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All-Solid-State Lithium-Ion Batteries in Energy Storage for Medical Devices

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With the continuous development of medical devices, modern medicine becomes more reliant on the capabilities of these devices for therapy and diagnostics. Sophisticated equipment is usually more expensive and prone to damage due to sudden power loss or power surges. However, emergency power supplies do not keep up with the development of medical devices, and thus with the development of their needs. Traditional energy storage for uninterrupted medical power supplies is based on lead-acid batteries. All-solid-state lithium-ion batteries constitute an alternative that can provide the needed modularity, scalability, and safety required for these applications.

topics: lithium-ion batteries, energy storage, all-solid-state lithium-ion battery

1. Introduction

Modern medical devices used for therapy and diagnostics are becoming more sophisticated and expensive. As the capabilities of the equipment increase, the likelihood of damage due to sudden power loss also increases. For example, the cost of most up-to-date total-body positron emission tomography (PET) systems capable of simultaneously imaging of all tissues and organs of a patient exceed $10 million [1–4]. Such advanced multi-detector systems, including thousands of independent sensors, required precise calibration and synchronization, and even if a sudden power supply failure did not damage the system, it would require the running of new calibration and synchronisations procedures.

To prevent a situation where patients are not able to receive the needed therapy or diagnostics, uninterrupted power supplies (UPS) and emergency power generators are used. Currently used UPS are based on lead-acid batteries [5]. Although the electrochemical properties of this kind of batteries are well suited for this application, the high weight and volume cause difficulties in preparing a suitable energy storage installation [5]. Due to the weight [6], the ability to expand the energy storage is limited, which also limits the possibility to add new or upgrade existing protected medical equipment, because any such change will either reduce the backup time or force the devices to operate without adequate protection.

The properties of lithium-ion batteries show that they are a suitable alternative to energy storage for medical devices. Their lightness, energy density [7], and mobility also testify to their popularity in electrically powered mobile devices, ranging from smartphones, laptop computers, and power tools to electric vehicles and photovoltaic energy storage. Additionally, due to their growing popularity and availability, their price has come close to that of lead-acid batteries in recent years [7]. Replacing the liquid electrolyte in lithium-ion batteries with a solid electrolyte could address the safety concerns, making all-solid-state lithium-ion batteries a good alternative to lead-acid batteries not only in an economical level, but also in a safety level.

2. Lithium-ion batteries

A modern lithium-ion battery has three main components: anode, cathode, and an electrolyte layer separating them. The electrode materials are deposited on copper and aluminum metal foils, which act as mounting points and current collectors. During the charge and discharge cycle, lithium ions flow through the electrolyte from one electrode to the other. To enable the flow of lithium ions and to prevent the electrodes from touching, thus preventing an internal short circuit, liquid electrolytes need an additional layer of porous and nonconductive separator. Figure 1 illustrates a schematic of a lithium-ion battery [8].

Due to their high gravimetric and volumetric energy density[7], lithium-ion batteries can be a good alternative to lead-acid batteries, as shown in Table I.

The cost of energy storage [$ per kWh] ranges from 150 to 200 and from 126 to 800 for lead-acid and Li-ion batteries, respectively. Although the cost of lithium-ion based energy storage is usually

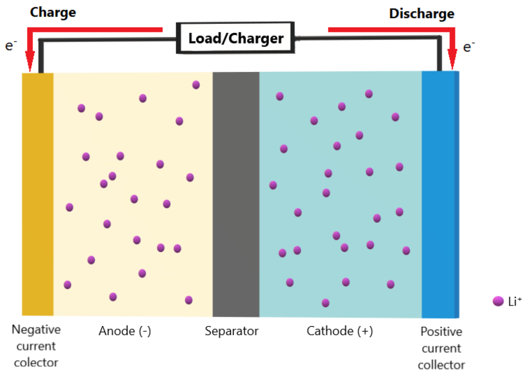

Fig. 1. Schematic of a lithium-ion battery [8].

TABLE I

Comparison of selected parameters of lithium-ion and lead-acid batteries [6, 7].

