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The future of lithium and lithium-ion batteries in implantable medical devices

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Abstract

New implantable medical devices and applications are being developed at a rapid rate. Many of these applications have higher power and/or energy requirements than existing applications. These needs will drive the development of new primary lithium chemistries and the implementation of rechargeable lithium-ion technology. © 2001 Elsevier Science B.V. All rights reserved.

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1. Background

Lithium primary batteries have played a vital role in the successful development of a wide range of battery-powered, implantable medical devices. The universal adoption of lithium battery technology in these applications can be ascribed to the high energy density and high voltage afforded by the lithium anode. High energy density is critically important to minimizing the size of the implanted device, and high voltage allows circuits to be powered by a single cell. The ability to develop systems that exhibit excellent long-term (>10 years) material and performance stability has been of equal significance.

The major battery chemistries used in implantable applications are summarized in Table 1. With careful attention to battery design and manufacturing practices, each of these battery chemistries has proven to be extremely safe and reliable and well suited to its particular application. Thus, the development and/or implementation of other battery technologies will occur only if there are substantial driving forces.

Power requirements for selected applications are also summarized in Table 1. These should be viewed only as representative examples. In certain cases, such a neurological stimulators (e.g. spinal cord stimulation), actual power requirements can vary by a wide margin and it is difficult to define a "typical" situation.

2. Future needs

There are many driving forces that are likely to dramatically change the battery technology used in implantable medical devices over the next several years. Many developing technologies will affect either the peak power requirements or average power requirements for the battery. Some examples are summarized below.

2.1. Microprocessor-based devices

Modern pacemakers (and the majority of other implanted devices) incorporate microprocessors and substantial amounts of memory. The development of complex processing algorithms drives the implementation of higher clock speeds, more memory, and longer processor duty cycles. All of these contribute to higher peak power requirements during processor use. While these power requirements may be insignificant compared to peak power requirements for certain devices (e.g. cardiac defibrillators), they severely tax the rate capability of the lithium/iodine batteries used in present-day pacemakers. Hence, extreme attention must be given to power management in microprocessor-based pacemakers.

2.2. Improved telemetry systems

Transfer of data to or from an implanted device is accomplished via an antenna internal to the implanted device and an external antenna ("programming head") placed directly over the device. Future devices will be

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Table 1
Most common applications and batteries for implanted medical devices

Most common application	Implanted device	Typical battery chemistry	Typical power requirements
Bradycardia (too slow heartbeat)	Pacemaker	Li/I_2	30–100 μW
Ventricular tachycardia (too fast heartbeat) or fibrillation (disorganized beat)	Cardioverter defibrillator (ICD)	Li/SVO ($Li/Ag_2V_4O_{11}$)	30–100 μW (pacing) + 10 W for defibrillation
Management of chronic pain/deep brain stimulation	Neurological (spinal chord) stimulator	$Li/SOCl_2$	300 μW to several mW
Spasticity (resulting from injury or disease)	Drug pump	$Li/SOCl_2$	100 μW to 2 mW

capable of communication over greater distances (several meters) to facilitate remote monitoring of the device via the Internet. In addition, the availability of large amounts of memory in the implanted device permit increasing storage of diagnostic data, device/patient history, and statistical information. Data transmission rates and corresponding power requirements must increase proportionately to maintain telemetry sessions of acceptable duration.

2.3. Smaller size

Batteries occupy approximately 25–60% of the volume of a typical implanted device. For power intensive applications, such as ventricular defibrillation, smaller battery size can only be achieved by improving power density. For applications with high average power requirements, such as spinal cord stimulation, higher energy density is the more critical parameter.

2.4. New applications

There are an incredible number of new applications that require only relatively minor changes to existing technologies. A prime example is the extension of conventional pacemaker technology to congestive heart failure applications. This involves pacing the left ventricle in addition to the right side of the heart, increasing the average power (and hence, energy) requirement. Several other future applications are listed in Table 2.

