AN EFFICIENT LOW-POWER DC-DC CONVERTER ENABLES OPERATION OF A CARDIAC PACEMAKER BY AN INTEGRATED GLUCOSE FUEL CELL

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Abstract: We present an abiotically catalyzed glucose fuel cell and demonstrate its application as energy harvesting power source for a cardiac pacemaker. This is enabled by an optimized DC-DC converter operating at 40% conversion efficiency, which surpasses commercial low-power DC-DC converters. The required fuel cell surface area can thus be reduced from ~125 cm² to 18 cm², which would allow for its direct integration onto the pacemaker casing.

Key words: energy harvesting, cardiac pacemaker, glucose, fuel cell, DC-DC converter, medical implant

1. INTRODUCTION

1.1 A battery-independent implant power supply

While primary and secondary batteries are at present the only practically available power source for active medical implants, there are a number of efforts to develop alternative power supply concepts based on *energy harvesting*. These concepts aim at converting chemical, thermal, or kinetic energy available from the environment into sufficient electricity to power a medical implant [1-3]. This way the present necessity for regular surgical replacement of spent batteries or cumbersome external re-charging mechanisms may be circumvented, and the patient's life-quality would be dramatically improved.

1.2 Implantable glucose fuel cells

Among the currently investigated energy harvesting concepts are also implantable fuel cells [4;5] operating on glucose available from body fluids. In contrast to mechanical [6;7] and thermoelectric [8;9] generators, glucose fuel cells promise a continuous energy supply that is independent of body movement or temperature gradients within the body.

Whereas enzymatic glucose fuel cells exhibit considerable power densities of up to 430 μW cm^{-2} under physiological conditions [10], their operating time is limited to a few weeks only due to the low enzyme stability [11]. This can be circumvented by the application of abiotic catalysts (noble metals, activated carbon) that promise long-term stability and are amenable to proven heat sterilization techniques – a basic prerequisite for implantation. While the feasibility of implantable abiotically catalyzed glucose fuel cells has already been demonstrated in the 1970s [4;12;13], these devices exhibit a comparably low power density in the range of 4 μW cm^{-2} to 8 μW cm^{-2} under physiological conditions [4]. Their application is thus limited to low-power medical implants with a power demand well below 100 μW, such as cardiac pacemakers.

The operational concept of an abiotically catalyzed glucose fuel cells roots on the electrochemical reaction of glucose and oxygen at two spatially separated electrodes. Electrons, released upon the electro-oxidation of glucose flow through an external load circuit to the cathode, where oxygen is reduced as terminal electron acceptor. Both, glucose and oxygen either diffuse from blood or interstitial fluid to the electrodes. As main reaction product of glucose oxidation on platinum electrodes gluconic acid has been identified [14]. The resulting electrode reactions are illustrated in Fig. 1 [15].

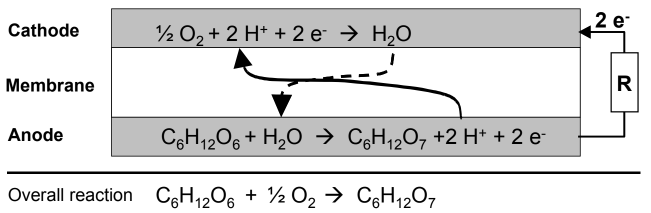

Fig. 1: Electrode reactions of an abiotically catalyzed glucose fuel cell [15].

An important constraint for the operation of an abiotically catalyzed glucose fuel cell in a physiological environment is the simultaneous presence of glucose and oxygen. Since most available noble metal catalysts catalyze both, glucose oxidation and oxygen reduction, a separation of reactants is necessary to circumvent the formation of mixed electrode potentials and the consequent decrease in fuel cell performance.

The favorable concept for reactant separation features a permeable activated carbon cathode placed in front of the anode that selectively catalyzes oxygen reduction [16] (Fig. 2). This way oxygen, diffusing into the fuel cell from the environment, is removed from the reactant mixture and the interior of the fuel cell becomes essentially anoxic. At the anode glucose can thus be electro-oxidized without the detrimental interference of oxygen. The main advantage of this embodiment is that reactant access to the fuel cell from one side is sufficient, enabling its direct integration on the surface of a medical implant [17].

