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Mini review

Towards glucose biofuel cells implanted in human body for powering artificial organs: Review

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ABSTRACT

This review summarizes different approaches and breakthroughs of implantable fuel cells from the first noble-metal glucose fuels to the recent use of biocatalysts for selective glucose oxidation and oxygen reduction inside mammal's bodies.

Contents

1. Introduction

Since the first surgical implantation of a cardiac pacemaker in 1960 [1,2], many battery-powered implantable medical devices were developed for treatments ranging from neurological disorders to hearing loss. This area of research is continuously driven by great improvements in robotics and microelectronics. Concerning the power supply of such devices, lithium batteries, developed in the late 1960s, provided a small and reliable energy source with extended durability of more than 5 years in human bodies. For instance, pacemakers consume continuously 10 to 40 μW, which is easily provided by sealed lithium batteries. However, other implanted electronic devices need more energy, which represent an obstacle for their development. In particular, artificial organs require mW to Watts of power for their functioning.

Therefore, numerous efforts have been made to develop small power-supply devices, able to operate independently over prolonged periods of time without the need of surgical replacements. For instance, mechanical [3] and thermoelectric [4,5] generators take advantage of the energy created by body movements or temperature differences to harvest energy and to supply implanted devices. Inductive power transfer via radiofrequencies is also investigated in supplying or recharging electronic devices such as cochlear implants [6,7].

2. The glucose fuel cell

Glucose is one of the most important energy sources of many living organisms. It is provided by metabolic processes after breakdown of carbohydrates and is then generally oxidized to CO_2 and water via various aerobic metabolic pathways [8]. Glucose can provide up to 16 kWs per gram generating 12 electrons per molecule during these oxidation processes [9]. Fuel cell technology relies on the conversion

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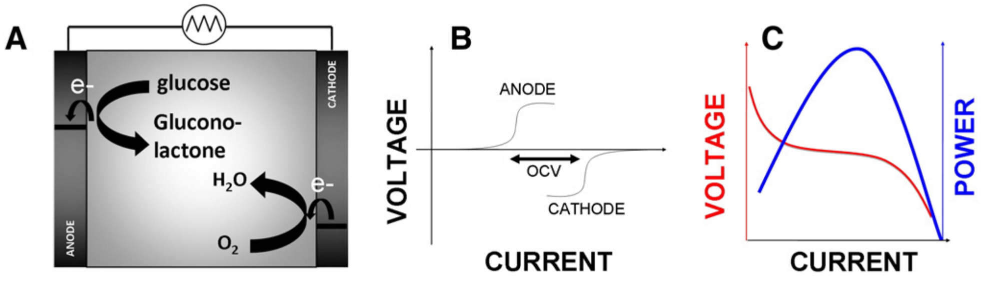

Fig. 1. (A) Schematic representation of a glucose fuel cell (B) simulated polarization curve for bioanode and biocathode (C) schematic polarization curve and power profile of a fuel cell.

of chemical energy into electrical energy from small molecules containing high amount of energy like glucose. Initially, the basic idea was to exploit only the first oxidation step of glucose providing two electrons at high voltage for the fuel cell device. The formed gluconolactone is then reinserted in the metabolism of the organism.

A glucose fuel cell (GFC) is a subtype of conventional fuel cells (using hydrogen or alcohols as fuels) that oxidizes glucose and reduces oxygen to give electric energy. A GFC is composed of two catalytic electrodes: the anode oxidizes glucose while the cathode reduces oxygen via electrocatalytic processes (Fig. 1A). At both electrodes, the electrocatalysis has to be performed at low overpotentials and high turnover to maximize fuel cell voltage and current (Fig. 1B). Generally, glucose is incompletely oxidized by a two electron/two proton process to generate gluconolactone whereas oxygen is reduced via a four proton/four electron process to water. Because glucose and oxygen are both present and continuously replenished in physiological fluids by the metabolism, this revolutionary approach is theoretically able to provide enough energy along the patient lifetime without any need of battery replacements. Furthermore, fuel cells can theoretically provide hundreds of mW of power if glucose and oxygen are efficiently and selectively oxidized and reduced.

The cell power is defined by the current production related to the output voltage. Its maximum power density, its maximum current density, and its open circuit voltage therefore define the performance of a GFC (Fig. 1C). Operational stability under continuous or discontinuous discharge is also a key parameter to characterize the viability of a GFC.

3. Physiological fluids: not a simple electrochemical cell

One important aspect for the design of implantable biofuel cell is their localization inside the body where the fuel cell is implanted. Several parameters have to be respected.

- Optimal availability of glucose and oxygen: the environmental body fluids should contain glucose and oxygen at maximum concentrations and should be rapidly replenished.
- The electrocatalytic reactions have to be optimal under physiological conditions (around pH 7 and at 37 °C). This parameter concerns in particular the efficiency of the catalyst under these conditions.
- The biocompatibility of implantable glucose fuel cells (IGFCs) is one of the highest challenges because, by definition, IGFCs cannot be completely sealed and have to be at least partially in contact with the body fluid. Therefore, all IGFC components have to be fully biocompatible and protected from the external medium via selective membranes.

Taking into account that highest glucose and oxygen concentrations are found in blood, ideally, IGFC should be implanted in the blood vessels. In addition, blood flow provides a constant supply of glucose and oxygen that are consumed by the IGFC. However, the presence of foreign objects can alter blood circulation, induce cardiac or circulatory troubles, and can lead to blood clots, thrombosis, or embolism [10]. Moreover, blood is a rather complex medium. Positioning a cell in a

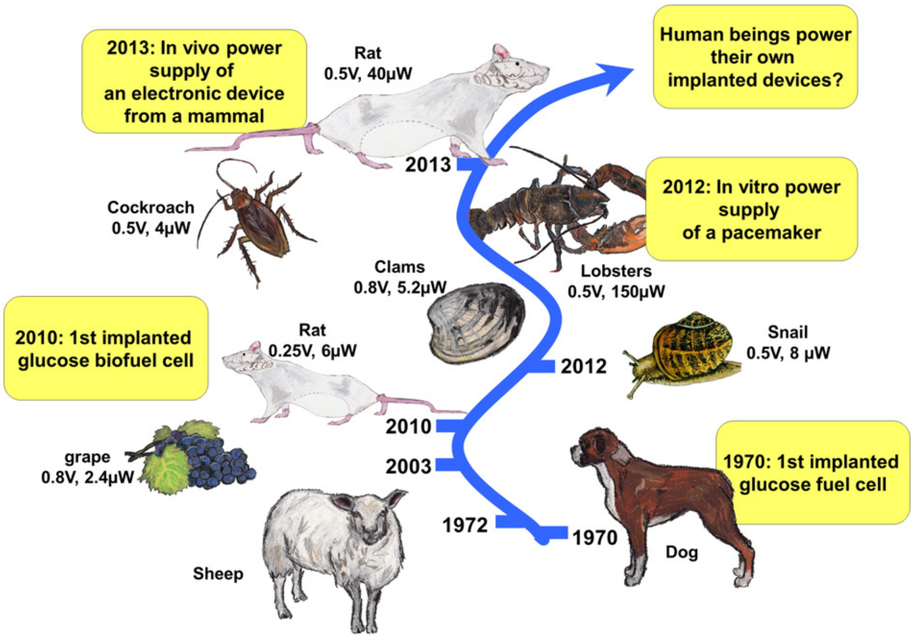

Fig. 2. Most relevant examples of abiotic and biological GFCs generating electrical energy from living organisms.