Electrochemical Power Sources and the Treatment of Human Illness

by Curtis F. Holmes

Battery-powered implantable devices have been in use for over forty-three years. The first successful cardiac pacemaker was implanted in 1960. Since that time, a variety of implantable battery-powered devices have been developed and introduced for the treatment of everything from neurological disorders to hearing loss. The development of lithium batteries in the late 1960s led to better, smaller devices that showed multiyear longevity and high reliability. Indeed, the use of lithium batteries in implantable devices was perhaps the first successful commercial applications of that technology.

The use of pacemakers to treat bradycardia is now a commonplace event. Over 500,000 are implanted annually. The implantable cardioverter/defibrillator (ICD) is also a commonly used medical treatment for tachycardia and ventricular fibrillation. Recent development of biventricular pacing (also known as resynchronization therapy) has led to a promising new treatment for congestive heart failure. Left ventricular assist devices (LVADs) can serve as a bridge to heart transplant or, more recently, as a treatment itself for severely damaged hearts. The totally artificial heart actually replaces the human heart with a mechanical device that takes its place. Implantable drug delivery devices are used for treatment of chronic diseases such as diabetes as well as the administration of medication for pain relief and chemotherapy. Neurostimulators can treat epilepsy, Parkinson's disease, chronic pain, and incontinence. There are a variety of implantable devices to treat hearing disorders, all using implantable batteries.

In addition to the implantable devices mentioned above, there is a great variety of external battery-powered medical devices in common use today. Ambulatory drug-delivery systems, external defibrillators, Holter monitors, hearing aids, and wheelchairs are among the many devices powered by electrochemical power sources.

Biomedical devices present unique challenges to battery developers and manufacturers. The need for the highest level of safety and reliability is obvious. Life-saving devices simply must operate reliably, and the power source must be designed, manufactured, and tested with this goal in mind. The devices mentioned above present a variety of requirements to the battery developer. Pacemakers demand only microampere-level current delivery. ICDs, however, must operate at microampere-level currents for the monitoring and bradycardia functions but must deliver forty or more joules to circuitry and capacitors within a few seconds when ventricular fibrillation is detected. Neurostimulators and drug delivery systems typically demand milliampere-level currents. The LVAD presents such high current demands that a primary battery cannot possibly be designed to show adequate longevity. The device therefore employs rechargeable batteries to provide its power.

Millions of patients have benefited from battery-powered devices. Such devices have demonstrated great reliability and safety. They would not be possible without the advances seen in the development of high energy density batteries over the past four decades. Electrochemical power sources are among the most important contributions of electrochemistry to medical science in modern times.

This paper will focus on the battery-powered devices used to treat disease and disorders. Treatment of medical disorders by medical devices will be discussed from the viewpoint of the diseases, the devices, and the batteries used to treat disorders.

Treatment of Cardiac and Circulatory Disorders

Bradycardia is an illness in which the heart beats too slowly. It can be caused by a variety of conditions, ranging from parasites (Chagas disease) to sick sinus syndrome. In most cases, the heart may beat 20-40 times per minute and the patient cannot incur any activity. Syncope is a common symptom. It was known in the 1940s that electrical stimulation of the heart could cause the heart to beat at a more normal rate and, in the 1950s, external pacemakers were developed. The first successful implantable pacemaker was implanted in 1960[1] (Fig. 1). During the first ten years of the use of the pacemaker, the power source of choice was the zinc/mercuric oxide battery of Ruben.[2] This system made the first pacemakers possible, but the system evolved hydrogen gas, making true hermetic sealing impossible, the longevity ranged from eighteen months to three years, and the approach to battery end-of-life was sudden and without adequate warning.

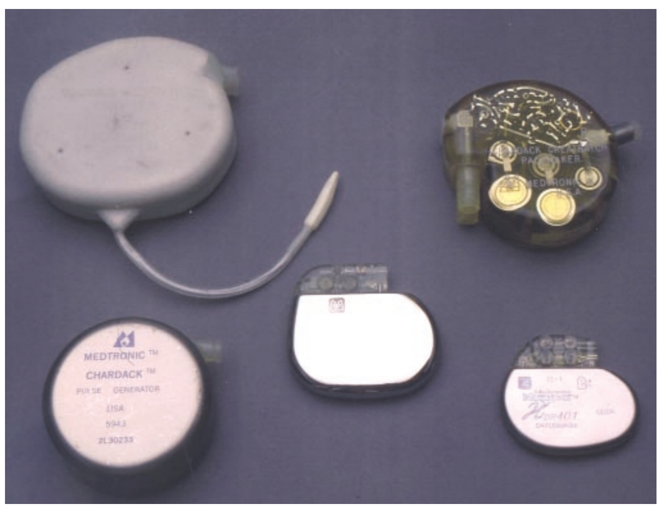

Fig. 1. Battery-powered implantable devices have been in use for over 40 years, and the first successful cardiac pacemaker was implanted in 1960. Shown here is a "history of pacing" — from the first implantable (upper left) to the Kappa DR 401 (lower right). Image courtesy of Medtronic.