2.5. More electrodes for neuro-stimulation devices

The number of chronic-pain patients treatable by neurological stimulators and the efficacy of the therapy can be dramatically expanded by increasing the number of sites (along the spinal cord) that can be stimulated. This is accomplished by increasing the number of stimulation electrodes and, proportionately, the average power requirement. In addition, multiple lead systems can permit stimulation in two or more locations. Dual lead systems are also important in deep brain stimulation applications (e.g. treatment of Parkinson's disease and other movement disorders) to allow stimulation of both sides of the brain with a single implanted device. These types of devices are already available and will continue to grow in complexity and importance.

2.6. Treatment of multiple disease states

Many patients that receive implanted devices suffer from more than one disease state. Hence, devices that treat multiple disease states are becoming increasingly important. A recent example is the Medtronic Jewel AF® which provides therapies for ventricular tachycardia and fibrillation, atrial tachycardia and fibrillation, as well as conventional pacing. In the future, the combination of multiple therapies into a single device will become increasingly important and may become the norm rather than the exception.

Table 2
Summary of new implantable applications requiring power sources

New application	Description or example
Congestive heart failure (CHF)	Pacing in left ventricle (in addition to right ventricle and right atrium) to increase cardiac output Increases average power requirement
Atrial tachycardia	Preventative or therapeutic pacing of the atrium Therapies involve high pacing rates
Deep brain stimulation (DBS)	Exciting new treatment for symptoms of Parkinson's disease and tremor Similar to existing neurological stimulator technology
Cochlear implants	Direct stimulation of the auditory nerve to treat profound deafness Small size with high energy requirements
Monitoring-only devices	Pressure sensors placed in the heart to optimize drug therapy for congestive heart failure Continuous loop recorders to monitor infrequent cardiac events

3. Technical approaches

From the preceding discussion, it is clear that there are several needs that must be addressed to support future device requirements. These include the ability to maximize the battery performance for existing technologies, the development of a higher power battery system with high energy density to replace the Li/I_2 battery, and the development of a high energy system (i.e. rechargeable) for devices with high average power requirements. Each of these needs is discussed below.

3.1. Modeling and power management

In many instances, increasing peak power demands can be addressed by careful power management. This requires accurate discharge and transient response models of the battery. We have developed such models for the lithium/iodine and lithium/silver vanadium oxide battery systems. These models are physically-based (i.e. contributions to resistance are assigned to physical components and/or electrochemical processes) and can be used to accurately predict the performance of new battery designs under a wide range of steady-state discharge and transient conditions [1–4]. In addition, the identification and measurement of those physical elements that contribute to voltage loss allows typical battery-to-battery variation to be quantified. This information, in turn, can be used in Monte Carlo simulations to predict the performance variation of new battery designs. This information is extremely valuable in optimizing both circuit and battery designs to occupy the minimum possible volume.

An example of the output of this modeling approach for the lithium/iodine system is shown in Fig. 1a–d. The cathode of this battery is a two-phase material consisting of crystalline iodine and a conductive material produced by the reaction of iodine with poly-2-vinylpyridine. The phase boundary is illustrated in Fig. 1a. The resistance of the battery has been shown to primarily attributable to the cathode resistance, the electrolyte resistance (i.e. the LiI