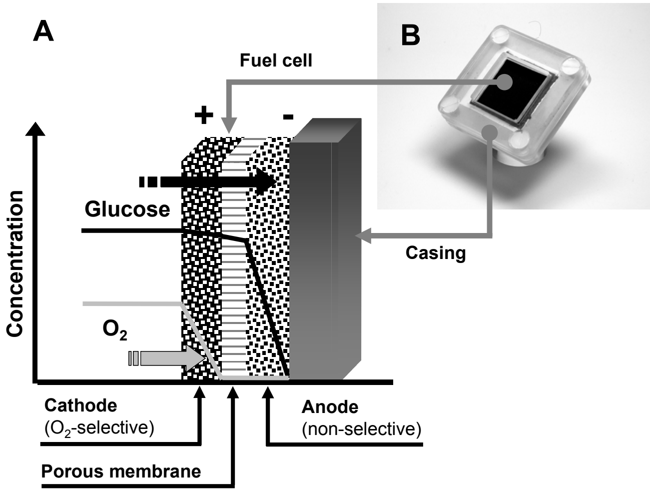

Fig. 2: A) Construction of an abiotically catalyzed glucose fuel cell with O_2-selective cathode, allowing for direct integration of the fuel cell onto the casing of a medical implant (see text for explanations). B) Photograph (front view) of the fuel cell used in this work.

1.3 Necessity for an efficient DC-DC converter

At current, the carbon-based glucose fuel cells developed in our lab exhibit power densities of up to 3 µW cm^{-2} under physiological conditions [18]. Theoretically it would thus be possible to power a 15 µW cardiac pacemaker with a glucose fuel cell as small as 15 cm², integrated as surface coating on the pacemaker casing.

However, for the practical application of the concept it is necessary to convert the relatively low fuel cell voltage of 0.2 V into the 3 V typically required by implant electronics. A limitation is the conversion efficiency of commercial low-power DC-DC converters, which at output powers in the µW-range amounts to approximately only 4 %. Consequently, a fuel cell of at least 125 cm² would be required to power a cardiac pacemaker – too large for direct integration onto the pacemaker casing. To minimize conversion losses we therefore specifically optimized a classic step-up converter design [19] for operation in conjunction with our glucose fuel cell and a 15 µW cardiac pacemaker. At the heart of the conversion circuit is a germanium transistor, enabling self-powered start-up of the device at input voltages as low as 150 mV.

2. EXPERIMENTAL

2.1 DC-DC converter characterization

To determine the conversion efficiency of different DC-DC converters their output was connected to a standard cardiac pacemaker in place of the removed battery (Microny Model, St. Jude Medical, Sweden).

Subsequently input voltages between 100 mV and 900 mV were supplied to the DC-DC converter with a potentiostat (G 300, Gamry Instruments, Warminster, Pennsylvania/USA), and the resulting input current was determined. In turn, the resulting voltage and current at the output of the converter were measured with a digital multimeter, while correct operation of the pacemaker was verified by visualization of the stimulation pulses (4V at 1 Hz) over a 3.3 kOhm resistor with an oscilloscope. Conversion efficiency of the DC-DC converter was calculated as the ratio of input power to output power.

2.1 Fuel cell construction

The complete fuel cell was assembled from two single fuel cells connected in parallel. Each single cell had a geometric electrode area of 9 cm², corresponding to the front and back of a pacemaker casing. Both, the fabrication of the electrodes as well as the assembly of the individual cells have been described in detail elsewhere [18]. In short, the electrodes consisted of activated carbon particles bound in a PVA-PAA hydrogel matrix with platinum mesh as embedded current collector. Whereas the cathode was fabricated from pure activated carbon, an activated carbon supported platinum-bismuth catalyst was used at the anode. Together with an in-between porous polyhersulfone membrane (Supor 450, Pall, East Hills, New York/USA) both electrodes were clamped between polycarbonate frames using silicon rubber gaskets. A schematic of the fuel cell construction is shown in Fig. 2.

2.1 Operation of the complete system

To prevent the growth of microorganisms the fuel cells were operated under sterile conditions. Thereto the fuel cells were mounted in an aseptic reaction chamber and autoclaved in phosphate buffered saline (PBS) at 121°C for 15 min. Subsequently the testing solution was exchanged with fresh PBS containing 3 mM glucose through 0.2 µm sterile filters to sustain sterility in the vessel. Throughout the experiment the testing solution was continuously purged with 7% oxygen in nitrogen, while the complete assembly was kept at 37°C in an incubator. The concentrations of both, glucose and oxygen were chosen to correspond to the conditions expected in subcutaneous tissue [4]

After reaching a stable open circuit voltage, the fuel cell was connected to the complete system consisting of our optimized DC-DC-converter, the cardiac pacemaker, and an oscilloscope as depicted in Fig. 3. Voltages and currents and the input and output of the DC-DC converter were recorded in 5 min intervals with a data acquisition system. Correct operation of the pacemaker as well as conversion efficiency of the DC-DC converter were determined as described above.

