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

the chest wall to deliver energy to 10 W light bulbs on the opposite side in canine experiments. Their work helped catalyze the development of TET systems, which was further enhanced by contributions from Heimlich and colleagues [21].

Modern TET systems power an LVAD, with several key components shown in Figure 1. First, external direct current (DC) power from a control module or battery is converted into a high frequency AC current by a power inverter. Next, a primary transmit coil transfers this AC power by inductive coupling through the skin to a secondary receive coil that is implanted subcutaneously. In other words, the external and internal coils act as a transcutaneous transformer. Finally, the AC power is changed back to DC power by an AC-to-DC converter circuit before powering the LVAD pump motor. TET can supply LVADs with more than enough power, reaching efficiencies of up to 72% for close coil separations [22]. The HeartWare-Dualis system (according to a press release) and Co-planar technology (Leviticus Cardio Inc) are examples of technologies based on TET principles [23, 24].

The limitations of pulsatile pumps delayed the use of TET in LVADs initially. Early LVADs that used pusher-plate mechanisms encountered volume compensation problems. To eject blood from a blood sac, volume changes in the rigid pump case caused the pressure to drop during systole and rise during diastole. This cycle of pressure changes led to greater loads on the motor and incomplete filling of the blood sac [25]. To resolve this design flaw, LVADs needed a percutaneous driveline to connect the pump with an external air venting system. This same driveline would be used to transmit electrical power for convenience.

Although TET had been incorporated into many LVAD designs as early as the 1980s by Thermedics Inc (Woburn, MA), there was no need to implement the technology until the driveline could be eliminated [26, 27]. The first mechanical circulatory support systems implanted with TET technology were the AbioCor TAH (Abiomed, Danvers, MA) and the LionHeart 2000 LVAD (Arrow International, Reading, PA). Slaughter and colleagues [26] provide an excellent review of how these devices overcame volume compensation.

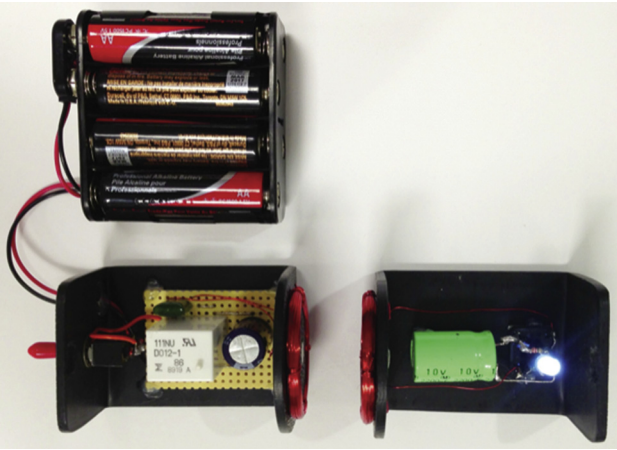

Fig 1. Transcutaneous energy transfer systems consist of a power inverter (converts direct current to alternating current), a primary transmit coil, a secondary receive coil, and a rectifier circuit. Here, an external battery pack wirelessly powers the light-emitting diode light bulb.

AbioCor TAH

The AbioCor TAH contains a rotary pump that drives hydraulic fluid back and forth within an active artificial septum in conjunction with a reciprocating switching valve [22, 28]. An internal lithium ion battery can power the thoracic unit for half an hour. For long-term power transfer, a transmit TET coil is secured externally over the internal coil with an adhesive dressing.

When 14 patients were implanted with the AbioCor TAH in feasibility trials, the 30-day survival rate was 71%, with 1 patient living for 512 days [26, 29]. Cerebrovascular accident was the major adverse outcome in these patients because many of them could not tolerate anticoagulation. Nevertheless, no device-related infections were reported, which is surprising considering the very sick cohort who underwent these implants. This clearly demonstrates the value of TET systems in reducing infections that otherwise would have been present due to a percutaneous driveline.

