Project ID: 1894G Project Title: Enzymatic Sugar Fuel Cell

Abstract:

So much in our society needs energy. Humans need energy. Batteries need energy. Most batteries used in applications that require implanting electronics into the body wear out before the human does. All humans carry "batteries" within them, in the form of sugar. To make batteries that last as long as humans, we propose a two part plan. One is a device that removes sugar from the bloodstream. The second part of the plan is a device that takes the removed sugar and converts it into electricity for electronics. These two devices will work in conjunction as a blood sugar battery-generator device that may power prosthetic limbs, pacemakers, sensors, and other implants.

Present Technology

Batteries today work off the same principle. There is a cathode, anode, and electrolyte. The cathode is the positive end of the battery and the anode is the negative end of the battery. The electrolyte can be a liquid, but it is more likely to be a dry powder. Batteries slowly use up the chemicals that make up the electrodes and electrolytes to generate positive ions that have had some of their electrons removed. The electrolyte acts like an insulator as well to prevent electricity from jumping from the negative end to the positive end so the electrons actually flow outside the battery.

Present technology for batteries within the body are similar to generic batteries of this day and age. For pacemakers, they are lithium iodide batteries that last about ten years with some variance according to manufacturer. Over the past few years, the specs of these batteries improve slightly. Their lifetime and power output might go up a little bit as time passes. If a person lives long enough, they will have to get their battery replaced.

As for technology that generates electricity from sugar, the most common one utilizes starchy or sugary plants. These plants are fermented to produce ethanol that can be mixed in with other fuel or burned in specially made engines. The most recent advance in sugar to electricity technology occurred in 2014 at the University of Virginia. A cartridge is filled with sugar. Then, a combination of natural enzymes that are not typically found in nature together were used to strip all of the potential charges off of glucose molecules. This technology needs to be miniaturized and adapted for human implantation for it to function inside a human's body.

History

Fuel cells have had a long history of development since the concept of creating batteries that convert chemically stored energy directly to electrical energy have actually existed for more than a century. Even so, researchers have continued to improve batteries in hopes for it to become more efficient and environmentally-friendly.

The quest for a more efficient energy sources in such batteries can be dated back to when Galvani first discovered a relationship between biology and electrical energy in 1791 by showing that the frog leg would twitch from an electric current. Then, in 1839, the first fuel cell was discovered by Grove, who based it on the principle of electrolysis of water in which an electrical stimulation induces a chemical decomposition of water into hydrogen and hydroxide ions. Later, in 1911, the idea of using respiring microbes to convert chemical energy into electrical energy was introduced by M.C. Potter a botany professor at the University of Durham. He later built the first half cell using E. Coli. Building upon Potter's work, Barnet Cohen from the University of Cambridge built a biofuel cell in 1931 capable of producing over 35 volts when connected in a series.

Research into fuel cells was also inspired by efforts to create an artificial heart that can act as a power source and by the interest of the National Aeronautics and Administration (NASA) in recycling human waste into usable energy on board spacecraft. Such ideas resulted in development and testing of many more fuel cells. Many fuel cells developed used urea or methane as its main biofuel for generating power. Moreover, a new fuel cell that made use of enzymes rather than microbes was discovered by Yahiro, Lee and Kimble, researchers from the Space-General Corporation. Now known as an enzymatic battery, the bio-battery they designed used glucose as their fuel and a redox enzyme called glucose oxidase (GOx) that helped to create oxidation-reduction reactions. Since these discoveries were made, many more advances continued to occur to this day since power outages and functionality have always been lacking compared to chemical batteries. Microbial bio-batteries and enzymatic bio-batteries still continued to be the two main types worked on.

Future Technology

To make enzymatic sugar batteries a more efficient source of power for implantable devices, we propose to design a fuel cell with artificial phospholipid bilayers enclosing a part of the anode, the negative electrode, and the cathode, the positive electrode. The cell membrane around the anode would be embedded with protein channels that can transport glucose from the blood. Inside the “intercellular” space created by the cell membrane, there will be immobilized redox enzymes that will oxidize glucose to extract its electrons as well as protons (actually positive ions) through an enzymatic pathway. Redox enzymes are enzymes that catalyze oxidation-reduction reactions, which involves the transferring of electrons from a substance. Moreover, the cell membrane around the cathode would only serve to keep the enzymes in its space and allow for water to readily diffuse across. Moreover, the cell membranes for each electrode ultimately increase surface area to increase the likelihood for glucose and water to make contact.

