</td>
</tr>
<tr>
<td>ABI-Baylor (1994)</td>
<td>TAH</td>
</tr>
<tr>
<td>Clinical Testing Guidelines</td>
<td></td>
</tr>
</tbody>
</table>

WorldHeart Novacor N100P, Thoratec VAD, and Thoratec HeartMate LVAS (IP and XVE) as the only four cardiac devices approved for commercial use in the United States. The CardioWest TAH recently received PMA, after the submission of a summary of safety and effectiveness data (SSEDD) to the FDA. Currently under investigational device exemptions, the FDA has approved the limited clinical use and testing of the AB-180, AbioMed ABioCor TAH, Arrow LionHeart, MicroMed DeBakey, and the Jarvik 2000 Flowmaker. Pumps that are still considered to be in the experimental evaluation phase include the American BioMed-Baylor TAH, Arrow CorAide, Cleveland Clinic-Nimbus TAH, Thoratec HeartMate III, Hemadyne, and MagScrew TAH. A summary of pump testing data is presented in Table 2.

Table 2. Commercially Approved Devices in the United States

<table>
<thead>
<tr>
<th>Device</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>WorldHeart Novacor</td>
<td></td>
</tr>
</tbody>
</table>

Successfully used as a BTT since 1984, the Novacor Left Ventricular Assist System (LVAS) is an electric, wearable system with a small electronic controller and a pair of rechargeable batteries. Since the initial design stages of the Novacor pump in the 1970s, three models have been the subjects of reliability testing. In an early attempt to begin failure and reliability studies, the first Novacor model (N120) was tested as part of an NIH Device Readiness Testing initiative to demonstrate device safety. Of the three VADS tested in this program, the Novacor was the only device to successfully pass the 2-year test. Following an improvement of the N120, the N100P was introduced with a wearable controller and later tested. The N100P was optimized in 1991 and clinically introduced as the new and improved N100P in 1993. Optimizations included new sealed bearings in the solenoid actuator, reductions in acoustic noise, and flow path improvements.

N120 and N100P

In 1988, the N120 was tested in 12 mock circulatory loop systems. The mock loop was designed to simulate human physiologic conditions including specific flow rates and pressures. By NIH standards, a failure was defined as a deviation from the design flow rate for more than 30 seconds, and more frequently than once an hour during continuous operation in the mock loops. A failure was also considered to have occurred if the pump could not produce and maintain an outlet pressure of at least 60 mm Hg. The systems were continuously monitored by a dedicated computer; fluctuations in the flow rate, inlet and outlet pressures, and power were recorded every 2 seconds. The 12 systems had been running continuously for a cumulative 14.3 years with an average of 14 months per pump and no failure occurrences according to Jassawalla et al. At the time of publication, the estimated overall reliability for a 2-year period was 88% with 60% confidence, exceeding the suggested NIH recommendation of 80% reliability with 60% confidence. Final performance data were published in the NIH Device Readiness Testing report and stated a cumulative 26.6 years of failure-free operation with mean test duration of 2.2 years. The expected 2-year reliability for 60%, 70%, and 80% confidence was 93, 91, and 89%, respectively.

Examples of performance degradation included: errors in the displacement transducers and flow rate reduction due to a leak. The report also discussed operator error including calibration errors, parameter adjustment errors, improper adjustments, power disconnects, and obstructed loop outflow. There were no apparent failures.

Following these mock loop experiments with the N120, the N100P was also tested for 2.9–3 years without failure. A 2-year reliability of 88% with 60% confidence was also achieved for the N100P.
Table 2. Summary of Available Device Performance Data

<table>
<thead>
<tr>
<th>Commercially Approved Devices in the United States</th>
<th>In Vitro Reliability</th>
<th>In Vivo Reliability</th>
<th>Clinical Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Novacor N120</td>
<td>88%; 60% confidence</td>
<td>No demonstration of device failure</td>
<td>Overall: 99.4 1 year</td>
</tr>
<tr>
<td>Novacor N100P</td>
<td>88%; 60% confidence</td>
<td></td>
<td>91.5% 2 year</td>
</tr>
<tr>
<td>Novacor N100PC</td>
<td>93%; 60% confidence</td>
<td></td>
<td>91.5% 3 year</td>
</tr>
<tr>
<td></td>
<td>Final testing:</td>
<td></td>
<td>(95% confidence)</td>
</tr>
<tr>
<td></td>
<td>99.9% 1 year</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>98.5% 2 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>87.4% 3 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(80% confidence)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thoratec VAD</td>
<td></td>
<td>18% of 67 patients had mechanical failures</td>
<td></td>
</tr>
<tr>
<td>HeartMate IP LVAS</td>
<td>93.5%; 90% confidence 2 months</td>
<td>35% device failure at 24 months No failures up to 12 months</td>
<td></td>
</tr>
<tr>
<td>HeartMate VE LVAS</td>
<td>84.7%; 1 year</td>
<td></td>
<td>8.2% failures of VE compared with 2.6% XVE failures after improvements</td>
</tr>
<tr>
<td>HeartMate XVE LVAS</td>
<td>Used data from device-tracking database to make improvements to VE LVAS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Investigational Devices in the United States</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AS-180</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AbioCor TAH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LionHeart LVAS</td>
<td>12 systems accrued 5,200 total hours/105-592 days</td>
<td>Longest survival was 244 days</td>
<td></td>
</tr>
<tr>
<td>DeBakey VAD</td>
<td>19 calves; survival up to 145 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HeartMate II</td>
<td>6 calves; all survived 90 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flowmaker 2000</td>
<td>51 calves, longest survival 200 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CardioWest TAH</td>
<td>11 units run over 6 years with no device failures</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>99% 30 days</td>
<td>10 patients survival beyond 6 months</td>
<td></td>
</tr>
<tr>
<td></td>
<td>98% 60 days</td>
<td>184 patients</td>
<td></td>
</tr>
<tr>
<td></td>
<td>88% 1 year</td>
<td>First patient survived 6 months</td>
<td></td>
</tr>
<tr>
<td></td>
<td>90% confidence</td>
<td>5-year support time of one patient</td>
<td></td>
</tr>
<tr>
<td>Devices in Experimental Evaluation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABI-Baylor TAH</td>
<td>Tested in Baylor mock loop</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Recognized importance of failure identification and corrective actions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CorAide VAD</td>
<td>31 calves tested&quot;reliable&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCF-Nimbus TAH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HeartMate III VAD</td>
<td>Consistent pump output between 3 and 6 l/min</td>
<td>Animal survival: 40, 27, 49, 42, 49 days</td>
<td></td>
</tr>
<tr>
<td>Hemadyne VAD</td>
<td>Subjected VAD to potential failures inlet/outlet blockage impeller imbalance bearing failure deposition on impeller</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MagScrew TAH</td>
<td>Tested in mock loop</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Empty boxes indicate that data were unavailable at the time of publication. MST, mean support time; N/A, not applicable.

