2.19 Batteries

2.19.1 Clinical Use and Principles of Operation

While not a medical device in itself, the battery, like the generator, is often the source of problems in developing world hospital equipment. The battery comes in a wide variety of forms and can be used to provide electrical energy and portability to all types of clinical devices, from surgical lighting to high drain clinical devices (e.g., x-ray machine). The underlying purpose of the battery remains the same, to simply convert stored chemical energy into electrical energy which can be readily used by a given device.

Batteries come in many shapes and sizes. These rechargeable (secondary) cells are lead acid (bottom right) and nickel-cadmium.

There are two main classes of batteries, primary (single use) and secondary batteries (rechargeable). Primary batteries are becoming more common as the number of hand held medical devices grows. Primary batteries, or dry batteries, are typically alkali-manganese (alkaline), lithium, or carbon-zinc. Each of these chemical combinations is called a battery chemistry or a battery technology. Secondary systems include nickel-cadmium, nickel-metal hydride and lead acid batteries. These secondary systems are used with instruments that require greater amounts of electrical energy and particularly when recharging is a viable option.

Besides being described by their technology, batteries are described by their voltage and their capacity. The battery voltage is determined largely by their chemistry. For example, all alkaline batteries are 1.5 volts or can be put together to get multiples of 1.5 volts. The battery capacity is largely determined by the physical size of the battery. Unfortunately, the battery capacity is not rated in Joules or Coulombs, which would make most engineering or chemical sense, but in Amp-hours (Ah). One Amp-hour is the equivalent of 3600 Coulombs of charge.

A battery cell consists of four principle parts: an anode, a cathode, an electrolyte that provides the mechanism for charge flow between the anode and cathode (a gel in modern primary systems), and a porous insulator which electrically isolates the cathode from the anode.

The carbon-zinc battery serves as a useful example. The case is made of zinc metal, serving as one electrode and a carbon rod coated with manganese oxide (MnO_2) serves as the other. The electrolyte solution is ammonium chloride (NH_4Cl). The following reactions take place:

Zinc electrode: $Zn \leftrightarrow Zn^{2+} + 2e^-$

Carbon electrode: $2Mn^{IV}O_2 + 2H^+ + 2e^- \leftrightarrow 2Mn^{III}O(OH)$

The zinc electrode is oxidized, giving off two electrons into the solution. The manganese is reduced at the carbon electrode by the presence of the two electrons and the hydrogen ions provided by the ammonium chloride solution. This chemical reaction stimulates the electron flow once the circuit is complete. The electrons will continue to flow until the battery is completely discharged, i.e., the chemical reaction can no longer take place if either electrode is entirely oxidized or reduced.

Secondary systems differ from primary systems in that the chemical reactions are reversible. When you supply the appropriate electric energy to the terminals you recharge the battery. The lead battery can serve as an example. The lead-acid battery is a liquid-system battery and comes in two main forms, sealed and unsealed. Narrow gratings of lead or lead oxide (PbO_2) serve as the electrodes. The liquid solution is 20-30% sulfuric acid, serving as the electrolytic charge carrier. The oxidation and reduction equations are:

Oxidation: $Pb + SO_4^{2-} <> PbSO_4 + 2e^-$

Reduction:

$PbO_2 + 4H^+ + SO_4^{2-} + 2e^- <> PbSO_4 + 2H_2O$

Unlike the primary cell and its chemical reactions, both reactions in the secondary cell are reversible, allowing the lead battery to be recharged.

2.19.2 Common Problems

The most common problem with batteries in the developing world is that the batteries in the machine have stopped working and an exact replacement cannot be found. The problem can be essentially divided into two parts: (1) determining that the batteries are, in fact, beyond their useful life, and (2) devising a substitute battery from batteries which are available. Determining whether a battery is beyond its useful life depends on the technology (or chemistry, NiCd, Pb-Acid, etc.). So, battery life will be covered for each individual technology below. The second most common problem in the developing world is that the charger has been lost or broken, and you cannot find an exact match for that charger in the market. Charging is also technology specific and will be covered below.

Substituting Batteries

Devising a substitute battery is a topic which cuts across all of the technologies. The easiest problem is when you can find batteries of the appropriate technology, but not the appropriate capacity or voltage. If different voltages or capacities are desired connect the batteries in series to obtain more voltage, or in parallel to obtain more capacity (see example below). It is very rare that such combinations cannot be directly substituted for the cells that have been removed.

Example Pack Substitution

Assume you make a pack of 12, 600 mAh, 1.2 V, NiCd cells connected 4x3
(three sets of 4 batteries in series, the three sets in parallel).