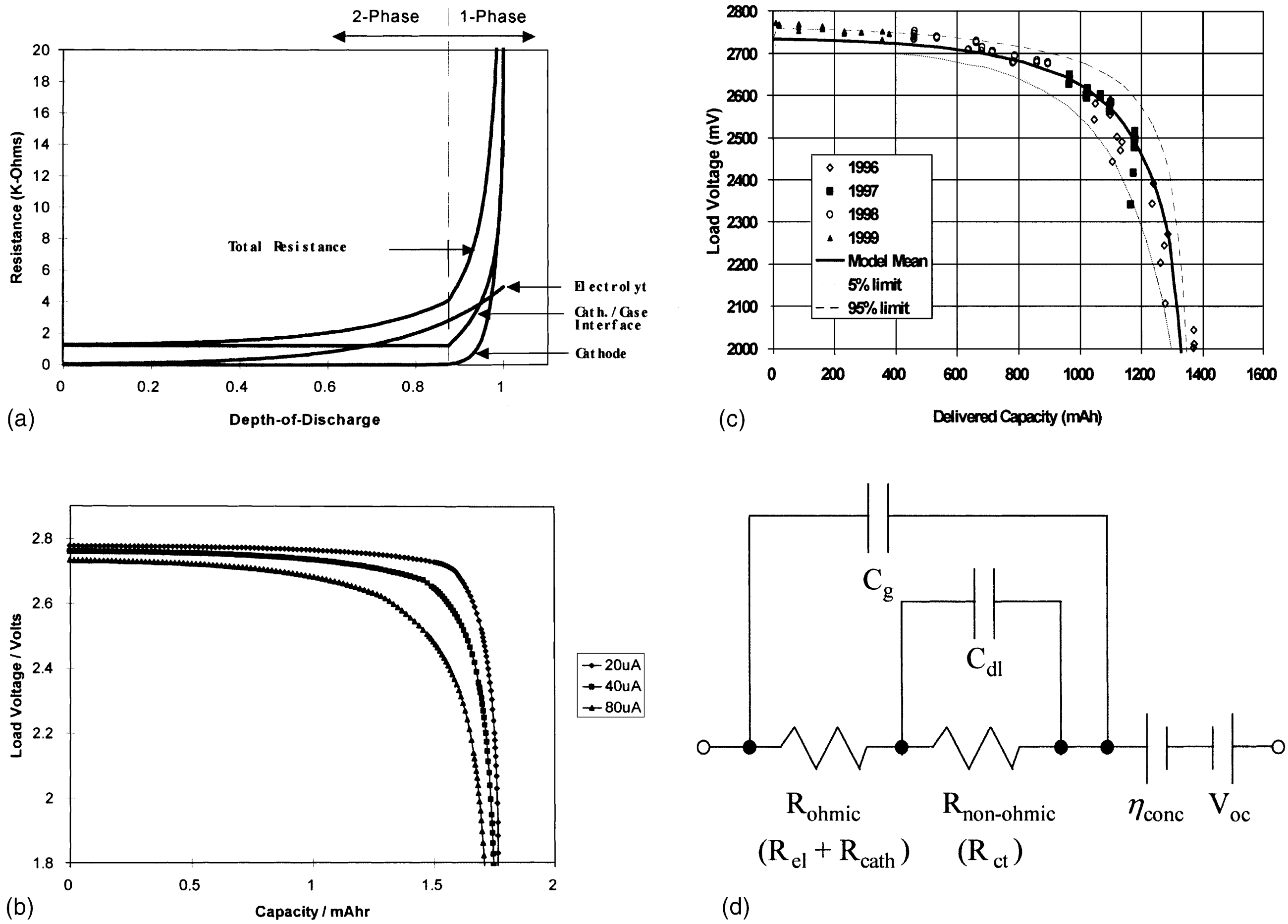

Fig. 1. (a) Contributions of various cell components to total cell resistance of the Li/I_2 battery; (b) predicted discharge curves as a function of current given the resistance model in (a); (c) predicted discharge curve with 5 and 95% tolerance bands based on a Monte Carlo Simulation of a constant load (43.2 kΩ) discharge. Data from 4 years of production samples are shown; (d) equivalent circuit model (C_g: geometric capacitance; C_{dl}: double-layer capacitance; R_{el}: electrolyte resistance; R_{cath}: cathode resistance; R_{ct}: charge transfer resistance at cathode/case interface; η_{conc}: concentration polarization; V_{oc}: open-circuit voltage).

discharge product) and the cathode-case interfacial resistance (the battery case serves as the cathode current collector). We have developed functions that describe each of these contributions to resistance. The functions are dependent on cathode composition, electrode area, current density, and 13 design-independent parameters that describe characteristics of the cathode, electrolyte, and interfacial resistance. The resistance contributions are shown in Fig. 1a, and the corresponding discharge curves calculated with this model are shown in Fig. 1b. By measuring the 13 design-independent parameters for a large number of batteries of various designs, it is possible to characterize their statistical distributions. This information can be used to estimate the performance distribution of a new battery design via Monte Carlo simulation. The output of such an approach is shown in Fig. 1c, where the model is compared to data from production cells. Finally, the assignment of resistance contributions to physical elements of the battery allows the construction of an equivalent circuit model from impedance spectroscopy data. This is shown in Fig. 1d. An equivalent circuit model such as this is extremely valuable in developing power management algorithms.

