Energy Transmission and Power Sources for Mechanical Circulatory Support Devices to Achieve Total Implantability

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Left ventricular assist device therapy has radically improved congestive heart failure survival with smaller rotary pumps. The driveline used to power today's left ventricular assist devices, however, continues to be a source of infection, traumatic damage, and rehospitalization. Previous attempts to wirelessly power left ventricular assist devices using transcutaneous energy transfer systems have been limited by restrictions on separation distance and alignment between the transmit and receive coils. Resonant electrical energy transfer allows power delivery at larger distances without compromising safety and efficiency. This review covers the efforts to wirelessly power mechanical circulatory assist devices and the progress made in enhancing their energy sources.

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Cardiac transplantation continues to offer patients with congestive heart failure the best outcomes. Nevertheless, due to the limited availability of donors, mechanical circulatory support systems, such as left ventricular assist devices (LVADs), have been used not only to bridge patients to transplantation but also as long-term treatment options. The original vision of a totally implantable device that offers the patient full autonomy, however, remains elusive decades after the original request for proposals was made by the National Institutes of Health.

Current LVADs require a percutaneous driveline to receive power from external batteries or an electrical outlet. As a result, these patients remain susceptible to driveline infections that lead to sepsis and lower survival [1]. The major impediment to total implantability continues to be the power source and the transmission of electrical energy to the pump. We will review here modes of transmitting energy from an external source to the implanted pump without direct contact as well as LVAD battery technology.

Material and Methods

A literature search was conducted for studies through May 2013 on energy sources and innovations in power delivery to mechanical circulatory support devices in the MEDLINE PubMed database. Key words and MeSH terms used in the search included "left ventricular assist device," "total artificial heart," "driveline infection," "transcutaneous energy transmission," "battery," "energy converter," "electric power supplies," "heart-assist devices," "heart failure," "wireless technology," "prosthesis-related infections," and "solar energy." These references and their related articles were reviewed for relevancy. Books on the historical development of LVADs were also used.

Wired LVADs

The concept of mechanical circulatory support originated from the invention of the heart-lung machine by Dr John Gibbon Jr [2]. Its success suggested that other devices could be developed to provide circulatory support for longer durations. To this end, the National Heart, Lung and Blood Institute (NHLBI) established the Artificial Heart Program in 1964 [3]. The NHLBI conducted clinical trials in the 1970s to study the performance of first-generation VADs. In that decade, William Pierce and James Donachy developed the Pierce-Donachy VAD—later renamed the Thoratec pulsatile VAD—at Penn State [4]. In 1980, the United States Food and Drug Administration (FDA) approved this device for postcardiotomy recovery and bridge to transplantation. Its design served as the blueprint for later LVADs and total artificial hearts (TAHs).

The Videos and Appendix can be viewed in the online version of this article [http://dx.doi.org/10.1016/j.athoracsur.2013.10.107] on http://www.annalsthoracicsurgery.org.

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Subsequently, in 1984 NHLBI awarded contracts to four companies for their design concepts of completely implantable ventricular assist systems: Abiomed (Danvers, MA), Nimbus (Rancho Cordova, CA), Novacor (Oakland, CA), and Thermo Cardiosystems (Woburn, MA) [4]. From later testing and clinical trials, the Novacor VAD and the Thermo Cardiosystems HeartMate XVE emerged as the frontrunners. After FDA approval of the pneumatic HeartMate VE in 1994, the Novacor VAD and electric-powered HeartMate XVE received FDA approval in 1998.

Despite their clinical promise, these devices were only implanted for short periods, such as in bridge-to-transplantation patients. Thus, the Randomized Evaluation of Mechanical Assistance for the Treatment of Congestive Heart Failure (REMATCH) and Investigation of Nontransplant-Eligible Patients Who Are Inotrope Dependent (INTrEPID) trials were conducted to compare the HeartMate XVE and Novacor against optimal medical treatment for their long-term effect on patients who were ineligible for cardiac transplantation [5, 6]. The results from these studies overwhelmingly favored LVAD use. For instance, the HeartMate XVE group showed a 48% reduction in the risk of death from any cause and experienced a greater improvement in quality of life at 1 year compared with patients receiving optimal medical treatment. This served as the impetus for the 2002 FDA approval of the HeartMate XVE for destination therapy.

