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Performance and management of implantable lithium battery systems for left ventricular assist devices and total artificial hearts

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Abstract

A lithium ion cell designed for implantable medical devices was tested for its performance as a power source for left ventricular assist devices (LVAD) or total artificial hearts (TAH). These two cardiovascular devices require high power, and thus a high current (0.5–3 A) and high voltage (20–30 V). Since these are implantable medical devices, in addition to high power capability, the power source should have long cycle life and calendar life, as well as high safety. The QL0700I, a 700 mAh cell, was cycled at 0.5*C* rate as well as at 1.5*C* rate, and the cycle life capacity retention was evaluated after numerous cycles. A battery pack consisting of seven QL0700I cells in series, with a battery management system (BMS) connected, was tested for rate capability as well as safety protection.

Keywords: Lithium ion battery; Implantable; Medical device; TAH; LVAD

1. Introduction

An implantable battery system is a crucial component of implantable medical devices. Lithium ion secondary batteries have been shown to be preferable for implantable systems due to their high energy density, long cycle life and relatively small change in temperature during cycling [1]. Additionally, an implantable power source should have qualities such as custom shape, reliability, advanced safety, hermeticity, long calendar life and low self-discharge, which can also be achieved by a lithium ion battery [2–5].

In addition to the above implantable battery characteristics, cardiovascular devices such as the left ventricular assist device (LVAD) and total artificial heart (TAH) have high power requirements, demanding high currents and high voltages. These power requirements are so high that they usually require a large external power source. The addition of an implantable rechargeable power source can allow the patient to be completely disconnected from the external power source for about 30 min. The LVAD is a pump system, which can assist a weak heart in pumping blood through the body. The TAH is a mechanical pump, which completely replaces the heart of the patient. Both of these devices require a battery, which is capable of cycling at high rates, in the range of 0.5–3 A of current, but on average around 1 A. The battery must be able to do so without compromise on performance and long life, since it is expected to last for several years. It is also necessary to combine batteries in series in a battery pack, in order to achieve high power requirements, with a working voltage of between 20 and 30 V. This battery pack should include a battery management system, in order to control the cycling of the pack and also to provide extra safety precautions to the system.

In the present paper, the performance of a lithium ion battery in LVAD and TAH applications will be discussed. The performance of a battery pack with a battery management system will also be discussed.

2. Experimental

Cell performance was tested at 37 °C, simulating body temperature. The QL0700I, a 700 mAh cell, was cycled in the

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range of 2.7–4.1 V with one of two different cycling schedules. The first, 0.5*C* cycling, consisted of 0.5*C* charge to 4.1 V and constant voltage charging until the current declined to 0.05*C*, and a 0.5*C* discharge current until 2.7 V. The second, 1.5*C* cycling, had the same charge schedule, but a discharge at 1.5*C* current instead of 0.5*C* current. At 1.5*C* rate, the continuous discharge is at 1.05 A, which is the average current necessary to supply power to drive a TAH [6]. The rate capability of the cell was also tested, with similar charge schedules as described above, but with discharge rates at 0.2*C*, 0.5*C*, 1*C* and 2*C*. Pulse capability with 0.5 s, 3 A pulses was also performed.

The pack performance at different rates was also tested, similarly to the individual cell testing. In addition, safety performance of the pack was tested, by overcharging the pack at 1.5*C* rate continuously, until the battery management system shut down the current by increasing the resistance of the circuit.