N100PC

In one of the few publications to present specific reliability data about the N100PC, Lee et al.9 identified several steps taken to add system reliability, most importantly, maintaining a simple design and reliable components. For example, controller components were fabricated using proven reliable processes. Redundant power sources support the controller and prevent interruption of pump operation. The power packs were designed to incorporate warning circuitry to identify internal cable faults or to warn of impending energy discharge. Extra-corpooreal components that can be easily replaced have also been made available to provide a practical solution to component failure.9 The N100PC received PMA from the FDA in 1998 after in vitro, in vivo, and clinical tests. Reliability studies involved submerging 12 units in saline at 37°C and testing the units under different load conditions using mock loops. Failure was defined as the inability of the device to maintain an average pump output of 4 l/min, an afterload of 60 mm Hg, and/or a preload of 15 mm Hg or less.10 The cumulative test duration was 50.5 years with an average duration of 4.2 years per system (the longest duration of operation was 5.59 years). All 12 units exceeded 3 years of operation without failure.11 During in vitro testing, the first failure occurred after 3.04 years due to wear of the energy converter main shaft and bearing. A 97% reliability was achieved at a 60% confidence level for a
1-year mission time. A commonly used exponential reliability model was employed to describe random failures that can occur during the lifetime of a group of devices.

An SSED, submitted to the FDA for the N1000PC, contains comprehensive information concerning the final mock loop reliability testing. Multyear reliability calculated for the N1000PC, according to a Weibull model with 80% confidence, was 99.9% for 1 year, 98% for 2 years, and 86% for 3 years. After 3 years of successful testing, the pumps were run until failure. The types of failures were not specified in the publication.

Animal testing of the N1000PC systems was also conducted in twelve male sheep with no demonstration of device failure or abnormalities. Clinical data in the SSED also showed zero events of mechanical and electrical failures, including no pump/drive failures and no control system failures. A complete verification and validation of the integrated systems was performed; display accuracy, alarms, interconnections, human factors, environmental limits, packaging, and electrical safety and electromagnetic compatibility demonstrated performance to, or within, applicable standards.

One of the first clinical trials with N1000PC occurred in Europe between 1993 and 1996 with a cumulative test time duration of 24.8 years. There were no catastrophic device failures. Although this study was not initiated with the goal of identifying specific failures, it was noted that one patient suffered high residual volume in the pump, secondary to a kinked outflow graft. Four others experienced nonlethal system failures, as seen in Table 3, where a description of the failure is stated with implemented corrective actions. Although these solutions are practical, the resulting system does not eliminate the need for a long-term, effective solution for such device-related failures.

Between 1996 and 1998, a multicenter trial of the N1000PC was conducted across the United States. The aforementioned experimental and clinical tests played a major role in the final FDA approval of this pump for use in patients. Of the 129 patients participating in the US clinical trial, 75% were considered successes. From European clinical trial data from 1997 to 2001, 37 recipients were monitored after 1 year of mechanical circulatory support by following the Durastudy protocol. This protocol involved five methods of extensive evaluation for patients with an implant, including patient monitoring (electrocardiogram, vitals, blood pump monitoring), data collection during fill and empty modes of the pump (tuning values, failsafe current, energy changes, and engineering parameters), exercise testing, driveline sampling for metallic particles, and patient medical and clinical history. These evaluations were used to develop device lifetime predictions based on characteristic downward trends in position sensor signaling, drift followed by an abrupt increase in energy, cyclic variations in sensor tuning, metallic content in the vent filter, and isolated, incomplete ejections resulting from premature misfire. There were two categories of detection: 1) early wear, with a remaining life of 3–6 months; and 2) late wear, with a remaining life of 1–3 months. Despite ongoing clinical trials, the FDA approved the Novacor N1000PC LVAS for patient use in September 1998.

In addition to clinical trials and testing the device within the patient, it is also valuable to evaluate LVAS performance during electromagnetic interference. Patients requiring a VAD are also likely transported to a hospital via helicopter or on vacation by airplane. An electromagnetic interference environment was simulated in the lab, followed by testing it in a mock circulatory loop during airborne flight. Long-range electronics, the global positioning system, course deviator indicator, and distance measuring equipment were examined over high- and low-frequency components in the operating range of the aircraft electronics. At both high (> 1.08 MHz) and low (< 450 kHz) frequency ranges, where aircraft instrumentation and controls operate, the pump did not interfere with the instrumentation and controls of the airplane. The nominal parameters were stated to be 5.6 l/min, a pump rate of 102 beats per minute, a stroke volume of 55 ml, and a residual volume of 13 ml. The pump operated under these conditions without incident. Actual patient experience was also used to validate the test experiments when the first flight with a patient occurred in 1996 on an international flight from Japan to California. Since then, over 37 flights have occurred with devices showing no interaction with aircraft electronics.

More recently, in more than 1,500 device implants there have been no deaths attributed to device failures. The only long-term failure of the device is wear of the main pump bearing. This is detectable with noninvasive parameter interrogation.

**Thoratec VAD and HeartMate LVAS**

The FDA has approved two Thoratec devices for commercial use: the Thoratec VAD and the HeartMate LVAS. The Thoratec VAD is approved for left or right and biventricular support for BTT. The HeartMate LVAS has been approved as an implantable pneumatic (IP) or vented electric (VE) LVAS for BTT. Furthermore, the XVE LVAS is the only artificial blood pump with PMA for destination therapy.

