Biosensors and Bioelectronics 25 (2010) 2156–2160

Contents lists available at ScienceDirect

Biosensors and Bioelectronics

journal homepage: www.elsevier.com/locate/bios

A microbial fuel cell as power supply for implantable medical devices

Yufeng Han, Chaoling Yu, Hong Liu*

Lab of Environmental Biology and Life Support Technology, School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China

ARTICLE INFO

Article history:
Received 30 July 2009
Received in revised form 5 February 2010
Accepted 18 February 2010
Available online 25 February 2010

Keywords:
Microbial fuel cells
Implantable medical devices
Power supply
Large intestine
Transverse colon

ABSTRACT

This study seeks a new way to provide lasting and secure power for implantable medical devices (IMDs) using a microbial fuel cell (MFC) which was proposed to be placed in human large intestine and could utilize intestinal contents and microorganisms to generate electricity. Based on the anatomic structure and inner environmental conditions of large intestine, transverse colon was chosen to be the appropriate location for the implantation of MFC. The performance of the MFC which simulated the environmental features of transverse colon by controlling dissolved oxygen (DO) and pH and was inoculated with simulated intestinal fluid (SIF) was investigated. Stable power generation of MFC was obtained after two months operation with open circuit voltage (OCV) of 552.2 mV, maximum power density of 73.3 mW/m^2, and average voltage output of 308 mV (with external resistance of 500 Ω). Moreover, the changes of environmental conditions in the chambers of MFC did not have a significant impact on human body based on the analysis of pH and DO values. Further studies on internal resistance and power density showed that the MFC could generate power of 7–10 mW according to the size of intestinal surface area, which was enough for IMDs. These results suggested that MFCs located in large intestine could be a promising power source for IMDs.

1. Introduction

With rapid development of biomedical engineering technology, tremendous progresses have been made in implantable medical devices (IMDs). Appropriate working of an active IMD heavily relies on the continuous supply of electricity. Because of the characteristics of working time and environment, IMDs' power supply should possess such properties as long running life, low self-discharging rate, high reliability and biocompatibility with human body. Although the requirement of each IMD is different, the necessary power they need generally falls in the level of μW–mW (Szczesny et al., 2006).

At present, the most popular power supply of IMDs is lithium battery which has been widely adopted for its relatively high energy density and safe performance. Although its longevity is up to 10 years (Mallela et al., 2004), its actual service life is far from enough to meet the needs of patients. For example, more than 60% of the implanted cardiac pacemakers need to be replaced for the reason of battery within 5–8 years (Orhan, 2002). Thus, when batteries of IMDs run out, the patients require surgeries to replace the whole IMD, suffering great pains and enormous financial burdens.

Although the nuclear battery's life can reach more than 15 years, the potential radioactive danger as well as the expensive cost makes it still unacceptable (Drews et al., 2001). In recent years, many newly emerging technologies in the fields of magnetics, thermotics, acoustics and electricity are gradually being introduced as power supplies for the IMDs and some progress have been made (Suzuki et al., 2002; Weiner and Cooper, 2005; Wang et al., 2007; Liu et al., 2006). However, they still have obvious bottlenecks respectively and have not been applicable yet. How to provide energy for IMDs via a highly safe, efficient and continuous way is, therefore, extremely important in biomedical engineering and related research fields.

Microbial fuel cell (MFC) technology has been developed to produce electricity from organic matters using microorganisms as the biocatalyst since 1970s (Logan et al., 2006; Li et al., 2008). In the recent 10 years, plenty of studies on MFC have been carried out (Bond et al., 2002; Liu and Logan, 2004; Yang et al., 2009). Taking into account the close symbiotic relationship between human and microorganisms, MFC could be a continuous, long-life and safe power source for IMDs. Siu and Mu (2008) once managed to develop a micro-MFC using glucose in blood as organic matters, however the location of MFC was proposed in blood vessels which might lead to thrombosis and rejection reaction of patient.

Considering locations of microorganisms and organic matters in human body, we think the best implantation site of MFC is the large intestine. Our group has carried on studies of MFC inoculated by extracted solution of feces and found that MFC could produce a maximum power of 240 mW/m^2 (Du et al., 2010). This indicates that the microorganisms in large intestine can produce

* Corresponding author. Tel.: +86 10 8233 9837; fax: +86 10 8233 9837.
E-mail address: LH64@buaa.edu.cn (H. Liu).

0956-5663/$ – see front matter
doi:10.1016/j.bios.2010.02.014

Table 1
Environmental conditions in different parts of colon.

Measurement site	pH[a]	Length (cm)[b]	Diameter (cm)[b]	ptO_2 (mmHg ± SD)[c]
Ascending colon	4.9–5.8	15.6 ± 5.8	6.3 ± 0.5	33.7 ± 7.5
Transverse colon	5.7–6.2	40.3 ± 8.5	5.0 ± 0.7	40.7 ± 8.2
Descending colon	5.8–6.3	23.2 ± 7.2	3.5 ± 0.6	31.8 ± 7.4
Sigmoid colon	6.0–6.7	34.3 ± 10.0	3.0 ± 0.3	41.2 ± 8.7

[a] Average pH values of the contents inside the colon (Michelle et al., 2003).
[b] Peng et al. (2000).
[c] Partial pressure of oxygen here is measured from the surface of the tissues and is not equal to the partial pressure of oxygen inside the colon but can reflect the oxygen amount in it. SD means standard deviation (William et al., 1987).

electricity and the power output can meet the standard requirements of IMDs. Large intestine is divided into caecum, colon consisting of ascending colon, transverse colon, descending colon and sigmoid colon, and rectum. Caecum is very short and keeps inner acidic condition. Rectum presents unstable inner environmental parameters because it is the place for temporary storage of feces. Thus, neither of them but colon is suitable for the implantation of MFC. Environmental conditions in the different parts of colon are shown in Table 1. Based on the comprehensive analysis of environmental conditions, such as pH, length, diameter and partial pressure of oxygen in various parts of colon, we suggest that transverse colon is a reasonable implantation site for MFC because of its nearly neutral pH and relatively large length and diameter.