3. Results and discussion

3.1. Cell performance

The capacity of the cell versus cycle number is shown in Figs. 1 and 2, for the 0.5*C* and 1.5*C* cycling, respectively. Both tests were performed at 37 °C and are still continuing. The 0.5*C* cycling has reached 2000 cycles, with 550 mAh of capacity still remaining, which is 75% retention of the original capacity. The 1.5*C* cycling has completed 1000 cycles,

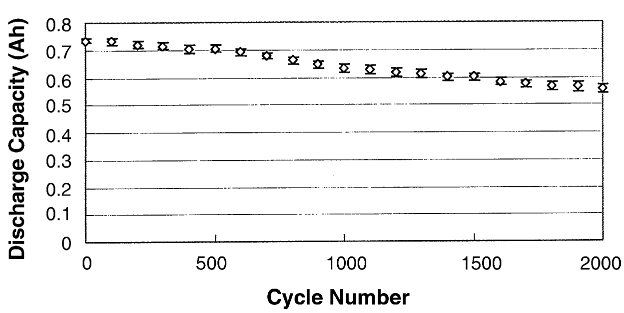

Fig. 1. Cycle life of QL0700I cell at 0.5*C* rate, 37 °C. After 2000 cycles, the capacity retention is 75%.

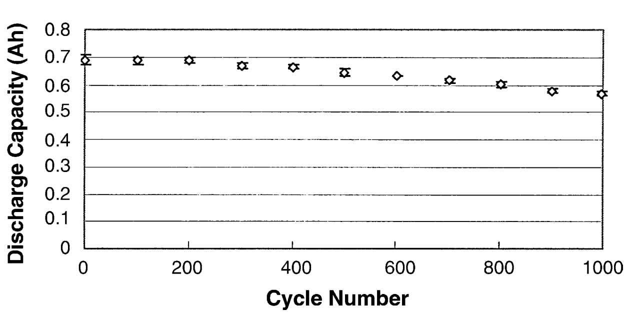

Fig. 2. Cycle life of QL0700I cells at 1.5*C* rate, 37 °C. After 1000 cycles, the capacity retention is 81%.

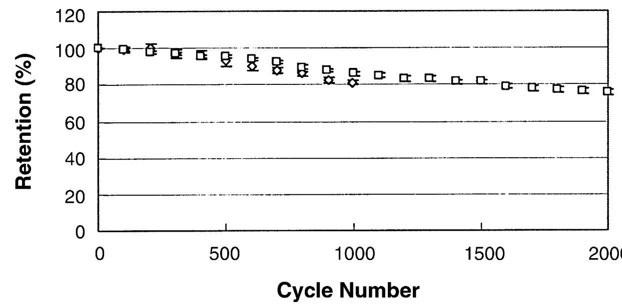

Fig. 3. Comparison of cycle life at 37 °C, with different discharge rates. The discharge capacity retention vs. the initial capacity is plotted, vs. cycle number, for 0.5*C* rate (□) and 1.5*C* rate (◇).

with 570 mAh and 81% capacity retention. Fig. 3 compares the retention of capacity for the two different cycling schedules. Since the average discharge current for LVAD and TAH is around 1 A, the 1.5*C* cycling performance, which includes a discharge rate of 1.05 A, is especially important. In this case, the 1.5*C* cycling is comparable to the 0.5*C* cycling performance. It is also important to note the uniformity of the cycling performance of several cells. The standard deviation of the capacity retention is 1–3% for the different cycle numbers. If the cycle life was not uniform, then with varying cell capacities, the cells would not cycle in sync with each other. Therefore, the cells of the battery pack would reach their maximum charging voltages at different times, so some cells may be charged to a higher voltage than the optimal voltage for the design, and the performance would degrade more quickly. For the same reason, matching of cell capacities may be required. Therefore, with uniform cells of matching capacities, the performance of the pack is maximized.

The rate capability and pulse capability of a power source is also important when dealing with cardiovascular devices. The QL0700I cell was tested for continuous discharge rate capability up to 2*C* rate, which is 1.4 A. The capacity retention at 2*C* was 87% of the capacity obtained by cycling the cell at a lower rate of 0.2*C*. As shown in Fig. 4a, the average discharge current for 2*C* rate discharge is about 3.45 V, which allows for high power, especially if cells are connected in series. Fig. 4a shows the discharge curves for the cell during discharge at different rates. Fig. 4b displays a comparison of the capacity retention for different discharge rates compared with 0.2*C* rate. Fig. 5 shows a pulse discharge of the QL0700I. This cell is capable of 3 A pulses, while still maintaining its nominal capacity. Such pulse and high rate capabilities are required by LVAD and TAH devices. Since this cell can still achieve high capacities at these high rates, it is a good candidate for these applications.