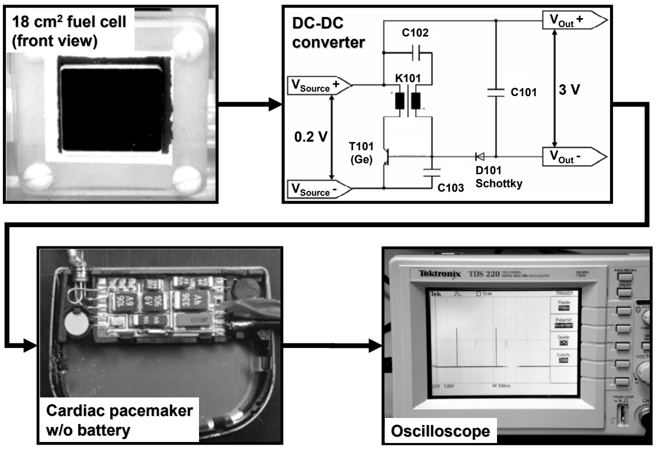

Fig. 3: Experimental setup comprising glucose fuel cell, DC-DC converter, and pacemaker. An oscilloscope visualizes the stimulation pulses delivered by the pacemaker.

3. RESULTS AND DISCUSSION

3.1 Efficiency of DC-DC converters

The conversion efficiencies and operational characteristics of three different low-power DC-DC converters are summarized in Table 1. The *Texas Instruments* converter turned out to be not suitable for the present application, since it requires a minimum operation voltage of 0.50 V, which is above the open circuit voltage of the glucose fuel cell. In contrast, the *OnSemi* model only requires input voltages as low as 0.15 V and could thus be operated together with the glucose fuel cell. However, at 0.20 V input voltage (typical voltage of the operating fuel cell) its conversion efficiency amounts to only 4 %. Taking into account the power density of 3 µW cm^{-2}, a fuel cell of at least 125 cm² in size would thus be required for power supply to a 15 µW pacemaker.

At 35 % the optimized DC-DC converter presented within this work exhibits considerably higher conversion efficiency. According to the above calculation a fuel cell of only 14 cm² would already be sufficient for pacemaker operation.

Table 1: Characteristics of low-power DC-DC converters with 3 V output voltage.

Type	Conversion efficiency at 0.20 V input voltage	Minimum startup voltage	Minimum input voltage
Optimized converter (this work)	~ 35 % (~ 40 % at 0.17 V input)	0.15 V	0.15 V
OnSemi NCP1440A	~ 4 %	0.80 V	0.15 V
Texas Instruments TPS 61201	n/a (~ 3 % at 0.60 V input)	0.50 V	0.50 V

3.2 Power supply to a pacemaker

The evolution of fuel cell voltage and DC-DC conversion efficiency during continuous pacemaker operation over a period of 3.5 days is shown in Fig. 4. Starting from an open circuit potential of approx. 0.4 V the fuel cell voltage gradually approaches equilibrium in the range of 170 mV over the testing period. At this operation point the conversion efficiency of the DC-DC converter amounts to 40 %.

Remarkable is the fact that despite the pulsating current demand of the pacemaker the fuel cell voltage remains stable. This can be related to equalization of the pacemaker's peak current demands by both, the input capacitance of the DC-DC converter as well as the capacitance of the fuel cell itself.

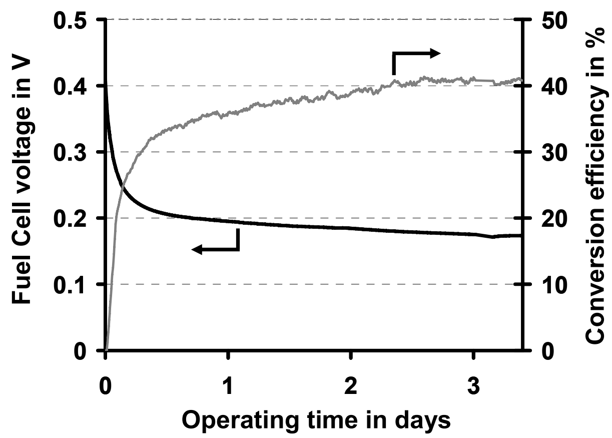

Fig. 4: Fuel cell voltage and DC-DC conversion efficiency during continuous pacemaker operation (4V stimulation pulses over a 3.3 kOhm resistor at 1 Hz).

4. CONCLUSION

In this work we successfully demonstrated the continuous operation of a 15 μW pacemaker with an energy harvesting abiotically catalyzed glucose fuel cell as sole power source. This is enabled by an optimized DC-DC converter, which exhibits a conversion efficiency of 40 % and thus surpasses commercially available circuits. As a consequence, the required geometric fuel cell area can be reduced to 18 cm^2. This approximately corresponds to the external surface of a pacemaker, which would allow the future integration of the fuel cell as power supply directly integrated onto the pacemaker.

We thus have shown that the operation of a cardiac pacemaker by means of an abiotically catalyzed glucose fuel cell is not only theoretically possible, but can also be achieved when the inevitable conversion losses occurring in practice are taken into account.

Regarding the increasing energy efficiency of modern implant electronics, an example is the novel bionic ear processor with by the factor of 25 reduced power consumption [20], the application of abiotically catalyzed glucose fuel cells as sustainable power supply may in future also become possible for other types of medical implants.

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