**Thoratec VAD**

The Thoratec VAD is a paracorporeal system powered by an external dual drive console or by a TLC-II Portable Driver, which improves patient mobility. It was approved in 1996 for use as a BTR or BTT. For this device, mock loop systems were used to test the controller algorithm. It uses LabView as the graphical development environment for data and signal acquisition measurement analysis, data presentation, and closed loop control. Eight systems were controlled in a mock loop for 6 months without interruption or failure. Additionally, during animal trials, the controller successfully functioned in two healthy animals for 45 continuous days. In this case, the

### Table 3. Device Complications from a European Study with the Novacor N1000PC

<table>
<thead>
<tr>
<th>Type of Failure</th>
<th>Description</th>
<th>Action</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinked outflow</td>
<td>High residual volume</td>
<td>Reoperation</td>
<td>Transplant</td>
</tr>
<tr>
<td>System failure</td>
<td>High eject current, 3x fail-safe</td>
<td>Controller changed</td>
<td>Transplant</td>
</tr>
<tr>
<td>System failure</td>
<td>Autozero out of range</td>
<td>No defect found</td>
<td>Ongoing</td>
</tr>
<tr>
<td>System failure</td>
<td>Clogged filter</td>
<td>Filter changed</td>
<td>Transplant</td>
</tr>
</tbody>
</table>
reliability bench testing provided valuable information for the FDA application submission.

In a retrospective study, the first 111 patients implanted with the Thoratec VAD were reviewed. Of the 111 patients, 44 were implanted as BTR, and 67 were BTT. Of the BTR patients, one mechanical failure occurred and was readily corrected (the failure is not specified). Mechanical failures occurred in 18% of the BTT patients and, according to McBride et al., they were usually minor inconveniences resulting in no harm to the patient.

From the earliest clinical trials, Thoratec Corporation has been making improvements to the original Thoratec VAD. It has since evolved into the current device with improvements to the cannulation and connector systems, fabrication of the pumping chamber and cannulas from a special elastomer, and a microprocessor-based pneumatic control console. Although it is not designed as a permanently implantable device, it has established a reliable history of BTR and BTT for patient use.

HeartMate IP LVAS

The HeartMate IP LVAS, the original HeartMate, is an implantable pump with an external power source that drives the pusher-plate creating pulsatile flow. After 9 years of clinical trials, the IP LVAS became the first commercially available VAD in 1994. Published literature for the IP LVAS is limited for mock loop and animal trials; however, there is some evidence of clinical testing. In a retrospective study in 1995 of device usage between January 1986 and October 1994, 133 patients survived to transplantation. Although there were adverse effects such as infection, neurologic dysfunction, and right heart failure, no device malfunctions were reported during the study. As of May 1997, another 753 patients were implanted with the IP LVAS. During this trial, pump sensing failures, pump drive-line rupture, inflow conduit valve perforation, console safety fuse failure, and console battery malfunctions occurred, as shown in Table 4. It is unknown whether any patient deaths resulted from these device failures. Furthermore, during another clinical test with this device, physicians noted a rupture of the inflow conduits in multiple patients described by Scheld et al. It was hypothesized that the metallic cage covering the Dacron tube was responsible for these tears. Of the two cases, one patient died due to a massive cerebral air embolism, ultimately caused by air entering the pump via the Dacron tear. These reports resulted in a redesign of the metallic sheath to reduce the risk of future tears.

In another study, investigators report on IP LVAS as "remarkably free of mechanical failures." Nevertheless, a pneumatic driveline separation from the pump housing was discovered while the pump was implanted in a 50-year-old male patient. Although this is the first report of such a malfunction, rapid diagnosis and appropriate management are important in these cases. With proper algorithms for failure inspections, detection, and diagnosis, situations such as these could be preventable.

HeartMate VE LVAS

The VE LVAS, similar to the HeartMate IP LVAS, is powered by an electric motor that displaces the pusher plate of the diaphragm. Documentation for FDA approval was submitted in 1998 with an SSED that included studies for in vitro, in vivo, and clinical testing. Additional published reliability and failure studies have supported the claim that patient quality of life has significantly improved; however, there have been complications with device implants such as kinking of the outflow conduit and system failure.

Published studies from the SSED show that the VE LVAS demonstrates a 2-month reliability of 93.5% based on a 90% confidence interval in mock loop testing. No critical failures were observed during this time. There is an 84.7% probability that the device was failure-free after 1 year of use. The cumulative test time was 49.1 years of support. The clinical studies revealed 1 failure out of 148 device failures, but did not specify the actual failure.

In a clinical report of a 60-year-old male patient with a VE LVAS implantation, blood pump failure was detected by a distinctive pattern noted on the electrocardiogram. A standard 12-lead electrocardiogram evaluation was completed and confirmed periods of electrical current excitement synchronous with the LVAS. A postmortem examination revealed blood clotting over the stator, magnet, and cams. The motor can draw an additional 5 A current when there is increased resistance to pumping. With this increased resistance, if blood enters the pumping chamber, a series of high current spikes are visible on the patient's electrocardiogram. Another reason for this may have been current leakage due to blood contamination in the motor compartment. Piccione et al. suggest that a pattern of this type should "alert the clinician to potential impending failure." Although this was only one type of detection test, valuable information was obtained regarding potential failure prevention.