3.2. Pack performance

The combination of seven QL0700I cells in series results in a battery pack with a terminal voltage of around 24 V. For individual cells cycling in the range of 2.9–4.1 V, this

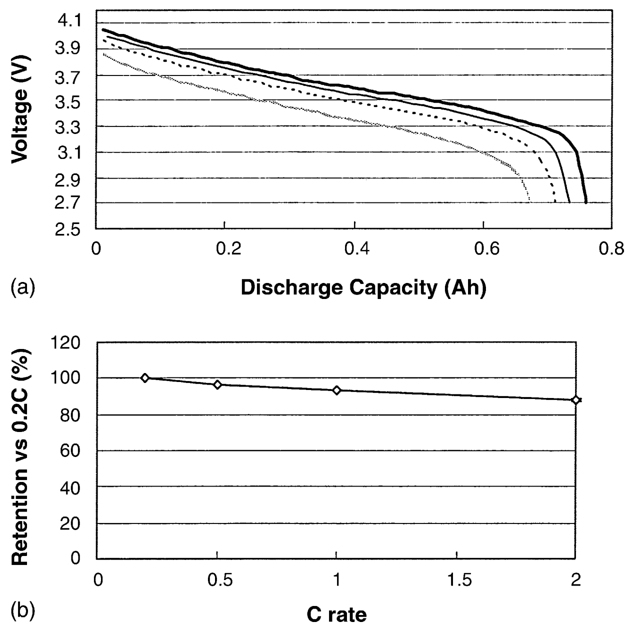

Fig. 4. Rate capability of QL0700I cell. (a) The discharge curves at different *C* rates are shown from 4.1 to 2.7 V, at 0.2*C* (thick line), 0.5*C* (thin line), 1*C* (dashed line) and 2*C* (dotted line). (b) Plot of the capacity retention vs. 0.2*C* discharge capacity.

translates to a pack voltage range of 20.3–28.7 V. The cells are connected to a battery management system (BMS), which manages the seven cells in series. The BMS includes the following important features: overcharge, overdischarge and high current protection, as well as battery voltage and temperature detection. The protection features function based on detection of individual cell voltages. The circuitry is designed to stop current flow if any of the cells exceed 4.3 V (overcharge protection) or decrease below 2.3 V (overdischarge protection). Another protection is for high currents, of over 3.3 A. When such a current is detected, the BMS shuts down any current flow. This important safety feature protects against short circuits, since it prevents unsafe discharge which occurs in such a case.

The overcharge protection is illustrated in Fig. 6. A cell pack was charged at 1.5*C* rate until the current was shut down

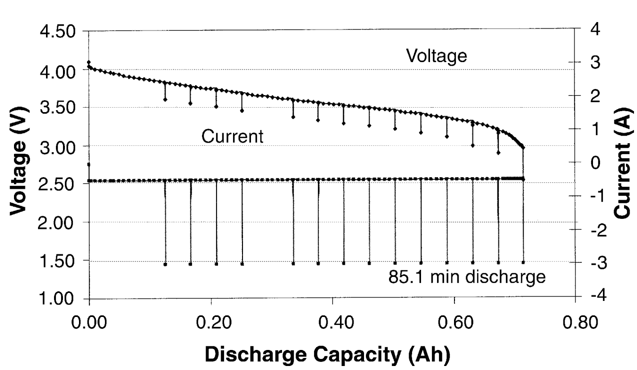

Fig. 5. Pulse capability of QL0700I at 3 A. The cell was discharged at 0.5 A for 5 min, alternating with 3 A pulses for 0.5 s until 2.7 V.