The four cells in series provide
1.2 V x 4 = 4.8 V

The three sets in parallel provide
600 mAh x 3 = 1800 mAh

Therefore, you have created one, 4.8 V, 1800 mAh battery pack. To charge your pack, use
Trickle charge: 1800/100 = 18 mA for a few days
Max charge: for NiCd=C=1800 mA (1.8 A)

It is also common that you can find the batteries of the correct technology and the correct voltage and capacity (either by combination or alone), but the connection type is wrong. For example, the batteries that you have use solder tabs, but you need button connections. In these cases, simply solder wires to the circuit board and wires to the battery. When soldering onto a battery with button connections, use coarse sandpaper to rough up the surface. Then cover it with a large amount of solder – holding the soldering iron on the battery for as short a period as possible. Finally, melt the solder on the battery while holding the wire on top. You may still need to tape the wire on the side of the battery to avoid any physical strain on this relatively weak combination.

A more difficult problem is when you cannot find the correct technology, but must find a substitute battery. First you must typically match the voltage to within 0.7 volts. That is to say that the voltage of the replacement cell must match the original cell, or must be higher than the original cell. If the replacement cell is less than 0.7 volts higher than the original, you can probably use the substitute without modification for voltage. If the difference is larger than 0.7 volts, than use a diode in series with the battery to drop the replacement battery to within 0.7 volts of the original.

The capacity of the replacement cell is the most difficult item to match because capacity affects both the charge within the battery and the maximum amount of current that the battery can provide. The maximum amount of current that the cell can provide is sometimes specified as the cells internal impedance. Unfortunately, changing battery technology, even when identical capacities are selected, changes the internal impedance of the cell. Therefore, if the battery was selected by the designer purely based on its capacity (hand held devices without motors are often in this category), than a substitute technology will probably work as the impedance is not critical. In many situations, the medical staff will accept a shorter time between replacement cells (or recharging), so a lower or higher capacity substitute technology can be used, as long as the voltage criterion is met.

However, if the battery size was selected by the designer to meet a maximum current specification (x-ray, defibrillation, and many motor driven devices are in this category), then a change in battery technology, and therefore in internal impedance, could render the device useless. If you know the internal impedance of the cells you are removing (it can often be found on the manufacturer's web site, if you have internet access), then you can simply select a cell of lower internal impedance from a substitute technology. However, more typically, you will not have internet access. In this case, if you can find a working model of the device, you may be able to measure the maximum current drain and select a substitute battery capacity based on its ability to deliver that maximum current.

If there are not working examples of the equipment, you may have to resort to trial and error. As a starting point, for all primary and secondary cells (except lead-acid selected for current drain) you can probably switch battery technologies if the replacement cell has twice the capacity of the original cell. For lead-acid selected for current drain (such as x-ray and some motor applications), you will need a far higher factor of capacity to substitute technologies. Lead-acid batteries are available in the larger cities of the developing world. So, substitution of technologies in this case is not recommended.

In summary, the first step is to match the voltage of the replacement cell. The second is to select a capacity either based on the longevity of the device between replacement (or recharging), or on the ability to deliver the needed current.

When changing technologies, if the original battery was a primary cell, it should be replaced with a primary cell. They are cheaper to replace and will last longer before needing replacement. If you replace them with a secondary cell, then the hospital will have to find a replacement secondary cell at greater expense in just a few years.

However, if the original cell was a secondary cell, replacement with a primary cell is possible. In general, primary cells of the same capacity and voltage will have lower impedances and can be used as direct substitutes. If the charger is internal, however, primary cells cannot be substituted except in an emergency (a defibrillator that won't discharge without cells, for example), because charging primary cells can destroy the equipment and the cells.

If the original cell was a secondary cell and the replacement technology was a secondary cell, then you must be concerned with charging your replacement cells. It is generally impossible to find a battery which will both operate the device and will achieve the same performance charging as the original technology. If the difference is simply that longer charging times are needed, this can be explained to the staff. However, if the charger delivers excessive charge, then the cells and device may be damaged. You will have to also replace the charger, when you replace the secondary cells. Select the charger based on the replacement technology, as described below.

Substituting Chargers

A more and more common problem in the developing world is that the charger for a battery operated device is missing or broken. Most chargers are wall transformers with female coaxial connectors at one end. When replacing a broken charger, you need only match the input voltage (typically 110 or 240 V), the output voltage, the output type (AC or DC) and the output current capacity. Any physical characteristics of the charger are irrelevant, including the connector, since you can simply snip off the connector from the broken charger and solder it to your replacement, being careful to match the original polarity for DC chargers. There is nothing magical about wall transformers. You should feel free to substitute any power supply, including a variable, bench-top power supply, as long as it meets the specifications stated earlier.

If you do not have the original charger and the device is marked, then the original problem is only more complex in the sense that you do not have the connector. It is often acceptable to open the device and wire in a new connector (if you can find a male and female in the market). If you cannot find any connectors, simply bring out clearly marked bare wires (with alligator clips on the charger). There is little danger to the staff or device for any charging voltages below 24 volts.