LionHeart 2000 LVAD

The LionHeart 2000 LVAD relies on a pusher plate to compress the blood sac [30]. Its design replaced the percutaneous driveline with TET to become totally implantable with an internal rechargeable battery lasting 20 minutes. The LionHeart LVAD was implanted for destination therapy in 23 patients during the European LionHeart Clinical Utility Baseline Study (CUBS) [31, 32]. Although some form of infection developed in 17 recipients (74%), most were not device-related. Infections of the compliance chamber and pump pocket occurred in 1 and 7 patients, respectively, but no inflow or outflow tract infections were noted. Overall, there was a 37% decrease in sepsis incidence as well as a 26% reduction in death due to sepsis; this result may be attributable to the absence of a driveline. Again, given the very sick population of the patients who were enrolled in this trial, these risk reductions were impressive. Nonetheless, problems associated with misalignment of the coils in patients and battery leaks limited the success of the device. Arrow discontinued sales of the LionHeart LVAD for financial reasons in 2005 [4].

Rotary Pumps and TET Systems

With the advent of continuous-flow LVADs, volume compensation no longer presented a problem. This created an incentive for newer devices to use TET as their mode of energy transmission. The HeartMate II, an axial-flow rotary blood pump developed by the Nimbus-University of Pittsburgh team, had percutaneous and transcutaneous configurations [33, 34]. The latter design improved upon older TET designs by moving the

AC-to-DC converter circuit within the receive coil [35]. This minimized the size of the system and lowered the heat load of the implanted motor control module [36]. Moreover, this change allowed for a switch from stiff and bulky Litz wires (tightly wound copper wires that create a more concentrated magnetic field for carrying alternating current) to conventional wires that are smaller in diameter [37]. In light of the results from REMATCH, which showed that mechanical pump failure was the limiting factor for patient longevity, the expediency of fixing mechanical failure issues by switching to rotary pumps overshadowed the desire for wireless energy transfer. As such, TET was not included in the HeartMate II and the driveline remained.

Although TET is still being investigated to power LVADs, its range and alignment problems limit its applicability [38, 39]. This form of energy transmission by itself consumes approximately 20% of the power input, which is less efficient than direct electrical delivery through a percutaneous driveline [37]. In addition, the transmit and receive coils in the TET design must remain close, within a few millimeters. This proximity restriction requires that the receive coil be implanted just under the skin and that the external transmit coil be secured in a single position on the skin surface. As the distance between the 2 coils increases, efficiency drops off. Furthermore, TET coils do not tolerate angular misalignment. If the separation between the coils is too great or a misalignment occurs, excess power is transmitted to compensate for the diminished efficiency. For these reasons, alternatives to TET have been explored to allow for greater separation and freedom between the transmit and receive coils.

Free-Range Resonant Electrical Energy Delivery System

Several investigators have attempted to transfer wireless power at a distance. Most of the proposed ideas exploit the phenomenon called resonance, a property related to the frequencies at which objects oscillate at maximal amplitudes. The idea of magnetic resonance originated from the work of Nikola Tesla and has been recently revived and used for wireless power transfer in modern applications [19, 40, 41]. Resonance makes listening to the radio, watching television, and cooking food with a microwave possible.

In fact, every object in nature has a natural resonant frequency at which it can vibrate. When an opera singer hits a note that matches the resonant frequency of a wine glass, the glass will start to vibrate as the acoustic energy is converted to kinetic energy. The energy absorbed can even cause the glass to shatter. Here, the shattering is not because of an extremely high note but due to resonance and the matching of frequencies, which allows the energy to be transferred efficiently.

In the case of a radio transmission, we are able to listen to the radio broadcast by "tuning in" to a particular frequency. If one visualizes the electromagnetic wave spectrum, this can be achieved in the "near field," where there is no risk of "ionizing radiation" (Fig 2). Theoretically, one should be able to capture the energy that has been broadcast by the radio tower. But the radio set picks up only a fraction of the radio wave energy being transmitted and thus is very inefficient in harvesting energy.