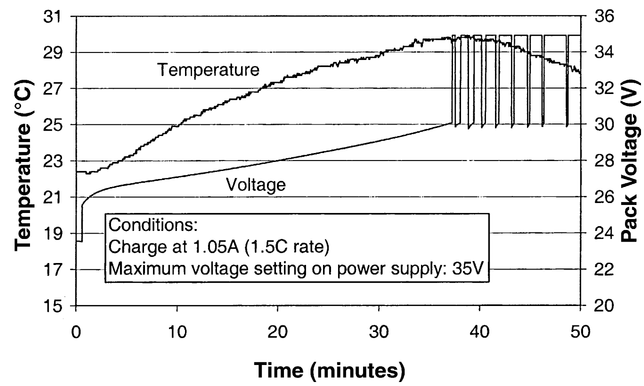

Fig. 6. Overcharge protection test. The temperature of the face of the battery pack is recorded, as well as the pack voltage. When the overcharge voltage of 30.1 V was reached, the battery management system shut down the current flow to the pack.

by the circuit, at 30.1 V (corresponding to 4.3 V for seven cells). When the voltage reached 30.1 V, the circuit caused a large resistance, and thus the voltage jumped to the maximum of the power supply used, 35 V, and the charging current was stopped. Once the cell voltages decreased below 30.1 V, the BMS would allow current to flow again.

The cycling performance of the pack is similar to that of the individual cells, as long as the cycle life of the individual cells is uniform. The rate capability of the pack is also similar to that of the individual cells. Fig. 7 shows the rate capability of the pack, with both the discharge curves for 0.2*C*, 0.5*C*, 1*C* and 2*C* and the capacity retention versus the 0.2*C* rate discharge capacity. Therefore, the packaging of the individual

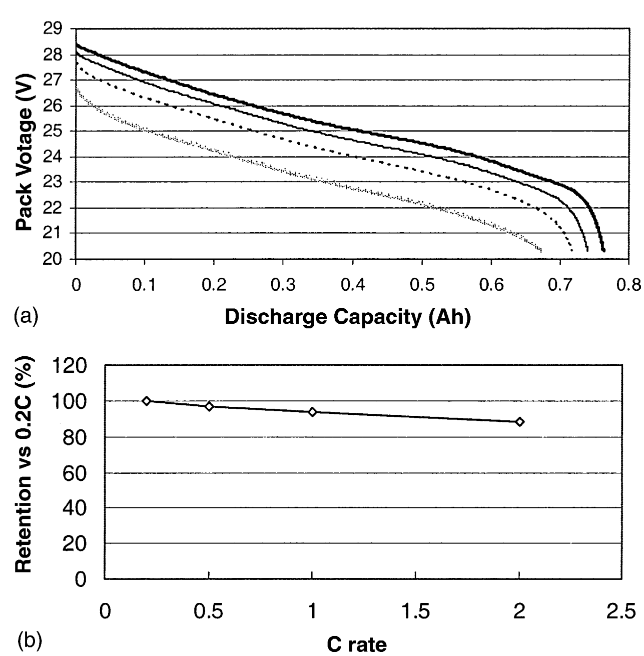

Fig. 7. Rate capability of battery pack. (a) The discharge curves at different *C* rates are shown from 28.7 to 20.3 V, at 0.2*C* (thick line), 0.5*C* (thin line), 1*C* (dashed line) and 2*C* (dotted line). (b) Plot of the capacity retention vs. 0.2*C* discharge capacity.

cells into the cell pack with the BMS does not adversely affect the cell performance.

4. Conclusions

An implantable battery pack with high power and long life is an essential component of both LVADs and TAHs. Without this pack, these devices would only be able to function by use of an external battery pack, limiting the freedom of patients to do certain activities. This pack can also serve as a backup to the external pack, in case the power is unexpectedly disconnected. In order to achieve the longest run-time of the device without external power sources, this implantable battery pack must have high energy density and also long life at high currents.

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