	Lead-acid	Li-ion
volumetric energy dens. [Wh/L]	80–90	90–450
gravimetric energy dens. [Wh/kg]	35–40	150–250
cost for 1 kWh [$]	150–200	126–800
high temp. performance	to 40°C	to 50°C
low temp. performance	to −30°C	to −20°C
cycle life	1500–5000	1000–5000

higher, due to continuous development, it is rapidly declining and has reached a point where it can compete with lead-acid based systems on an economic level. Additionally, by comparing the volumetric and gravimetric energy density, respectively, 80–90 Wh/kg and 35–40 Wh/L for lead-acid batteries and 150–250 Wh/kg and 90–450 Wh/L for lithium-ion batteries, the Li-ion-based storage system can be up to 7 times lighter while using 5.5 times less space than the lead-acid based counterpart. Due to the growing popularity and advances in research and technology, the cost of lithium-ion batteries has started to be comparable to the lead-acid alternative.

However, despite these advantages, they also have some disadvantages. The main ones are toxicity and flammability. Due to the large amount of stored energy, in the event of a catastrophic failure of a single lithium-ion cell, it is possible to produce enough heat to set fire to the electrolyte contained in the battery and damage the next cells, thus causing a thermal runaway event and the release of toxic combustion products. The reasons that can cause this type of failure are mechanical damage, an internal short circuit caused by e.g. lithium dendrites or overheating to the point where the separator melts and does not fulfill its function. Most of these problems are closely related to the liquid electrolytes used in lithium-ion cells. This is the main driving force behind research into all-solid-state lithium-ion batteries, in which the liquid electrolyte is replaced by a solid electrolyte.

3. All-solid-state lithium-ion batteries

Replacing the liquid electrolyte and the separator with a solid electrolyte could eliminate some or all of the above-mentioned disadvantages. Due to the form in which it is used, the solid electrolyte in all-solid-state lithium-ion batteries (ASSLIB) combines the functions of a separator and an ion conductor, while blocking the development of lithium dendrites, which can significantly extend the life of the lithium-ion battery and increase the safety of its use. However, solid electrolytes have their own challenges, the greatest of which are mechanical properties, conductivity, and ensuring proper bonding between the electrolyte and electrode materials. The current developed solid electrolytes for all solid lithium batteries can be classified into three main groups, namely inorganic solid electrolytes, organic solid electrolytes and composite solid electrolytes.

Table II shows examples of the conductivity for selected solid electrolytes in comparison with the typical conductivity of liquid electrolytes [9–12]. These conductivities are close enough that it can be considered that an important milestone in the development of solid electrolytes has been achieved. In this respect the already obtained solid inorganic and composite electrolytes can be a functional alternative to liquid electrolytes. However, there is still a need for suitable solutions having better mechanical properties and ensuring a suitable connection between the electrode materials and the electrolyte. Providing a connection allowing lithium ions to transfer from one electrode to the other during the charge/discharge cycle has proven to be a difficult task. Strategies that have proven successful include adding a small amount of liquid electrolyte [13], casting, aerosol jet printing, and 3D printing methods such as fused deposition modeling and stereolithography [14, 15]. An important advantage of solid electrolytes is their ability to suppress the growth of lithium dendrites, and thus allowing the usage of a lithium

TABLE II

Examples of conductivity of selected groups of solid electrolytes [9–12]. NASICON — sodium super ionic conductor; LISICON — lithium super ionic conductor.

Materials type	Electrolyte type	Conductivity [S/cm]
perovskite	inorganic	10^{-4}–10^{-3}
anti-perovskite	inorganic	10^{-4}–10^{-2}
NASICON	inorganic	10^{-4}–10^{-2}
LISICON	inorganic	10^{-6}–10^{-4}
sulfide	inorganic	10^{-5}–10^{-2}
polymer	organic	10^{-8}–10^{-3}
gel polymer	organic	10^{-4}–10^{-3}
liquid electrolyte	composite	10^{-3}–10^{-2}

metal anode. Although dendrites can still penetrate the electrolyte layer through cracks and grain boundaries [7, 16].

Inorganic electrolytes, which exhibit excellent ion conducting properties [9–12], tend to be brittle and therefore prone to cracking. This limits the possible shapes of the battery and increases the probability of shortening the lifespan of the designed battery due to mechanical damage. Polymer-based materials usually have good mechanical properties and can be more easily formed into the desired shape of the battery, although they exhibit a lower conductivity [9–12]. Therefore, composite electrolytes, combining two types of materials, seem to be a promising field for further research.

4. Conclusions

As medical devices, even PET tomography systems, start to become lightweight, transportable, and modular [17, 18], the power storage systems needed to protect them also must be developed in this fashion. All-solid-state lithium-ion batteriesdue to the rapidly declining price, constantly improved safety, development of new recycling methods, and departure from toxic heavy metals, seem to be the most suited for this kind of application. Though, there is still a need for more research to develop a suitable, environmentally friendly, and safe in operation solution.

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