The introduction of lithium batteries in the early 1970s made possible the development of pacemakers with longevities in excess of ten years, and the reliability was greatly improved. The first lithium powered pacemaker was implanted in Italy in 1972.[3] In the next few years, the zinc/mercuric oxide system was totally replaced with lithium batteries. Various systems were used, including cathodes of iodine-polyvinylpyridine (PVP), cupric sulfide, thionyl chloride, and silver chromate. By the mid 1980s, only lithium/iodine-PVP remained as the battery system of choice. Invented by Moser and Schneider[4,5] and optimized by Greatbatch, Mead, and Rudolph,[6] the cathode of the system is iodine, some of which is reacted with PVP to form an electronic conductor, and the solid electrolyte is lithium iodide, formed between the anode and the cathode as the battery reaction proceeds. Virtually 100% of all pacemakers produced today use this system. The battery is a high-impedance system, and the internal resistance increases as the discharge reaction occurs. Consequently the use of solid cathode, liquid electrode systems such as lithium/carbon monofluoride[7] or a hybrid cathode system reported by Schmidt and coworkers[8] may be seen in pacemakers requiring higher current delivery over the life of the device to power such features as telemetry.

Tachycardia is a medical condition in which the heart beats too fast. Untreated, the condition can degenerate into ventricular fibrillation, in which the heart stops beating and shakes uncontrollably. Absent intervention, ventricular fibrillation is almost always fatal. In 1980, a device was developed and implanted that could sense ventricular fibrillation and provide a shock that would stop fibrillation and restore normal sinus rhythm via an electrode sutured onto the heart.[9] The device was powered by the lithium/vanadium pentoxide system.[10] The device was demonstrated to be effective in treating ventricular fibrillation, and development efforts in several organizations led to improved devices. The lithium/vanadium pentoxide system was replaced by a new system using the cathode material silver vanadium oxide (SVO, $Ag_2V_4O_{11}$).[11,12,13] This system is used in most ICDs today (Fig. 2), although the lithium/manganese dioxide system is used in one such device. A new system was recently reported using a "sandwich" cathode design with an inner cathode material of carbon monofluoride and an external cathode layer of silver vanadium oxide.[14]

The development of the ICD advanced quickly in the 1990s, and soon devices that treated tachycardia before it led to fibrillation were developed. Advances in battery technology, capacitor technology, lead and electrode technology, and electronics have produced ICDs with volumes less than 35 cm^3, a reduction of well over 100 cm^3 from the first devices produced in the mid-1980s. Today's ICDs perform bradycardia pacing, sense tachycardia, and attempt to pace the patient back into normal sinus rhythm, and provide a 40 joule shock via a transvenous lead if ventricular fibrillation occurs.

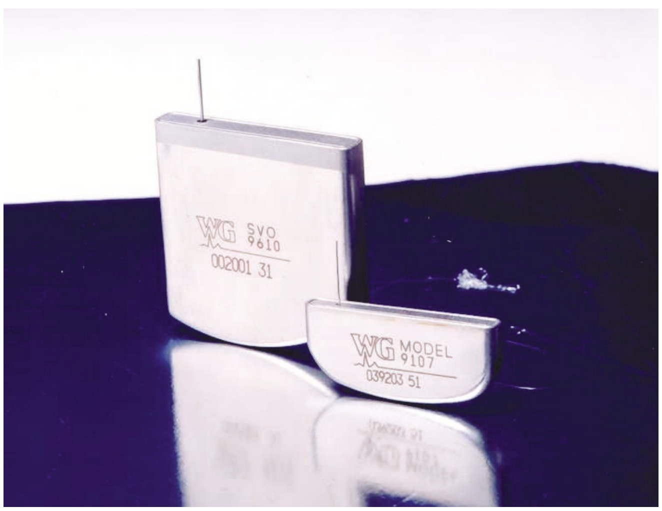

FIG. 2. A lithium/silver vanadium oxide battery (left) used in an implantable cardioverter/defribrillator, and a lithium/iodine pacemaker battery (right). For size perspective, the battery on the right is 0.5 inches tall. Image courtesy of Wilson Greatbatch.