A multicenter trial, the Randomized Evaluation of Mechanical Assistance for the Treatment of Congestive Heart Failure (REMATCH), compared long-term implantation of the VE LVAS to conventional medical therapy. Although the FDA had already approved the pump for clinical use, physicians wanted to learn more regarding optimal pharmacologic management compared with long-term mechanical circulatory support patients who were not eligible for cardiac transplantation and to further evaluate device reliability. A total of 129 patients were enrolled in the study; 68 received the VE LVAS and 61 were

Table 4. Thoratec IP LVAS and VE LVAS Performance

<table>
<thead>
<tr>
<th>Malfunction</th>
<th>Number of Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>IP LVAS</td>
<td></td>
</tr>
<tr>
<td>Pump-sensing failure</td>
<td>3</td>
</tr>
<tr>
<td>Pump drive-line rupture</td>
<td>1</td>
</tr>
<tr>
<td>Inflow conduit valve perforation at explantation</td>
<td>1</td>
</tr>
<tr>
<td>Console safety fuse blow-out</td>
<td>3</td>
</tr>
<tr>
<td>Console battery malfunction</td>
<td>5</td>
</tr>
<tr>
<td>VE LVAS</td>
<td></td>
</tr>
<tr>
<td>Inflow conduit valve dysfunction</td>
<td>1</td>
</tr>
<tr>
<td>Inflow conduit valve perforation at explantation</td>
<td>1</td>
</tr>
<tr>
<td>Corrosion and rust in pump</td>
<td>2</td>
</tr>
<tr>
<td>Alarm malfunction</td>
<td>2</td>
</tr>
<tr>
<td>Battery malfunction</td>
<td>1</td>
</tr>
</tbody>
</table>

IP LVAS, implantable pneumatic left ventricular assist system; VE LVAS, vented electric left ventricular assist system.
treated with medications. The probability of device failure was 35% at the end of 24 months with no device failures up to 12 months. Mechanical parts failures, such as the rupture of the pump lining, motor failure, and bearing wear, were noted to limit device durability and reliability.26 Data regarding the inflow valve failure and late erosions of the outflow graft secondary to kinking were used to make improvements upon the device, later introduced as the HeartMate XVE.

**HeartMate XVE LVAS**

The HeartMate XVE LVAS is the result of slight design improvements introduced after the VE LVAS had already supported 2,300 patients. After a retrospective study of 1,865 devices and their performance (1998–2003), design improvements were made to the percutaneous leads, the flow path, outflow conduit, and system controller.27 Data were obtained from a device-tracking and complaint-handling database. Furthermore, this study tested the hypothesis that the XVE had increased reliability. Serious mechanical failures were defined in the study as inflow valve dysfunction, percutaneous lead breaks, outflow graft erosions, pump disconnects, diaphragm fractures or punctures and bearing failures. The VE LVAS experienced a total of 8.2% device failures as compared to 2.6% failures for the XVE LVAS. With over 75 years of BTT, the HeartMate XVE was approved as a destination therapy device in 2002 to support patients not eligible for cardiac transplantation.27

**Reliability Comparison of Novacor and HeartMate LVAS**

Both the Novacor and HeartMate devices, approved by the FDA for the treatment of end-stage CHF, have been compared in various studies of device safety and reliability. At a single center study in the United States from 1996 to 1998, the Novacor N100 and HeartMate VE LVAS were utilized to treat patients awaiting cardiac transplantation.28 The same team performed the surgical procedure with each pump. The hemodynamic outcome of each patient was comparable; however, in terms of reliability, the HeartMate performed poorly compared to the Novacor LVAS. Software faults in the HeartMate’s controller led to decreased system performance. There were also driveline cracks due to the usage of the pump (> 300 days). In one patient, fluid in the motor compartment 8 weeks after implant led to failure of the HeartMate. In a second patient, failure occurred after 14 months due to cracks in the membrane, causing blood to enter the motor chamber. Failure of the motor commutator also occurred in another patient. Compared to the Novacor, there were 3 HeartMate failures in a population of 27 patients, and no device failures in a total of 76 patients with the Novacor. While these failures were noted, no comment was made regarding a possible solution to prevent future HeartMate failures.

A retrospective study by the medical and surgical directors at the Washington University Medical School at Barnes-Jewish Hospital was completed to offer clinicians more objective information (than previously available) when choosing a device to use to treat their patients. Comparing the HeartMate VE and Novacor, data obtained from in vitro durability testing by the manufacturers were subjected to 90% confidence intervals. These reliability values are presented in Table 5. Each device was operated to failure or to a fixed termination period. According to the data after 1 year, on average 1 in 10 patients would have a serious device component failure of the HeartMate with an average implant time of 112 days (to date, 2- and 3-year data have not been published for the HeartMate). However, 72% of these patients would survive until transplant when the backup components were used. For comparison, during the REMATCH trials, there were no system failures of the HeartMate that occurred over 12 months of testing. Beyond 12 months, there were inflow valve failures and outflow graft erosion resulting from kinking. Mechanical parts also malfunctioned, including rupture of the lining, motor failure, and bearing wear.26 For 2 years, device failure was estimated to be 35%.

The Novacor has less reliability information readily available than the HeartMate due to the early status of the clinical trial of Investigation of Non-Transplant Eligible Patients who are Not Inotropic Dependent (INT:EPID). WorldHeart initiated this trial in an effort to demonstrate safety and efficacy of the Novacor N100PC. Successful trials have already shown seven patients supported beyond 3 years and two of these patients beyond 4 years. The wear of the pump bearing and shaft, as discussed earlier, are the only concerns that have been addressed.1,13,15

Noria et al.29 analyzed 274 BTT experiences. Between the Novacor and HeartMate VE and IP, there were 20 instances of device malfunction in the HeartMate and 1 in the Novacor. HeartMate device failures were caused by late inflow valve assembly bleeding, driveline fracture, controller failure, inflow cannula dislodgement with exanguinations, outflow graft obstruction, aspiration of blood into driveline vent, and two unexplained pump failures. Based on this study, failure-free operation was stated to be 96%, 90%, 86%, and 82% at 30 days, 3, 6, and 12 months, respectively (with 68% confidence limits).29

**Table 5. Reliability Data for HeartMate VE LVAS and Novacor N100PC**

<table>
<thead>
<tr>
<th>Device</th>
<th>2 Months</th>
<th>1 Year</th>
<th>2 Years</th>
<th>3 Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>HeartMate LVAS VE</td>
<td>93.5%</td>
<td>84.7%</td>
<td>Unavailable</td>
<td>Unavailable</td>
</tr>
<tr>
<td>Novacor N100PC</td>
<td>&gt;99.9%</td>
<td>&gt;99.9%</td>
<td>98.3%</td>
<td>85.9%</td>
</tr>
</tbody>
</table>