How to construct an MFC which generally consists of anaerobic anode and aerobic cathode compartments in transverse colon is further considered. In the colon, there are a large number of anaerobic microorganisms tightly adhering to the intestinal mucosa, while in the lumen there are many aerobic microorganisms flowing with the contents (Macfarlane et al., 1992). Accordingly, the anode of MFC can be made tubular in the transverse colon adhering to the mucosa while the cathode can be located at the center of the lumen.

According to the above conception, an MFC which simulated the environmental features of transverse colon was constructed and its power output and changes of environmental conditions were studied to identify its feasibility. In addition, further studies on resistance and power density were carried out to improve the power output.

2. Materials and methods

2.1. MFC configuration

The experiment MFC consisted of two chambers made of plastic materials (Plexiglas) (shown in Fig. 1). Each chamber was of rectangular parallelepiped (10 cm long by 2.5 cm wide by 10 cm high) with net volume of 125 mL. The anode electrode was made up of activated carbon fiber cloth in size of 6 cm × 6 cm without catalyst. The cathode was a carbon paper electrode (thickness of 0.29 mm, area of 12 cm^2) containing 0.5 mg/cm^2 of Pt catalyst on only one side. The anode chamber was sealed to maintain anaerobic condition and the cathode chamber was connected to the air via a hole at the top of cathode chamber. There was a carbon paper with thickness of 0.29 mm between the two chambers to reduce the oxygen diffusion from cathode chamber which would affect the growth and electricity generation reactions of anaerobic microorganisms in anode chamber. The circuit was closed via titanium line with diameter of 0.5 mm and a resistor of 500 Ω.

2.2. Simulated intestinal fluid

The composition of electrode solution was determined according to the contents of large intestine. With reference to experiments of colon-specific drug absorption (Tozaki et al., 1997), the simulated intestinal fluid (SIF) was made, which contained 110 mM $NaHCO_3$, 20 mM $Na_2HPO_4 \cdot 12H_2O$, 8 mM NaCl, 6 mM KCl, 0.5 mM $CaCl_2 \cdot 2H_2O$, and 0.4 mM $MgCl_2 \cdot 6H_2O$. Fresh fecal samples were added into the above solution with the mass fraction of 30% (w/v). Subsequently the mixture was filtrated with 4 layers of gauze and sparged with N_2 before being added into the reactor to maintain anaerobic conditions and prevent aerobic oxidation of the organic matters. The obtained SIF was preserved at 4 °C.

2.3. Working conditions in anode and cathode chambers

Working conditions of MFC were mainly based on the conception mentioned above that the anode of MFC could be made tubular in the transverse colon adhering to the mucosa while the cathode could be located in the center of the subsequent lumen. So the pH in anode chamber was determined to be about 7.8 according to the combined effect of mucus and the average pH value of contents in transverse colon (Table 1). To exclude the interference of microorganisms, the cathode chamber was filled with SIF without fecal samples (pH 8.3). Moreover, according to the physiology researches and the oxygen-resistant extent of microorganisms in intestinal contents, the partial pressure of oxygen close to the intestinal wall is about 10 mmHg with that in the lumen of 20–30 mmHg. Therefore the concentration of dissolved oxygen (DO) in anode chamber is maintained at about 0.14 mg/L, with that in cathode chamber of 0.27–0.45 mg/L in the experiment to be consistent with those in colon of wall and lumen, respectively. In addition, the MFC was

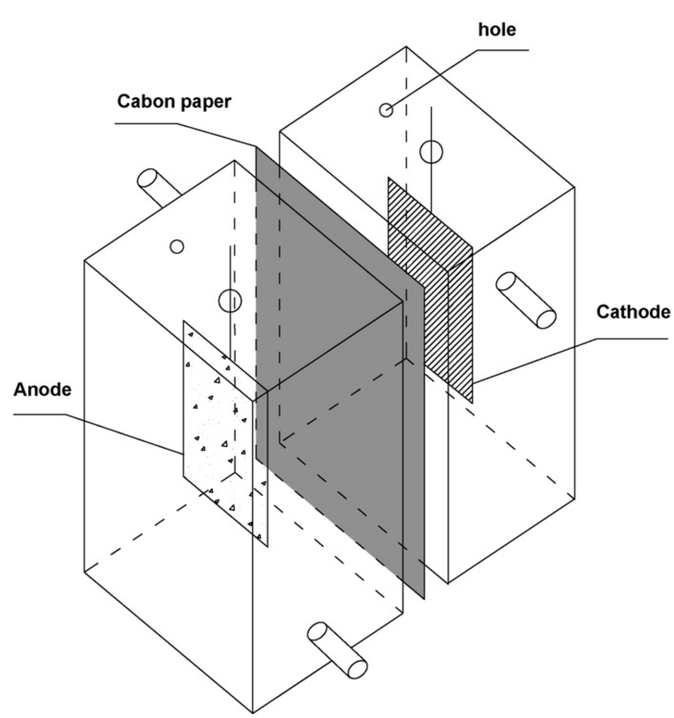

Fig. 1. Schematic prototype of MFC.