It has been shown that pacing in both the left and right ventricles can treat a disease known as congestive heart failure.[15] This very serious disease is a leading cause of death in the world. Biventricular pacing (also known as resynchronization therapy) improves the heart's contraction sequence and reduces the symptoms of congestive heart failure for the majority of patients. Some units provide biventricular bradycardia pacing only and are powered by lithium/iodine batteries (Fig. 2), and others can also function as an ICD and are powered by lithium/SVO batteries.

The left ventricular assist device is a pumping mechanism that is attached directly to the heart to provide assistance to the heart's pumping function. Originally developed to provide patients waiting for a heart transplant with a life-sustaining mechanism, the device is now also used for patients who may not be candidates for transplant. The power requirements for this device are such that an implantable battery, even a secondary system, would be too large for implantation. The patient therefore wears a pack of secondary batteries in a vest-like garment, and power is transmitted into the device through the skin. Some such devices also provide an implantable secondary battery to allow the patient some freedom from the external system and to provide a backup in case of failure of the external system. The internal battery is designed to function for about one hour per day.[16] The totally artificial heart is powered, as is the LVAD, with an external battery pack and an internal backup battery. Lithium ion battery technology is increasingly being used in this application.[17]

Treatment of Pain, Epilepsy, and Parkinson's Disease Through Neurostimulation

Neurostimulators are pacemaker-like devices that are used to treat various illnesses and other medical conditions. The most common is the treatment of chronic pain through stimulation of sites along the spinal column to block the sensation of pain. Milliampere-level pulses are provided to these sites and result in dramatic pain relief for the patients. These devices are also used to treat incontinence by stimulation of the sacral nerve,[18] Parkinson's disease through deep brain stimulation,[19] and the treatment of epilepsy by vagal nerve stimulation.[20] All of the above conditions are serious threats to health and human life. The treatment of chronic pain was the first use of neurostimulation. Everyone is aware of the devastating nature of Parkinson's disease, and a device for treatment of this disease is a welcome addition to the arsenal of treatments for this affliction.

The treatment of epilepsy by vagal nerve stimulation is now an accepted form of treatment. Neurostimulation of the vagus nerve has been shown to be very effective in reduction of grand mal seizures, and many patients have been given a more normal life because of neurostimulation.

Neurostimulation devices look and function much like implantable pacemakers. They generate pulses and provide these pulses to the site of therapy via leads and electrodes similar to those used in cardiac pacing. However, the devices typically require higher-current pulses than do pacemakers. Whereas pacemakers can operate effectively by delivering pulses of between five and twenty microamperes, neurostimulators must deliver milliampere-level pulses to be effective. Consequently, they require batteries capable of higher current delivery than can be provided by the lithium/iodine-PVP system used in cardiac pacing. The lithium/thionyl chloride soluble cathode system and the lithium/carbon monofluoride solid cathode liquid electrolyte system are commonly used in these devices.

Treatment of Cancer, Cerebral Palsy, Chronic Pain, and Diabetes Through Implantable Drug Delivery Devices

There are many diseases that require regular administration of drug therapy for months, years, or even throughout the life of the patient. Many such diseases can be treated very effectively if the drug can be delivered directly to that part of the body undergoing treatment. Other diseases, such as diabetes, are treated much more effectively by controlled administration of drugs during the day rather than a single dose or injection each twenty-four hours. Moreover, by delivery of the drug internally rather than orally or by injection, the amount of drug required to treat a medical condition can often be greatly reduced.

Such conditions are effectively treated by implantable drug delivery systems.[21] These systems combine electronic controls, a drug reservoir that can be refilled transcutaneously, a pumping mechanism that delivers the drug in a precise, controlled manner, or with a battery (typically lithium thionyl chloride or lithium/carbon monofluoride) and a catheter that administers the drug to the desired part of the anatomy.

The first such devices were simply an implantable bellows pump.[22] The bellows was compressed by the injection of the drug through the skin to the reservoir, and the mechanism allowed the bellows to force the drug through an orifice to a catheter. There were no electronics or batteries, so there was no control over the drug administration other than that provided by the mechanical components.

More sophisticated devices were subsequently developed. These devices are capable of being externally programmed to deliver the drug in a controlled manner over the period of treatment.

Important applications of this technology include the administration of chemotherapy and the treatment of chronic pain.[23] Drug dosage can be reduced, and the therapy can be delivered right to the desired site by careful placement of the catheter.