**Investigational Devices in the United States**

Companies apply for confidential investigational device exemption status when they are ready to clinically test their devices on patients. Based on available literature and press releases, there are five devices that fall into this category: the AB-180 centrifugal pump, AbioCor Implantable Replacement Heart, Arrow LionHeart, MicroMed DeBakey, and the Jarvik 2000 (FlowMaker). These devices have been tested in patients, after extensive in vitro (mock loop) and in vivo (animal) testing, and are currently awaiting clinical data to apply for PMA. The CardioWest TAH recently received PMA from the FDA. This status is usually reserved for those devices that prove safety and efficacy based on experimental testing.
AB-180 Centrifugal Pump

The AB-180, an implantable centrifugal pump developed at the Allegheny General Hospital, receives inflow from the left atrium and the outflow cannula is anastomosed to the ascending aorta. This pump was tested in sheep with a surgically compromised circulatory system. Sheep were induced with a myocardial infarction; "failure" was introduced into the system by purposely kinking the inflow cannula at a 90-degree angle. This enabled the study of effects of thrombus formation and thromboembolic occurrence. After viewing the impeller after infarct, a fibrin film was discovered despite heparinizing the animal. The alarm systems activated due to extreme deviations from design pressures and flow values, in addition to AC power failures. The alarm sensors acted appropriately and performed to specification. Three incidences of controller failure occurred because of an undercharged battery, failure to start the pump before implant, and one due to low impeller speed. Failures such as these should be detected early on during mock loop testing or by performing a FMEA. Solutions to these observed failures were not proposed.

This pump was used in 17 patients between 1997 and 2000. The mean circulatory support duration was 8.5 days. Magovern et al. reported no major device-related complications, and the AB-180 is reliable. Today, the AB-180 is no longer developed. Instead, the technology of this device has been utilized to develop a short-term (30 days), centrifugal, percutaneous VAD, called the TandemHeart pVAD.

ABIMED AbiCor TAH

The FDA approved the AbiCor TAH for clinical trials in 2001. A thorough literature search did not provide published data for in vitro and in vivo testing or reliability data for the AbiCor TAH. In a press release from ABIMED, they state that their replacement hearts meet the "company's reliability criteria" under its ABIMED Reliability Growth and Qualification Program. However, supporting data for this research have not been published. In vivo implantation occurred in 12 calves from 1998 to 1999. Only one death was attributed to device failure; however, there is no record of the actual cause of failure or attempts made to provide a solution. There was a claim that the experience with the bovine model "has demonstrated excellent function..." with maintenance of normal hemodynamic parameters and normal end-organ function. Adequate tissue perfusion was also demonstrated in the animals.

In a clinical trial, initiated in 2001, the AbioCor was implanted to examine the effect of the pump in patients with end-stage CHF. Secondary purposes were to determine adverse events from the pump, evaluate device malfunctions, and understand complications related to the presence of the device. After seven male patients were implanted, one had to have the internal battery replaced after 10 months. The pump system operated satisfactorily, although the pump skipped two beats in one patient due to a delayed hydraulic oil valve switching. There were no device-related infections and "early results...have demonstrated excellent function of all device components."

Over 14 patients have been implanted with the AbiCor TAH, with patients surviving beyond 60 days and 120 days. In a recent press release, AbioMed announced that they had submitted for special market approval of the AbiCor under the humanitarian device exemption. This would allow implantation of the device in very specific subset of no more than 4,000 end-stage heart failure patients. Shortly thereafter, the thirteenth patient died after 147 days of support due to device-related complications. The patient with the longest survival rate lived for 513 days on the AbiCor and was discharged home.

Arrow LionHeart

The Arrow LionHeart VAD is a completely implantable, pulsatile, volume displacement pump. It is the first pump to undergo clinical testing specifically as destination therapy for the treatment of HF and is the first pump to be completely implantable with a transcatheter energy transmission system. Initially developed at Pennsylvania State University, the LionHeart was tested in animals with the longest survival of 244 days. In all studies, the experiment was terminated due to device failures. Tubing was kinked; solder was found to have migrated across the tuning capacitor terminals; a small lesion developed in the skin, but remained stable, or failure was due to a defective Hall sensor. Weiss et al. remark that four failures were direct causes of poor soldering. There were no failures in the controller electronics or the implanted batteries. Solutions to these failures were proposed, though not specified in the publication and further testing was planned.

The early work at Penn State provided a foundation for the LionHeart, which was jointly developed with Arrow. Preclinical system performance testing of the LionHeart began in 1998 and 12 systems had accrued a total of 5,200 hours in mock loops by 2000, ranging from 105 days to 892 days.

In vivo system performance and reliability testing consisted of implanting 13 animals for intended support time of thirty and ninety days. System failures included controller and cable failures. The early in vivo studies resulted in modifications and optimizations to the system. Preclinical studies demonstrated that external components could withstand daily activities, and that the implantable components were reliable for the specified, 90-day study period.

As of 2000, six patients in Europe were implanted with the LionHeart. There were no reported system failures and no device-related deaths. In one patient, however, the internal battery had to be replaced after 22 months because of wear out. A controller/controller problem occurred during pump operation in another patient, but according to investigators this was not considered hazardous. As of 2003, 10 patients had been implanted with this device in the United States with patients surviving beyond 6 months. The longest survivor was 1,258 days (nearly 3.5 years) with one controller replacement due to a worn out battery.

In a recent press release, Arrow International, Inc. announced the decision to discontinue the development, sales, and marketing of the Arrow LionHeart.