3.2. New primary chemistries

The greatest need for new primary chemistries is in the areas of cardiac pacemakers and neurological stimulators. The former need is driven by higher peak power requirements while the latter is driven by higher average power requirements as described earlier. These batteries must maintain the high energy density and reliability of the lithium/iodine battery while offering much higher power capabilities. Possible replacements include existing chemistries such as Li/CF_x or new technologies such as Li/hybrid cathode systems [5,6]. An example of a viable Li/hybrid cathode system is shown in Fig. 2. This system uses a cathode composed of a mixture of carbon monofluoride and silver vanadium oxide (CF_x–SVO) along with a carbon conductivity enhancer and a PTFE binder. It is compared to a Li/I_2 cell in identical hardware (5.6 cm^3, 6 mm thick) and under identical discharge conditions. This hybrid system provides essentially the same capacity, with higher energy density (higher average voltage), no measurable self-discharge, and approximately a 50-fold increase in rate capability. This system also has higher energy density than the Li/CF_x system and provides much better end-of-service indication due to its more gradual loss of voltage as the cathode is depleted.

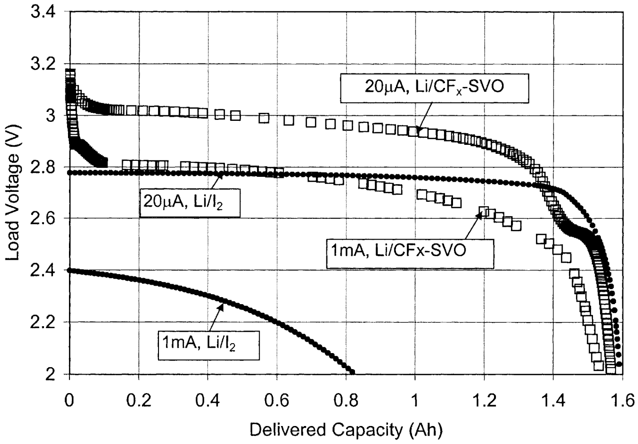

Fig. 2. Comparison of Li/I_2 and Li/CF_x-SVO batteries in identical hardware ("D"-shaped cell, 6.3 cm^3, 6 mm thick) under identical discharge conditions.

3.3. Rechargeable batteries

For those systems that require high average power or extended longevity, rechargeable batteries are a viable option. The batteries can be recharged by inductive coupling as was successfully demonstrated in a commercial pacemaker in the late 1960s. There are many likely applications for this technology in implantable medical devices. Some likely candidates are neurological stimulators, cochlear and middle-ear implants, and other non-life-support applications or features. We do not expect rechargeable batteries to be used as the sole power source for life-support devices or features. This is not related to any perceived reliability issues associated with the battery, but rather the undue stress and responsibility that would be rendered to the patient and/or physician. Alternatively, rechargeable batteries may be acceptable for life-support applications if the device incorporates a primary battery backup. This concept has been proposed by Terumo, a Japanese company that is developing rechargeable pacemaker technology [7].

The most likely rechargeable system for use in implanted devices is lithium-ion technology due to its high voltage, high energy density, and low self-discharge. A 5-year longevity is typically the minimum desired longevity for an implanted device. Thus, acceptable performance of this technology would likely require a 5-year lifetime with at least 50% capacity retention under a weekly (or less frequent) recharge regime. We have already demonstrated this performance using commercial lithium-ion cells. Four different cell types from four different manufacturers were tested. The cells were removed from consumer electronic power packs obtained in late 1994. All cells used a $LiCoO_2$ positive electrode but varied in the carbon material for the negative electrode and in electrolyte composition. The tests consisted of simulated application conditions (37°C, 2 h charge to 4.25 V without voltage hold, weekly or monthly discharge rate to 80% depth-of-discharge or 3.0 V). Typical results of these tests are shown in Fig. 3.