One can use the above principle to select 2 coils with the same resonant frequency and expect efficient power transfer between them. By passing rapidly alternating current through the primary coil, this creates a large magnetic field around it. Now, if we bring in the second coil, which is tuned to the same resonant frequency within this field, the efficiency with which the magnetic field is converted to electrical power within the second coil is dramatically improved compared with nonresonant coupled induction (like the TET system). Other objects that do not share this resonant frequency will not interfere or absorb energy away from this type of transmission. This is analogous to "tuning in" to a particular radio station; unless we tune in to the right one, we cannot receive the broadcast. This resonance is not to be confused with magnetic resonance imaging, which uses strong magnetic fields on the order of 1 to 1.5 Tesla to align water molecules within cells. In contrast, the magnetic field strength in resonant electrical transfer is minimal, at approximately 8×10^{-5} Tesla, which is comparable to the Earth's magnetic strength, 3.1×10^{-5} Tesla, to which we are exposed every day.

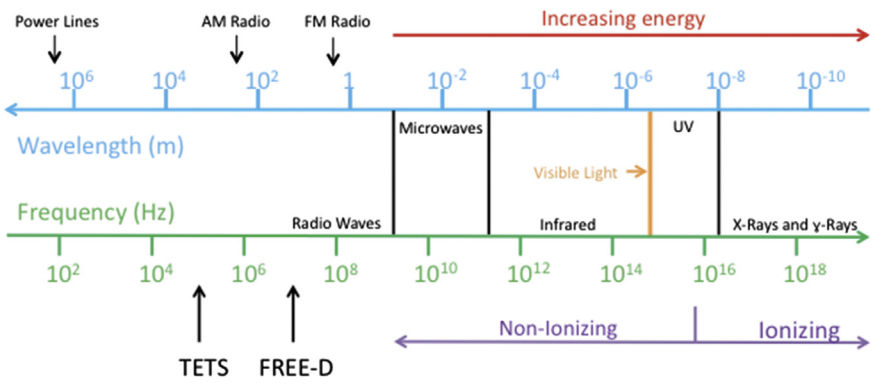

Fig 2. Electromagnetic spectrum. Different types of electromagnetic radiation fall in different regions of the spectrum, depending on the wavelength and frequency. Radio waves and the radiation emitted by transcutaneous energy transfer (TET; 1×10^{5} Hz) and free-range resonant electrical energy delivery (FREE-D; 1.36×10^{7} Hz) systems have low frequencies and belong in the nonionizing, near field of the spectrum. (AM = amplitude modulation; FM = frequency modulation.)

The free-range resonant electrical energy delivery (FREE-D) system uses high-efficiency resonant coupling technology to provide wireless power to an LVAD without compromising mobility or requiring direct contact between the patient and the energy source. The energy transfer range of this system significantly exceeds that of previous TET applications. A schematic of the FREE-D configuration is shown in Figure 3A. The transmit and receive resonators efficiently exchange energy by sharing magnetic fields that oscillate at a specific resonant frequency. The magnetic field that is not absorbed by the receive coil is reabsorbed by the transmit coil. For this reason, the system behaves more like a wired link than like a broadcast radio tower, which sends power in all directions regardless of whether any receivers are present.

The key feature that distinguishes FREE-D wireless powering of LVADs from prior inductive coupling technology is the use of 2 coupled high-efficiency resonators (Fig 3B) together with an automatic tuning scheme (autotuning) that keeps the system operating at maximum efficiency [19, 42]. Over some range of separation distances, a constant, maximum efficiency can be achieved if the ideal operating frequency is selected. This constant efficiency region corresponds to a V-shaped plateau. As the distance between the transmit and receive resonators changes, the frequency at which maximum efficiency occurs also changes. Accordingly, an autotuning scheme adapts to variations in distance and orientation between the 2 resonators by dynamically selecting the ideal operating frequency. Related techniques using adaptive impedance matching networks can achieve this same behavior at a single frequency. Videos further detailing the FREE-D concept and demonstrating its applicability to powering LVADs are available online (Videos 1–3) [43].