MicroMed DeBakey VAD

The DeBakey VAD is designed to be a safe, compact, effective, reliable, simple-to-operate, affordable axial flow pump. It is designed to achieve 5 l/min against 100 mm Hg pressure,
at a speed of 10,000 rpm. In 1999, 19 calves were implanted with this pump and monitored during and after surgery, with one surviving up to 145 days. At postmortem, organs and tissue were evaluated for evidence of thrombosis and other abnormalities. The pumps were also disassembled and inspected. In one animal, a myocardial muscle remnant became lodged in the pump as a result of surgical coring, causing the impeller to cease rotation. In another, there was a kink in the outflow graft, and in two others there was damage to the percutaneous cable assembly, leading to wire corrosion. A recording of pump current demonstrated no variability, indicating normal operation. Distorted current waveforms could indicate bearing obstruction or wear. A second study was completed in 2001 using four male and two female calves. The following complications were noted: bleeding, cardiovascular abnormalities, hemolysis, hepatic dysfunction, renal dysfunction, infection, and thromboembolism. Based on previously established guidelines, bleeding was considered to be minimal. There were also no abnormal thromboembolic events. All calves survived for 90 days.

As of November 1999, 18 patients in five countries had been implanted with the DeBakey VAD. Patients were supported from 9 to 119 days. Ten patients remained on the pump beyond 30 days; of these, six survived beyond 60 days. The average flow was maintained from 3.7 to 4.4 l/min for 9,600–9,900 rpm with 9.3–12.2 W power consumption. Two patients were implanted with a second pump. One patient suffered pump stoppage due to an embolus, the other due to a malfunctioning connector. The connector malfunction was resolved through corrective manufacturing actions.

Between November 13, 1998, and July 7, 2002, 150 patients were implanted with the DeBakey VAD. The longest support time was 441 days; 12 patients were supported for at least 6 months. According to the researchers, there was a 3.3% incidence of device infection, 11.3% incidence of pump thrombus, and 2.7% incidence of mechanical failure. The mechanical failures were identified as a recessed connector (n = 2), a broken wire (n = 1), and a controller failure (n = 1).

By April 23, 2003, 184 patients (including 30 in the United States) underwent device implantation. The longest bridge to transplant support time was 492 days, with a cumulative support time of 44.2 years, and 24 patients surviving beyond 6 months. The data from these recent trials suggest that 50–66% of patients can survive BTT.

According to an article discussing the safety and feasibility trial of the DeBakey VAD, published in 2005, 30 patients survived the implantation operation. The cumulative VAD support time was 42 months with 67% of patients successfully bridged to transplant.

Currently, the DeBakey VAD is being tested in a new clinical trial called the Destination Evaluation Long-Term Assist (DEXTALTA) and is being compared in a patient randomization scheme of 2:1 ratio of DeBakey to HeartMate XVE pumps. There is no published data because of the early stages of this trial.

**Thoratec HeartMate II**

The HeartMate II was originally developed as the Nimbus/University of Pittsburgh implantable ventricular assist system in 1991. It is an axial flow blood pump featuring a rotor that spins on two bearings and an electronic controller. The device, as reported by Butler et al., has been tested in 19 calves and appears to be well tolerated. There was no evidence of hemolysis or consistent mechanical problems. It was noted by the authors that it might be possible to sense house vibrations, due to the bearings. Should the vibrations of the housing change due to bearing wear, it can be detected by accelerometers. This is proposed as an early method of pump fault detection.

In 1998, the HeartMate II was acquired from Nimbus. With a transcatheter energy transmission system and one moving part, the rotor (which spins on the inlet and outlet ball-and-cup bearings), the pump is targeted for long-term use. As of 2001, the pump had been implanted in 51 animals for mean support duration of 47 days. Performance, biocompatibility, controller response, and mechanical wear were evaluated. The autopsies of the calves showed no signs of thromboembolism, and hemolysis levels remained within acceptable levels according to the reports. For this study, the longest support duration lasted over 200 days. Further testing of the VAD demonstrated an expected ball-and-socket bearing life of at least 5 years.

The first clinical trial occurred in Europe (2000) as an investigational device. After poor outcomes because of initial design issues, the HeartMate II was redesigned and is currently undergoing clinical trials in the United States. Originally, the VAD had an interior coating that was successful at trapping blood. A smooth, titanium surface was selected for the modification. More than 6 months after being implanted, the first patient supported by this device to transplant was successfully rehabilitated with no complications.

**Jarvik 2000 FlowMaker**

A completely implantable axial flow VAD, the Jarvik 2000 FlowMaker contains only one moving part in the system, the rotor. The rotor is suspended by ceramic bearings, as blood flows through a fluid gap. System performance was monitored when this pump was implanted into 37 healthy calves between 1991 and 1999. Output from the external control and power unit (which were not implanted) was monitored. During an average of 107 days, renal function and plasma free hemoglobin remained in normal ranges. The rotational speed of the device was maintained at 10,000 rpm, with a flow rate of 5–6 rpm. These studies were electively terminated due to a broken electrical wire, thrombus formation at the rotor, impeller friction against the housing, and infection. Bearing wear was not noticed in any pump. Although these failures were identified, a complete analysis of the failures with potential solutions was not presented. Future improvements included modifying the power pack to incorporate rechargeable batteries and titanium encased control system. Shortly after these observations, the Jarvik 2000 underwent reliability testing for individual components. Cable leads were tested by applying motion in the X, Y, and Z directions. The pump bearings were tested in a mock circulatory loop using heated saline and a simulated pulsatile left ventricle.

Clinical trials for the device began in 2000. Three patients received the device, and none had experienced device related problems. Patients have been sustained for more than 200
days, according to the Texas Heart Institute\textsuperscript{64} and this device has now been used in over 100 patients.\textsuperscript{57}

Most recently, Jarvik Heart, Inc. announced the 5-year anniversary of support for a lifetime-use patient in Europe. Additionally, the company has received conditional approval to begin a clinical trial of the Jarvik 2000 FlowMaker for BTT use in 160 patients. The primary endpoint of the study will be successful BTT or survival for up to 6 months and secondary endpoints include measures of quality of life, neurocognitive function, and rates of serious adverse events.\textsuperscript{58}

**Syncardia CardioWest TAH**

The CardioWest TAH is a pneumatic, pulsatile, biventricular, BTT device designed to replace a patient's entire heart. Because of its large, external console, patients in the United States cannot be discharged from the hospital. In 81 patients, there was a 79% survival rate to transplant, compared with a 46% survival in patients who did not receive the TAH.\textsuperscript{59} In a device safety and efficacy study from 1993–2002, 19 device malfunctions and 11 technical/procedural problems were discovered. Of these, only one, a perforated ventricular diaphragm, was deemed "serious," resulting in patient death. Corrected by surgery, a "poor fit" of the device was reported in another patient. All other events occurred within the external components and were easily addressed. No other device malfunctions were reported in over 12,000 days (32 years) of patient use.