Several conclusions can be drawn from these data. First, all of the cells performed well under the long-term 37°C exposure. Second, there is significant time-dependent loss of capacity in at least three of the cells (the prismatic cells are still able to deliver 80% of their initial capacity without

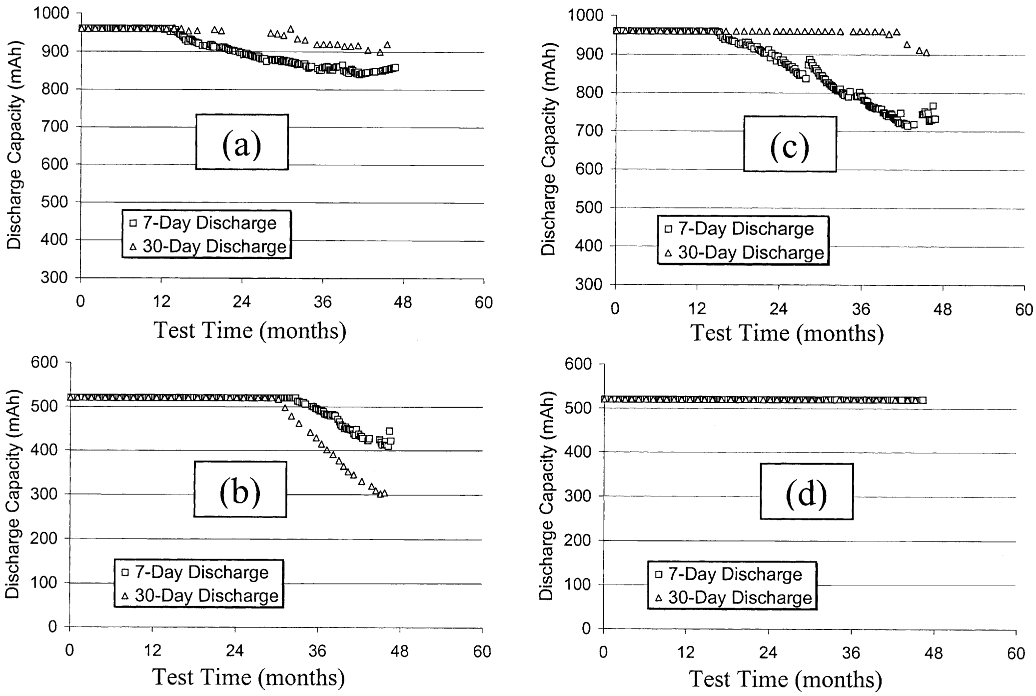

Fig. 3. (a) Vendor A, 18650, 1200 mAh; (b) vendor B, A-size, 650 mAh; (c) vendor C, 18650, 1200 mAh; (d) vendor D, prismatic, 650 mAh.

hitting the 3.0 V cutoff). In fact, time-dependence is a bigger factor than cycle number under these slow cycling conditions. Third, the cells can survive long-term, open-circuit storage with no apparent permanent loss of capacity. This is not apparent from Fig. 3 without further explanation. All of the cells in this study were stored for 9 months in an open-circuit mode due to a test system failure. This 9-month storage is not shown on the time axis of Fig. 3 (hence, the *x*-axis title of "test time"). The state-of-charge was not controlled during this storage, but the cells ranged from nearly fully charged (4.1 V) to fully discharged (3.0 V). No cells exhibited any measurable permanent loss of capacity after this unplanned storage. Therefore, it appears that lithium-ion technology is well suited for implantable applications in terms of long-term performance characteristics.

4. Conclusions

New implantable applications are being developed at a rapid rate, and many of these applications will have markets that will rival the traditional pacemaker and defibrillator applications. While the requirements for some of these applications may not yet be known in detail, several outcomes seem clear.

1. The energy and power density requirements for these applications will maintain the dominant position of lithium batteries.
2. Battery performance modeling will become increasingly important in the effort to optimize battery/circuit performance and minimize device volume.
3. The Li/I_2 batteries that have dominated pacemaker applications for the past 25 years will be replaced by higher power alternatives.
4. Rechargeable lithium-ion batteries will become an important power source for non-life-support devices or features that have high average power requirements.

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