Diabetes can be very effectively treated by administration of insulin with an implantable device. It has long been known that the matching of insulin administration with the eating habits and glucose profile of the patient can benefit the patient and help avoid such debilitating side effects of the disease such as kidney failure, degradation of vision, and gangrene. An implantable insulin-delivery system has been developed and is undergoing extensive clinical trials in the United States.[24] Current devices are programmable and can be programmed to deliver the drug in the most effective manner over the twenty-four hour time period. The ultimate goal is the achievement of a closed-loop system, combining a glucose monitor and a drug delivery system that would administer the insulin in response to the sensing of the glucose monitor. This system could accurately be called an artificial pancreas, since it would mimic the detection and insulin-delivery activities of that organ.

Treatment of Hearing Disorders

Millions of people suffer from hearing disorders. The social and psychological effects of hearing loss can be devastating, and many people turn to external battery-powered hearing aids for help. Such hearing aids are highly effective for many people, but some hearing disorders are not greatly improved by hearing aids. Several different implantable hearing devices have been developed in the last few years and are proving effective for treatment of hearing loss.

Cochlear implants treat profoundly deaf patients by stimulation of various sites in the cochlea with multiple electrodes. They have been demonstrated to be effective in treating deafness in patients and are in fairly common use today.[25,26] Such devices are powered by secondary batteries.

Other devices have been developed that treat less profound but still serious hearing loss. Such devices typically convert acoustic signals into mechanical energy. This energy is then used to stimulate either the ossicular chain[27] or other parts of the inner ear anatomy to increase hearing ability. Secondary batteries, often lithium ion batteries, are used in these devices.

One implantable hearing device under development and evaluation uses pacemaker-like technology combined with mechanical technology to treat hearing loss.[28] The device is implanted by interruption of the ossicular chain and installation of a piezoelectric sensor and driver and detecting sound from the malleus and stimulating the cochlea using the tympanic membrane as a microphone. The sound processing part of the device looks much like a pacemaker and is powered by a lithium/iodine pacemaker battery.

Treatment and Monitoring of Patients Through External Medical Devices

There are many external medical devices that rely on electrochemical power sources for their operation. These devices include life-saving products such as the automatic external defibrillator, external drug-dispensing devices, monitoring devices used in detection of cardiovascular problems, and more common devices such as wheelchairs and hearing aids.

External defibrillators have been in use for decades, but more recently, automatic devices that can be used by laypersons with little training have been developed.[29] These units have the capability of detecting as well as treating ventricular fibrillation. They are increasingly being installed in airports, businesses, office buildings, schools, and airplanes. They are powered by either primary or secondary batteries.

External drug delivery systems are used not only in hospitals but are worn by patients as well. Many insulin-dependent diabetics use an external drug delivery device that administers insulin through the skin via a syringe connected by a tube to the device.[30] These devices typically use commercially available primary or secondary batteries.

Several medical devices monitor various health-indicating parameters to provide health care professionals with information necessary to prescribe treatment. Battery powered glucose monitors provide diabetics with readings of their glucose level. Holter monitors are worn for twenty-four hours and continuously record and store electrocardiogram signals for analysis by the cardiologist. Advances in technology have reduced the size of such items from backpack-type devices in the 1960s to smaller, cell-phone sized devices today. Portable sphygmomanometers are commonly used by patients to monitor their own blood pressure.

Transcutaneous electrical nerve stimulation (TENS), uses external electrical stimulation through the skin to provide relief of pain. These battery-powered devices use high-frequency electrical stimulation to disrupt the pain signal. They provide relief for many patients.

The list could go on for many pages. Battery powered external devices are taken for granted today, and the ability to detect, monitor, and treat medical conditions with them is an important part of medical care.

Summary

The last forty years have seen remarkable advances in the development of battery-powered implantable and external devices for the detection and treatment of disease. Pacemakers forty years ago were the size of hockey pucks, lasted less than three years, and did nothing but provide pacing signals to the heart. Today's pacemakers are much smaller, last between six and ten years, and detect whether the heart has beat, adjust the heart rate automatically to body activity, record medical information, and treat congestive heart failure. Likewise, ICDs have been greatly reduced in size, and their capabilities have advanced from simple shocking devices to sophisticated treatment of tachycardia and ventricular fibrillation. A remarkable variety of diseases are treated by neurostimulators and drug delivery systems. Hearing loss can be treated more effectively by implantable devices.

Likewise, the development of external devices using batteries has progressed greatly in the past few decades. Health care providers and patients take for granted the availability of detection, monitoring, and treatment devices powered by batteries. Device engineers, medical professionals, and battery scientists have worked together to provide these remarkable devices, and these advances continue today with such "bionic man" devices as artificial vision, gait assist devices, the artificial pancreas, and other such devices under development.

Making all of this possible is the technology of electrochemical power sources. The advancement of both primary and secondary battery technology has made the development of medical devices possible. Electrochemical power sources are truly an integral part of modern health care. ■

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