According to the SSRO, in vitro studies were completed to demonstrate that the TAH system met intended specifications.\textsuperscript{60} These evaluations included pull and torque tests on ventricle-to-connector joints and the driveline, controller performance of alarms and system connections, battery longevity, electrical safety, and software. A total of 11 units were run (at various times each) over 6 years with no device failures. With a 90% confidence, after 30 days, device reliability was 99%, after 60 days it was 98%, and after 1 year it was 88%. Fifteen patients experienced 18 device-related malfunctions. Most of these incidents were kinks from patients rolling or sitting on their drivelines and 5 out of 18 drivelines leaked. One diaphragm tear led to patient death.

In a recent press release, Syncardia, Inc. announced that the CardioWest was approved by the FDA for use in patients with biventricular failure who are expected to die within 30 days. Because of the small number of patients enrolled in the clinical study, the FDA is requiring that 50 patients implanted with this device be monitored for 1 year.\textsuperscript{61}

**Devices in Experimental Evaluation**

The ABI-Baylor TAH, Arrow CorAide centrifugal pump, Cleveland Clinic–Nimbus TAH, Thoratec HeartMate III centrifugal pump, Hemodynamic centrifugal pump, and MagScrew TAH have reached various stages of development, experimental evaluation, and optimization. Some investigators have published data from mock loop studies, whereas others have published data regarding animal experimentation. As of publication date of this article, none of the pump manufacturers have submitted data regarding an FMEA or upcoming clinical trials.

**ABI-Baylor TAH**

In 1994, before blood pump testing recommendations from STS-ASAIO, the Department of Surgery at the Baylor College of Medicine developed the American BioMed (ABI)-Baylor TAH. It was tested in the Baylor mock loop, which consisted of right and left venous compliances with an 8:1 volume ratio.\textsuperscript{62} Compliance was adjusted by changing the volume of air over water in sealed chambers. Failure criteria were specified as a maximum flow < 3 l/min over 30 seconds with 20 mm Hg inflow pressure or a mean outflow pressure < 60 mm Hg. Orime et al.\textsuperscript{62} reported that in case of a failure, the cause would be determined and the status of system components would be documented. Although this type of study does not exactly follow a FMEA analysis, this was early recognition that studies like these were necessary to validate artificial blood pump performance.

In this early article regarding mock loop testing of blood pumps, the authors discuss the importance of in vitro testing.\textsuperscript{62} Testing takes place to serve a number of purposes including the validation of pump design and providing quality control data regarding consistency and accuracy of pump performance. Healthy and sick conditions as well as transient and steady state flow conditions are modeled. Additionally, it is valuable to verify the response of the system to special conditions such as failures of the controller or pump, and to educate manufacturers, surgeons, patients, and care providers with device function before implant.\textsuperscript{62}

**Arrow CorAide VAD**

The CorAide is a third-generation centrifugal pump that has three parts: 1) volute housing, 2) stator assembly, and 3) fully hydrodynamically suspended pump mechanism. It was tested in 13 calves between 1999 and 2000.\textsuperscript{63} Of the 13 calves, 3 were used for in vivo performance validation testing. The mean pump flow was maintained at 6.1 l/min with a mean arterial pressure of 97 mm Hg, a pump speed of 2,828 rpm, and a power consumption of 6.8 W. For these animal experiments, the durations of testing varied per animal (cumulative testing of 1.5 years) and the pumps were not run until failure. According to the results, there was no evidence of blood component mechanical wear, structural failure, bleeding or hemolysis, during short-term testing durations. The pump is described to be "reliable" after experimental testing.\textsuperscript{64}

In addition to initial animal tests in 2000, 18 more calves were tested in 2002. The animals remained hemodynamically stable, with no bleeding, end organ dysfunction, or mechanical failures. The mean flow was maintained at 5.9 l/min with a mean pressure of 98 mm Hg.\textsuperscript{64}

The CorAide was subjected to impact conditions, similar to testing of the Novacor N100PC.\textsuperscript{65} Performance and durability assessments were completed representing real-life scenarios, such as slipping and falling, while bathing, or climbing the stairs. The pump was connected to a continuous flow mock loop with a blood analog fluid. The flow rate and inlet and outlet pressures were measured and recorded. The pump speeds were varied from 2,500 to 3,200 rpm, and flow was adjusted from zero to maximum flow. The nominal design conditions were set to be 5 l/min, at a pressure rise of 100 mm Hg, and a speed of 2,750 rpm. Vibration and hydraulic testing
were performed along with magnetic induction evaluation. Results of this study indicate "no significant change in pump performance as demonstrated by...efficiencies of 16.5% and 17% before and after impact testing at nominal operating conditions."65

Cleveland Clinic-Nimbus TAH

The Cleveland Clinic Foundation-Nimbus TAH, an electrohydraulically actuated pump, was designed to meet the NIH performance goals of 8-l/min maximum output, a pressure rise of 110 mm Hg, and mean pulmonary pressure 25 mm Hg.66 Other criteria include minimal risk of thromboemboli, small overall size, low infection risk, and a 5-year reliable function. This device must operate for 40-80 million cycles per year without pump replacement. The pump was tested in vitro in a four-chamber mock loop and demonstrated a cardiac output of almost 10 l/min at physiologic pressures. Although this publication does list performance specifications for the pumps and seeks to explain the design and early testing of a TAH, there is no published record of further investigation into possible failures and solutions. No further research is conducted on this device.