As for the transferring of electrons to the electrodes, we plan to use the method commonly known as the direct electron transfer (DET) as opposed to the other method known as mediator electron transfer (MET), which uses mediators, usually cofactors that would assist in bringing the electrons to the surface of the electrodes. DET, as the name suggests, just means that the electrons will go directly to the electrode without the help of any mediator. The electrons and protons would flow from the anode to the cathode through the electrolyte. However, the separator would redirect the protons through the separator to the cathode end of the fuel cell while redirecting the electrons to flow around the fuel cell through the electrical load and back to the cathode. When the electrons reach the cathode end of the fuel cell, a reduction reaction will occur by adding the electrons and protons to oxygen, thereby creating water as a product. This whole process will complete the oxidation-reduction reaction and create the generation of electricity.

The redox enzymes that are used for the fuel cell are important, so after careful consideration, we have decided to use the enzyme glucose oxidase (GOx), laccase and some other synthetic enzymes in the prospect of new technological applications twenty years from now. Glucose oxidase from what we have researched is useful because it carries the flavin group, FAD, which allows the enzyme to be capable of undergoing oxidation-reduction reactions. Glucose oxidase enables the oxidation of glucose by first reacting with glucose to produce gluconolactone and hydrogen peroxide. The hydrogen peroxide is then used for oxidation, producing the necessary electrons and positive hydrogens ions. The other enzyme we chose, laccase, is an enzyme that would catalyze the reduction reaction of oxygen using electrons and hydrogen ions. Thus, while GOx is surrounded by the cell membrane around the anode, laccase would be surrounded by the other membrane around the cathode.

The material of the electrodes was also carefully considered as it is an important factor in electron transfer and efficiency. From the variety of choices, we decided to go with silver in order to make the electrodes because silver has high conductivity of electricity and has resulted in good performances when used for electrodes. Originally, we were going to use gold; however, because silver is less rare, has a higher conductivity and is cheaper, it became a better alternative. We hope to use a single wall carbon nanotube hybrid system on the electrode surfaces. Single-wall nanotubes or (SWNT) typically have a diameter of 1 nm and a thickness of a single atom.

Therefore, by employing it on the electrode surface, the micro nanotubes would increase surface area, an important factor in the fuel cell's performances in power density. Higher surface areas has actually been shown to increase the power density of a fuel cell because it would allow for larger areas of exposure to electrons. To attach the carbon nanotube of the SWNT on the electrode, we plan to covalently bond it to the electrode surface. Aside from increasing the surface area, the carbon nanotube also helps us improve the efficiency of the DET method. With the carbon nanotubes on the electrode surface, we can also immobilize the enzymes on the surface of the carbon nanotubes, using the same method of covalent bonds. This would bring the enzymes closer to the electrode surface, which would in turn increase the likelihood of glucose binding to the active site and the overall transfer rate of electrons to the electrodes. Other than increasing general rate of electron transfer, according to researchers, such methods of immobilizing the enzymes actually help extend their lifetimes. Generally, most enzymes last for a few hours to a few days, but by creating an enzymatic electrode in the sense, the life of the enzyme increases by more than a year.

Breakthroughs

To make the concept of an implant extracting sugar from one's own blood and turning it into electrical energy a reality, several breakthroughs are necessary. One is the creation of transport proteins so that only glucose and possibly oxygen enter the fuel cell. Also, any enzymes used in the fuel cell to strip off the membrane have to safely leave the body if the container ruptures or the container has to be made so it does not rupture. Consequently, the membrane also needs to interact in a way that it does not bother the immune system to the point where the immune system attacks the membrane. We also need a membrane that needs to last for a long time. In addition, a way to funnel out the waste products of water without putting too much water into the body needs to be discovered as well. The enzymes used in the fuel cell also have to last a long time without becoming denatured, which proteins typically do after being used many times. If the enzyme denatures quickly or the membrane degrades quickly, then they would have to be replaced regularly.Worst case scenario would involve doing so through surgery. Since this is extremely troublesome, we hope that the membrane and enzyme can last for much longer than one year. We hope that the battery could last for even more than 40 years through future technological advances. Finally, the fuel cell needs to find some way to utilize glucose molecules.

The sugar fuel cell created by Virginia Tech shows promise. According to researchers, the fuel cell they created has 596 amp-hours per kilo which is higher than the energy densities of lithium batteries. The problem with this is that the energy is generated from the glucose subunits of maltodextrin, which typically does not circulate through the blood of a human. Each glucose subunit produces 24 electrons, which means that a single molecule of glucose from blood will only yield 24 electrons. Maltodextrin is usually between 3 and 17 subunits long, meaning that in the worst case scenario with the experiment by Virginia Tech using 17 subunits, the glucose fuel cell would give 35 amp-hours.