At the time, most of the existing devices could be classified as positive-displacement pumps that used an air or electrically actuated pusher plate mechanism, both working on the principle of indirect actuation to pump blood forward. Although much progress had been made, these pulsatile LVADs had numerous drawbacks. They were still too large to be implanted in many patients, especially women, and suffered from frequent mechanical failures due to various moving parts, including valves.

Rotary LVADs that use axial and centrifugal flow were the solution to these problems because they simplified the pumping mechanism. By locating the actuation mechanism within the blood path, the rotary pumps eliminated many moving parts and the bulkiness of earlier devices. The first continuous-flow LVADs to be implanted included the DeBakey VAD, a product of collaboration between MicroMed Technology Inc (Houston, TX) and the National Aeronautics and Space Administration, the Jarvik 2000 Flowmaker (Jarvik Heart Inc, New York, NY), and the HeartMate II (Thoratec Corp, Pleasanton, CA) [4]. Soon after, the FDA approved the HeartMate II for bridge to transplantation in 2008 and destination therapy in 2010. The subsequent entry of the HeartWare HVAD (HeartWare Inc, Framingham, MA), a hydrodynamically suspended centrifugal pump, into the market defined the third generation of rotary pumps by removing the need for a pump pocket and reducing the invasiveness of the implantation procedure [7]. This device recently received FDA clearance for bridge to transplantation, and its destination trial is likely to conclude soon.

Drivelines

Current FDA-approved LVADs, such as the HeartMate II and HeartWare, directly transmit electrical energy through a flexible percutaneous cable. The driveline connects the implanted pump to an external power source, such as a power module that delivers AC electrical power or a pair of lithium ion batteries—14 V (4.8AHr, 71 Wh) in HeartMate II and 14.8 V (3.5AHr, 51.8Wh) in HeartWare. Drivelines hinder the patient's mobility, are easily damaged, and often cause infections that may lead to device failure over time. The rate of infection in LVAD patients is prohibitively high when compared with other cardiovascular implants, such as prosthetic valves (2% to 4%) and orthopedic implants, including hip and knee arthroplasty (<1%) [8–14]. Such infections often cause subsequent sepsis and require repeated hospitalizations for antibiotic treatment or surgical interventions [1, 13, 15–19]. As we move toward even longer durations of support on LVADs, the risk of percutaneous site infections continues to rise temporally, and the net result is reduced survival and increased cost, negating the intended benefit of LVAD therapy.

Because driveline infections frequently arise due to trauma to the driveline exit site, the ideal solution is to remove the entire driveline. To do so, the implanted energy source of the pump would need to last the duration of the patient's lifetime or have the capacity to be recharged without piercing the skin. An elegant solution to such a problem would be to transmit power at a distance, without a wired connection.

Electromagnetism and Power Transfer

A simplified explanation of electrical signal generation and transmission is provided in the Appendix. A transformer (the large cylinders one can see hanging on utility poles) is an ideal example of how electromagnetic energy can be harnessed for efficient wireless power transfer at short distances. A transformer passes electricity (at a frequency of 60 Hz) through a primary coil that creates a magnetic field around the coil. Because the electric current and magnetic field are both alternating, when a second coil is brought close to the first coil (separated by a few millimeters), an alternating current (AC) is generated in the second coil. This technique is called induction and works only when short distances separate the coils because the magnetic field decays quickly. Induction-based power transfer is present in cordless toothbrushes, induction stoves, and transcutaneous energy transfer (TET) systems.

Transcutaneous Energy Transfer Systems

In 1961, Schuder and colleagues [20] described an inductive coupling arrangement of two pancake-shaped coils that could transfer electromagnetic energy at radio frequencies across a closed chest wall. To validate the theoretic rationale, they demonstrated the transmission of power from a portable battery pack through both sides of