FREE-D offers multiple advantages over older TET systems, including reductions in infections, better patient safety, and improved quality of life; their differences are summarized in Table 1. The FREE-D vision constitutes a completely implantable cardiac assist system that affords the patient tether-free mobility in an unrestricted space. Thus, no power drivelines will traverse the patient's skin, with power delivered wirelessly over room distances. By converting living spaces into a safe, all-encompassing environment, the patient can receive power in any location, whether it is his or her home, office, or car (Fig 3C).

Of note, Thoratec Corp recently announced a collaboration with WiTricity Corp (Watertown, MA) on the development of a fully implantable ventricular assist system (FILVAS) that also uses a resonant energy transfer principle [44, 45]. They also proposed a 3-hour implantable battery that will be wirelessly recharged. The heart failure community eagerly awaits the arrival of Thoratec's FILVAS.

Advances in Power Sources

Battery Technology

Coupled with the progress in energy transmission are innovations that improve the energy source of LVADs. Totally implantable LVADs require a rechargeable battery pack that must satisfy three criteria: supply enough power to allow for long operating times, exhibit long implant life, and meet size and weight constraints to be implanted in a variety of body sizes. Thus, in many ways,

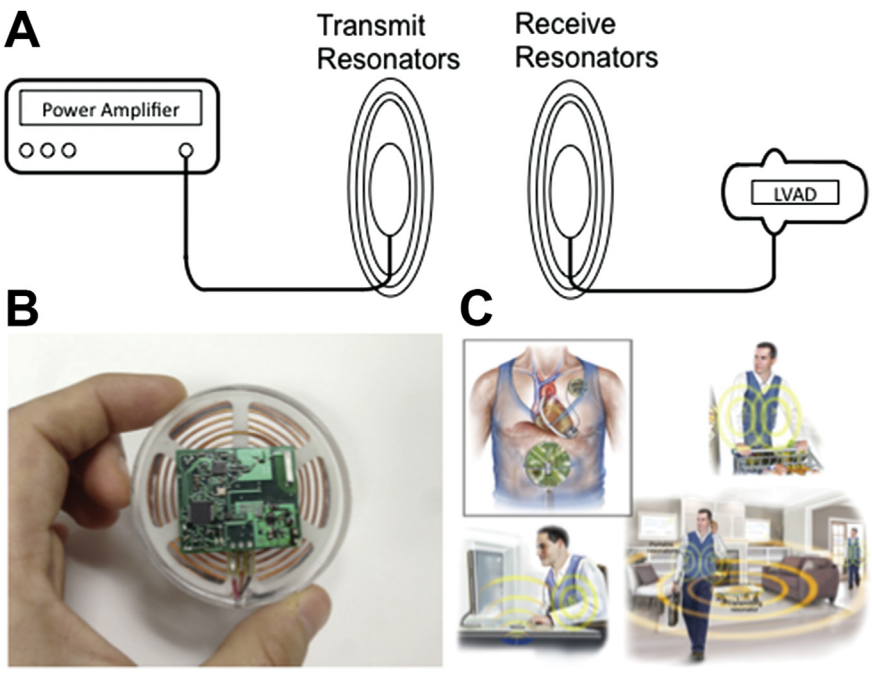

Fig 3. The free-range resonant electrical energy delivery (FREE-D) concept. (A) In FREE-D, the transmit resonator induces an electric current in the receive coil by high-efficiency resonant coupling technology. (B) The FREE-D implantable receive coil. (C) The FREE-D vision allows for a completely implantable cardiac assist device that can be recharged by a transmit resonator in any location, freeing the patient from restrictive drivelines.