A research experiment could be designed to measure the efficiency of the fuel cell. Create the fuel cell with a sensor measuring the amperage and voltage of the fuel cell and attach it to an animal with blood sugar levels close to a human. The amperage and voltage of the fuel cell should be measured over the course of a month and the animal should monitored for its sugar levels before, during, and after the fuel cell is attached to the animal.

Design Process

The first proposed idea was that the fuel cell would only get blood from the cerebrospinal fluid (CSF) that bathes the brain and protects it from banging into the skull. The lack of cells surrounding the brain would also prevent the body from initiating an immune response against the foreign membrane and coincidently, the blood cells here contain more glucose. However this is inefficient for the fuel cell to be in a certain place, while powering something in another location, as it would need a way of getting the power (physically) to other vital areas, without causing leaks or risk of leak.

The second proposed idea was to instead of have bio-batteries working off of enzymes, having bio-batteries working off of microorganisms on or in the host's body. Since the technology was already present, it had seemed like a good choice. But this idea did not seem feasible as it would be very difficult to isolate and extract these organisms without the contents getting contaminated with potentially dangerous microorganisms. Glucose in this case seemed more manageable, as it was not a live organism.

The last proposed idea was to separate the portion of the fuel cell that collects the sugars and the portion that converts it into electricity. In other words, the module that collects sugar would be a permanent insert placed into the body with a link module that sticks out of the body. The portion that converts the glucose into electricity would be detachable and would essentially act as a rechargeable battery that could be used for other electronics.. However, there are problems that arise from this, the first being that having detachable modules could leave room for contamination and cause more risks. Also the same problem of location arises as it does with the battery relying on the blood from the CSF. One would have to think of a way of getting electricity to a certain part of the body (suppose the heart) without causing any risk or intrusions. This would prove difficult, so a fuel cell attached to the desired device seemed more viable.

Consequences

The creation of a device that filters out sugar from blood and turns the sugar into electricity has numerous benefits and negative effects. In a world where prosthetics and implants are becoming more complex, longevity of batteries becomes a bigger problem.

Having a blood sugar fuel cell could eliminate the need for regular surgery to replace a battery for an implant. Simply put, a battery or fuel cell that generates its own electricity from sugar has no need to be replaced. This provides the benefit of not having to undergo surgery just to replace a battery for an implant deep in someone's body. A patient with a blood sugar fuel cell will not have to worry about their battery running out and getting surgery to place another one in. Less fear and anxiety is another psychological bonus.

On the other hand, a blood sugar fuel cell is bound to be expensive. Creating an artificial cell membrane and embedding it with transport proteins for glucose is a process that has been only used for science experiments. The power output of a glucose fuel cell also means that it probably cannot power a motor to move a prosthetic limb replacement, as MIT's prototype only produced enough power as a solar panel for a regular calculator, which is 2-3 volts. The power for this is more than enough for pacemakers and other devices.

The durability of the materials in this device is also questionable. Like all materials, they will degrade, especially inside something alive. There will be a large problem with any battery that breaks within the body. A biofuel battery will be full of enzymes that might wreak havoc on the body if the enzymes are let out of its container.

The glucose intake is also a problem. The amount of glucose that is filtered from blood will require more sugar to function as opposed to the glucose fuel cell that was bathed in cerebrospinal fluid. Cerebrospinal fluid has a concentration of 300 mg of sugar per deciliter whereas the concentration of sugar in the blood is between 70 to 100mh per deciliter in non diabetics and people who are not fasting. This means that a glucose fuel cell bathed in blood will produce about 0.47-0.69 volts. Glucose diverted into the blood fuel cell might be necessary for other body parts to retain optimal performance, which means out of the small amount of glucose in the blood, even less than that should be filtered out from the blood. Problems will arise from those who are diabetic and obese. The glucose draw from the bloodstream will increase the rate at which blood sugar drops. This could potentially limit high blood sugar for diabetics, but also increase the severity and frequency of low blood sugar. This may also potentially decrease the effects of excess sugar for obese people as well. The sugar battery developed by MIT mentioned previously has mentioned that the battery has been bathed in the glucose filled cerebral fluid without any side effects, so the glucose draw may even be negligible.

Overall, the benefits of an implantable blood sugar fuel cell outweigh the negative effects. The fuel cell will give its recipients a renewed feeling of independence, knowing that they do not have to be sliced open to replace the battery inside them and they are generating their own power.