If the device is not marked and the original charger is lost and you do not have the manual - a very common occurrence in the developing world - then a substitute must be divined. If you have made a substitute secondary battery, then you will also have to provide a replacement charger. In either case, you will have to determine the correct charging voltage and current based on the battery voltage, capacity and technology. Each secondary technology must be considered separately. The most common encountered in medical devices in the developing world are NiCd and Lead-Acid.

NiCd (Nickel Cadmium)

NiCd (pronounced Nye-Cad) batteries are less reliable in hotter climates because of an increased rate of self discharge. They are also less efficient at recharging at higher temperatures. A NiCd battery has a potential difference of 1.25 V which drops to 1.0 V when completely discharged.

To determine whether a NiCd cell is beyond its useful life, first measure the potential. If it is below 1.0 volts, the cells are probably not salvageable. Next, attempt to charge the cells (as described below). If the potential across a single cell does not increase to 1.25 volts, the cells are probably beyond their useful life. If the cells measure well open circuit, and can be charged, they may still have lost most of their capacity. Measure the voltage before and after a brief load of 10 times the recharging current of the battery (by placing a resistor across the cell of the correct size to obtain the required current for five seconds). Fully charged, properly operating cells will show only a slight difference, whereas older batteries will give a reading of less than 1.0 V after this brief load.

In some cases, apparently destroyed NiCd cells can be rejuvenated by erasing their "memory." This can be accomplished by fully discharging the cells at their charging capacity for one day. Then charge them at one-tenth of their charging capacity for 12 hours. Then, finally, complete a full charge of the cells.

NiCd batteries can be charged safely for essentially an infinite amount of time at 0.1 times their capacity (called 0.1C charging). In other words, if the cell is a 1000 mAh cell, then the cell can be charged at 100 mA for as long as you like. These are DC currents measured with the positive of the charger connected to the positive of the battery (or battery pack) and the negative connected to the negative of the pack. It will take 10 hours or more to completely charge a fully discharged cell. Charging at 0.1C is called trickle charging. Medical devices can be left on trickle charge for their entire non-use time. For faster charging, the NiCd can be safely charged up to 1.0C. In other words, a 2000 mAh cell can be charged at a maximum of 2000 mA. The cell will get very hot when charged at this rate, hot enough to burn. Be sure there is adequate ventilation to dissipate this heat or the cell will be destroyed. NiCd cells cannot be charged more than one hour when charged at 1.0C or they will be destroyed.

Lead-Acid

Lead Acid batteries have a voltage of 2.1 volts. However, they are typically sold and used in packages which include 3 or 6 in series, yielding 6.3 volts or 12.6 volts. The voltage does not change appreciably during discharge, perhaps 0.3 volts for a 12.6 volt battery when it is charged to 50% of capacity. A lead battery should be recharged by the time it has a residual capacity of about 30%. Any further discharging considerably shortens the life of the battery.

Take extreme care when working with lead acid batteries as hydrogen gas may build up if proper venting has failed. The buildup of hydrogen can cause the battery to explode. As you are dealing with a high capacity battery, care must be taken to avoid shorting the terminals. Remove all jewelry before working on the batteries. A single 12.7 volt lead-acid battery is sufficiently strong to destroy a finger if the a ring were to short the terminals. Keep the outside of the battery clean and free from damp and grease to avoid discharge between the terminals.

There are two main types of lead batteries, sealed and unsealed. A color indicator on the top of the sealed lead battery can tell you if it is necessary to recharge the battery. If no color indicator is available, it is easiest to perform a load test. A 100% charged 12V battery typically measures around 12.7V with a voltmeter, with only a 0.3V drop for a 50% charged battery. It is easiest to identify an exhausted battery by measuring the voltage before and after heavy use – the higher the difference in voltage the more depleted the battery.

The most reliable method to determine the battery capacity of an unsealed lead acid battery is to measure the density of (sulfuric acid) H_2SO_4. This can be done using a hydrometer. Hydrometers are available in auto parts stores in the developing world. The density of the sulfuric acid should be 1.23 kg/liter in tropical countries. If you do not have a hydrometer, you can typically get an auto parts store to measure your batteries for you. If you have a hydrometer, follow the directions on with the hydrometer. If no specific density measurement is possible, perform a load test as described above.

If the electrolyte level appears low or the acid level is too high, add water. Use only distilled water. If distilled is unavailable, bottled water or freshly collected rainwater may substitute in an emergency. If necessary make your own distilled water by cooling steam and collecting the condensate. Do not use tap water unless there is no alternative. If acid must be added, it can be purchased at auto parts stores.

When recharging lead acid batteries in tropical environments, the charging voltage should stay between 11.2 and 13.9 V. Limit the recharging current to less than one tenth of the capacity (<0.1 C). For example, limit the charging to 10 A for a battery rated at 100 Ah and 5 A for a battery rated at 50 Ah.

2.19.3 Suggested Minimal Testing

If the battery is operating and a proper charger is available, it is ready for release. There are no additional testing procedures required.