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Table 1. Comparison Between Older Transcutaneous Energy Transfer Systems and the Free-Range Resonant Electrical Energy Delivery System

Variable	Older TET System	FREE-D System
Patient contact needed	Yes (all the time)	No
Tethered operation	Yes	No
Adhesives/external anchoring	Needed	Not needed
Energy transfer range	10-mm maximum	Over meters
Temperature during operation	40°C or higher	<30°C
Radial misalignment	10°	Almost limitless
External peripherals	Remain	Eliminated

FREE-D = free-range resonant electrical energy delivery; TET = transcutaneous energy transfer.

advances in LVAD development have paralleled improvements in battery technology. A brief timeline of the major milestones in battery technology is shown in Figure 4.

Early pulsatile LVADs relied on lead acid and rectangular prismatic nickel-cadmium battery cells. These batteries had short cycle lives and low operating times, partly due to the inferior electrode material in the cell and because they were discharged under pulsatile loads [46]. To overcome the reduction in operating time and cycle life caused by pulsatile discharge loads, battery cells had to be larger. Inevitably, the more environmentally friendly and longer-lasting nickel-metal hydride batteries, which powered the HeartMate XVE and Novacor LVADs, replaced nickel-cadmium cells.

Lithium ion technology marked the next step in battery technology because of the higher specific energies and energy densities of the lithium battery [47]. Initially used by Wilson Greatbatch in 1972 to power pacemakers, the lithium battery is smaller and lighter than its predecessors and is now widely used with most current LVADs [48]. In addition to the HeartMate II and HeartWare, the Jarvik 2000 Flowmaker also relies on rechargeable lithium-ion battery power. Although lithium batteries are an improvement over older cells, their operating time is still too short for total implantability. For example, one pair of new 14-V lithium ion batteries (1 lb per battery) powers the HeartMate II for 6 to 10 hours under normal operating conditions [49].

Solar Cell System for Recharging the External Battery

Because LVADs and TAHs are currently powered through external battery systems that must be recharged constantly, these devices would benefit from a reduction in recharge times. A solar cell system that could continuously recharge the carry-on battery system would free patients from having to tether themselves to an AC outlet for charging. So far, photovoltaic devices that convert radiation energy into electrical energy for TAHs have been designed to extend operating times and reduce the size of the external battery [50].

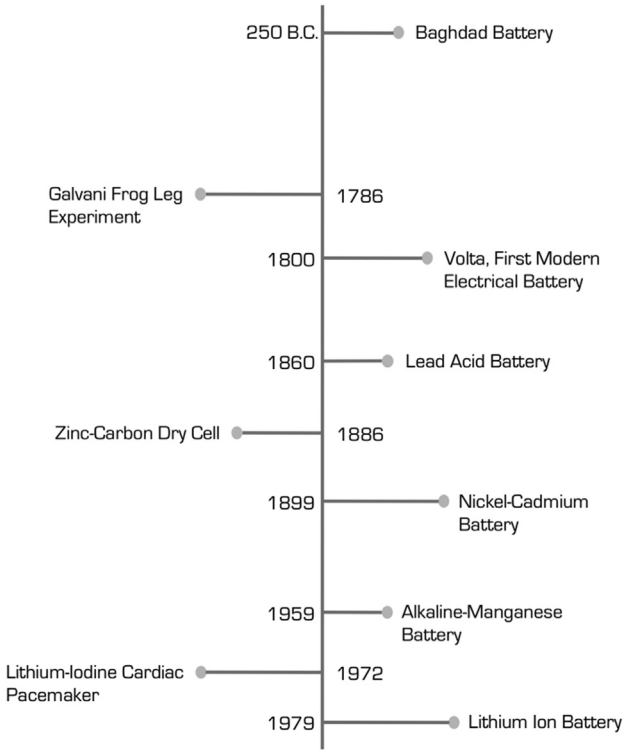

Fig 4. Chart shows development of battery technology. The Baghdad Battery, described by Wilhelm König in 1938, is believed to have belonged to the Parthian Empire and was used for electroplating. After Luigi Galvani's discovery that frog legs would twitch when connected by two different metals, Alessandro Volta developed the first modern battery by stacking copper and zinc disks into a "voltaic pile." Gaston Planté invented the lead acid battery, the first rechargeable battery, and Carl Gassner modified the Lechlanché cell to create the first dry cell. Next, the nickel-cadmium and alkaline-manganese batteries were invented by Waldemar Jungner and Lewis Urry, respectively. Wilson Greatbatch implanted the first totally implantable cardiac pacemaker and later improved the battery with lithium-iodine technology. In 1979, John Goodenough built the first rechargeable lithium-ion battery using lithium cobalt oxide.