Thoratec HeartMate III

The HeartMate III, developed by Thoratec, is a centrifugal pump with a magnetically suspended rotor designed for long-term use. It has undergone mock loop and limited animal testing.67 The pump was tested in a mock loop designed to simulate vascular compliance and the beating ventricle for in vitro testing. Water, glycerin-water (blood analog), and/or bovine blood were used in the loop and pressure head versus volume flow curves were generated from the testing. Pump output was consistently maintained between 3 and 6 l/min. There were no data presented on the length of time of testing. The HeartMate III has demonstrated low hemolysis, low thrombogenicity, and no mechanical or electrical failures in vivo. Animal studies with this pump indicate survival for 40, 27, 49, 42, and 49 days. Reliability data for this pump is unavailable.

Hemodyne

The Hemodyne centrifugal pump has six vanes on the impeller, which is suspended by bearings cooled with saline. The experimental data presented by Jammu et al.,68 are the only published data uncovered by these authors that discusses subjecting a VAD to five different failure modes to test reliability. The failures include: inlet and outlet blockage, blood or serum protein deposition on the vanes of the impeller, an imbalance of the impeller, and bearing failure.68 Simulated blockages were achieved by closing inlet and outlet valves by 50%. Deposition on the impeller was tested by applying a small piece of wax to the inner end of the blade, a location indicated as a common area for thrombus formation. A rotating mass imbalance was introduced in the system by attaching 0.5 g wax to one of the cooling fan blades. To monitor these simulated failures, radial and axial accelerometers, a dynamic pressure sensor, a current sensor, a microphone, pressure sensor, and fluid flow sensor were employed. These sensors detected the virtual thrombus deposition, cannula obstruction and failure, circuit problems, coil failures, and fractured solder joints. By allowing for early detection of faults using sensor monitoring, complex relationships between faults and sensors can be understood. For example, bearing failure produced changes in acceleration signals of the motor. These results support the hypothesis that effective condition monitoring of the bearings can be correctly developed and successfully used to monitor VAD failures.

MagScrew TAH

The MagScrew TAH (developed by the Cleveland Clinic Foundation and Foster-Miller Technologies) has two pusher plates guided by an actuator. Using water as the test fluid the MagScrew TAH was tested in a four-chamber mock loop.69 Compliance was carefully adjusted to simulate aortic and venous compliance; resistance was adjusted to provide a range of afterloads. Similar to the Frank-Starling mechanism, the controller automatically adjusts pump beat rate to match fluid pump return while holding approximately 90% left ventricle filling and maintains output over a range of afterloads. There is no published record of failure studies with this controller. The Cleveland Clinic states that the controller has been designed to operate in a failsafe mode, but that formal reliability testing has not yet begun.70

Discussion

This extensive literature search has revealed limited information on complete failure and reliability studies. However, with further evaluation during the design phase and human errors evaluation in conjunction with a failure and reliability analysis of device function, it may be possible to develop standards applicable to all artificial blood pumps. A complete evaluation of component failures and overall pump function should include: 1) in vitro testing, 2) in vivo testing, 3) clinical testing, and 4) human and other device interactions.

The NIH, STS-ASAIO, ANSI, and the AAMI (Table 1), present their own definitions of failure and the conduction of experiments for artificial blood pumps. Furthermore, at the Bethesda conference, methods for clinical trials and experiments were described.274 Ideally, any blood pump evaluation will include test models in addition to comprehensive experimental testing. Techniques for failure evaluation must be presented including FMEA, hydraulic or mock loop testing (in vitro), animal implant testing (in vivo), clinical testing, and human errors studies.

As detailed in Table 5, there are multiple definitions for device failure. It is imperative that the VAD device industry work together toward the common goal of achieving a single standard for the testing and development of a safe and reliable artificial blood pump industry. Through peer review of published studies, and with continued support from the FDA, it is reasonable to assume that device failure rates can greatly improve, ultimately improving the safety and health of patients receiving these devices.

As accurately represent pump performance in vitro, at the University of Virginia, a mock loop has been developed to not only simulate the normal function of the heart, but to also simulate CHF with representative changes (i.e., resistance, % systole). Testing the pump in such a loop can provide undeniable data that the pump is capable of supporting situations
where right or left ventricular failure occurs. Additionally, this loop has been used to test the performance of the pump and mock loop with a physiologic controller. Currently, in vivo testing largely consists of healthy animals. Heart failure models would provide valuable insight of the physiologic response to the heart.

Clinical testing and human interactions with the device in addition to other device interactions provide the most conclusive evidence for safe and reliable devices. In addition to noting device malfunctions and pump operating trends, certain abnormal physiologic data such as a patient's heart rate, respiratory rate, and blood pressure can be used to note device failure. Development of aggressive diagnostic tools incorporating these parameters will ultimately provide the best course of treatment for CHF patients. Human factors engineering is also a valuable aspect of device development. A user's attitude, knowledge, and decision making directly affect device design and usage. Up to 90% of failures with medical devices are in fact caused by human errors.

Conclusions

The importance of a thorough failure and reliability studies remains understated based on existing publications of device testing. Blood pumps such as the Novacor N100PC and Thoratec HeartMate were approved based on reliability studies completed by evaluating the pumps in vitro, in vivo, and in clinical testing. Additionally, each pump was optimized before final commercial approval to provide the safest and most effective blood pump. However, although this type of systematic approach has provided patients with a viable solution for short-term implantation, as researchers develop devices to last up to 10 years, the need for failure and reliability studies is obvious. To protect trade secrets and limit negative publicity regarding device performance, manufacturers are hesitant to publish their failure and reliability tests.

As the performance expectations of blood pumps increase to 10 years of successful operation while completely implanted, the importance of failure and reliability becomes critical. Constant reevaluation of pump design and monitoring patients with implanted devices are valuable tools to increase safety and reliability of these devices. Results generated from these studies are the solution to designing blood pumps able to function for extended periods without compromising patient health or increasing cost. With an expanding market for cardiac assist devices and a greater expectation for product reliability, evaluation of failure continues to be absolutely essential for a safe, effective, and reliable artificial blood pump. The blood pump industry is challenged to promote thorough device failure and reliability studies through sharing of information between designers, manufacturers, researchers, and clinicians.

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