Proton Exchange Membrane Fuel Cells

An alternative to conventional batteries is the small, air-breathing, proton exchange membrane fuel cell. Developed by General Electric (Schenectady, NY), this power source uses hydrogen as fuel [51]. Specifically, proton exchange membrane fuel cells generate electricity by exploiting the reaction of hydrogen and oxygen in air. Hydrogen is channeled to the anode, where a platinum catalyst causes hydrogen to split into protons and electrons. These protons then pass through the polymer electrolyte membrane to the cathode, where they react with oxidants. Because the membrane is electrically insulating, electrons are conducted through an external circuit to the cathode, thereby generating a current. Electrons and hydrogen ions react with oxygen to produce water at the cathode. For the hydrogen source, the AF Sammer Corp (Ringwood, NJ) has developed a hydrogen generator based on chemical hydrides [51]. The benefit of such a reaction is that the byproducts—oxides

and water—are environmentally safe. Furthermore, these fuel cells not only have high energy densities but can also be recharged within minutes. Application of such battery technology in the LVAD field has the potential to offer longer battery time with higher reliability.

Nuclear Energy

In the search for the ideal energy source, nuclear power has been considered another potential solution. LVADs would not be the first medical devices to incorporate nuclear batteries. Early cardiac pacemakers in the 1970s used plutonium (^{238}Pu) batteries, which have a half-life of 87 years [52]. The thermal energy generated from alpha particles emitted by the plutonium served as the energy source for these pacemakers. However, because of the toxicity of this metal and problems the radioactive fuel created during travel, these nuclear power sources were replaced with lithium batteries in pacemakers. Unfortunately, while pacemakers consume power on the order of microwatts, current LVAD pumps require 5 to 15 W of power. So, whereas lithium batteries extended the pacemaker battery life to approximately 10 years, the same technology can only power rotary pumps for a few hours.

Arguments have been made for a return to ^{238}Pu as a power source to solve the high-power requirements of intracorporeal pumps because of its high energy density (4 W/cm^3) and long half-life [53]. Still, a nuclear-powered system raises many concerns. Poirier [54] writes that the existing thermal-to-electric energy converters are unable to achieve the level of efficiency needed to power an LVAD using nuclear power sources. In fact, with the converters operating at their current efficiencies ($< 10\%$), too much fuel would be required. This amount of ^{238}Pu accompanied by the size increase in the energy convertor is impractical to implant into a human body. Furthermore, ^{238}Pu is scarce, and the cost associated with constructing reactors to generate this isotope would be unwieldy and unlikely to receive support from the public.

Skeletal Muscle Energy Convertor

Other research has attempted to bypass battery power altogether and harness the sustainable energy generated by skeletal muscle contraction in a linear configuration as the power source for circulatory assist devices. In such systems, the insertion of the latissimus dorsi onto the humerus is removed and attached to a piston hydraulic energy converter [55]. When stimulated by a pulse generator, the muscle contracts, creating a mechanical force that is converted to the hydraulic energy necessary to power the pusher plate mechanism of an implanted VAD. This has limited applications in today's context but may be useful for partial support devices [56–58].

Conclusion

In the effort to achieve total implantability in mechanical circulatory devices like LVADs and TAHs, the field has made significant progress in incorporating better energy sources and in developing new modes of power delivery. Although battery technology continues to improve, as evidenced by newer lithium polymer cells, a battery that can last the duration of an LVAD's lifetime remains far from reach. Therefore, the most realistic approach to total implantability is through a system that charges internal batteries wirelessly. TET and the FREE-D systems offer the most promising solutions to this challenge.

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