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Gastric-fluid-utilizing micro battery for micro medical devices

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ABSTRACT

A variety of micro medical devices have been developed to provide more advanced and less invasive medical treatment. An effective power supply is crucial to the operation of these devices. Currently, two types of power supply are used: small batteries or radio-power transmission. However, the former limits the operating time of the devices, while radio-power transmission affects other medical devices due to the electromagnetic waves. In this paper, we report on a gastric-fluid-utilizing micro battery (GMB) that utilizes the gastric fluid in the stomach as an electrolyte. The GMB is designed to be used in the stomach and to generate electricity based on the principle of the voltaic cell. It consists only of biocompatible materials, including the electrodes, porous ceramic filter, and polydimethylsiloxane casing. Platinum deposited on a thin glass plate and a zinc plate work as positive and negative electrodes, respectively. Though zinc dissolves during the generation of electricity, it is an essential trace metal for humans and, given the small amount released, is not toxic. The porous ceramic filter placed between the electrodes filters out any foreign materials in the stomach fluid and holds the gastric fluid by capillary attraction. In experiments, GMB successfully generated 1.0 mW (0.42 V, 2.41 mA) with a 200-Ω external load. It generated a stable output voltage of 0.6 V for more than 39 min with a 5-kΩ external load. We demonstrated the feasibility of the GMB for medical applications by successfully supplying power to a telemetric system and a tiny DC motor that is commercially available.

1. Introduction

Medical diagnosis and treatment methods based on the use of micro medical devices that can be swallowed or embedded in the human body have recently been developed [1–5]. A swallowable capsule endoscope is considered one of the most promising of these devices. The endoscope, which is swallowed by mouth, acquires images from inside the digestive organs and stores or transmits them. An appropriate power supply is crucial to further enhance the performance of these devices. Currently, either a small battery or radio-power transmission is utilized to supply power, but both technologies have critical shortcomings. A small battery limits the application and working time of medical devices since the energy that can be stored by a battery is proportional to its volume, which becomes critical on a micro scale. Radio-power transmission affects other medical devices due to the electromagnetic waves.

Micro power sources have, thus, been developed using MEMS technology (MicroElectroMechanical Systems) such as micro gas turbines using hydrocarbon fuel [6–10], micro fuel cells using hydrogen and methanol [11,12], and micro batteries based on electrolytes of sulfuric acid and hydrogen peroxide [13]. These technologies are termed as power MEMS [14].

Power MEMS that exploit energy from the human body have also been explored. These MEMS are particularly effective for micro medical devices used inside or in the vicinity of the human body: for example, a thermal power generator that uses the difference between the temperature of the body and the external temperature [15,16], and a power generator that uses the vibration generated by the movement of the body [17]. Devices that utilize energy from the surrounding environment to generate power, such as those mentioned above, are termed "energy harvesting devices" and are currently the subject of intensive research [18,19]. To supply power to implantable devices, the use of micro fuel cells that use blood glucose has been explored over years [20–22]. Batteries that use subcutaneous fluid as an electrolyte, with a zinc electrode, have been reported [21]. For on-demand medical diagnosis, a micro battery activated by water, including body fluids and blood [23] and a chemical battery that acquires energy from human urine [24] have also been reported recently.

In this paper, we propose a micro voltaic cell that uses gastric fluid as an electrolyte. The gastric-fluid-utilizing micro battery, which is termed as GMB can supply power to micro medical devices – such as a swallowable capsule endoscope–that work in or pass through the stomach, which contains gastric fluid. The GMB is

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designed to be small enough to fit into a commercial capsule endoscope and consists only of biocompatible materials. While the GMB may not replace current battery technologies, it has great potential to supply additional power to micro medical devices, enabling them to perform better and provide more diagnostic and treatment functions.

2. Theory and design of the GMB

Fig. 1 shows a schematic diagram of the GMB. The GMB is a voltaic cell and generates electricity according to the standard principle of a primary cell [25]. Gastric fluid, which acts as the electrolyte, is an acid solution consisting mainly of hydrochloric acid and small quantities of potassium chloride and sodium chloride and is generated in the stomach [26]. Platinum (Pt) and zinc (Zn) are employed as the positive and negative electrodes, respectively, taking biocompatibility into account. Zn is an essential trace metal and is not toxic given the small amount that is released from the GMB. The outer case of the GMB is made from polydimethylsiloxane (PDMS), a biocompatible polymer that has been widely used for micro structures [27,28]. A rectangular parallelepiped filter made of porous ceramic material is placed between the electrodes to hold the gastric fluid in the GMB and to also filter out any foreign materials in the stomach fluid. The porous ceramic filter retains the electrolyte by capillary attraction. Immediately after the GMB is dipped in the electrolyte, the filter fills with the electrolyte and starts generating electricity.

The working principle of the GMB is illustrated in Fig. 2. The electrochemical reactions of the GMB are as follows:

$$\begin{aligned}&(-)\mathrm{Zn} \rightarrow \mathrm{Zn}^{2+} + 2\mathrm{e}^- \\ &(+)2\mathrm{H}^+ + 2\mathrm{e}^- \rightarrow \mathrm{H}_2\end{aligned} \quad (1)$$

The hydrogen ion and Zn work as the anode and cathode, respectively. During the chemical reactions which generate electricity, the Pt does not dissolve and works as an electron collector. The zinc dissolves into the electrolyte, resulting in a relatively short lifetime for the GMB. Nafion coating of the electrode may solve this problem [29]. However, in this paper we focus on demonstrating the operation of the GMB and do not discuss this problem further. Electrons are generated at the negative electrode (Zn), flow through the external load resister, and are collected at the positive electrode (Pt). From the standard electrode potential, the theoretical voltage of this battery is 0.76 V. Although the working principle that the GMB is based on has been widely studied, the GMB is differentiated from other proposals by the fact that gastric fluid is used as the electrolyte, given that the aim is for the battery to be used in devices placed in the stomach or other digestive organs.

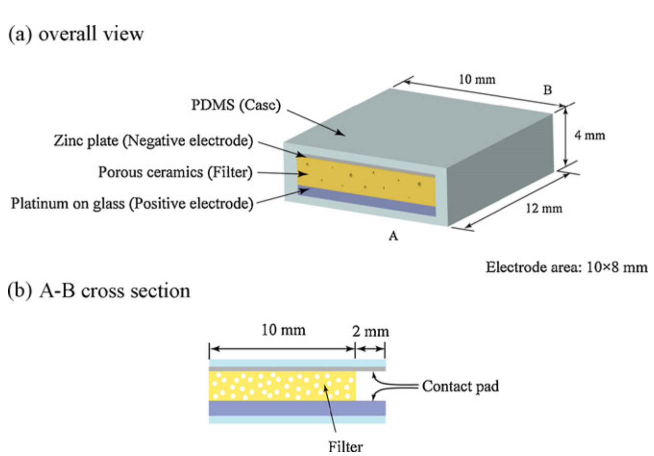

Fig. 1. Schematic diagram of gastric-fluid-utilizing micro battery: (a) overall view of micro battery, and (b) A–B cross-section of micro battery.

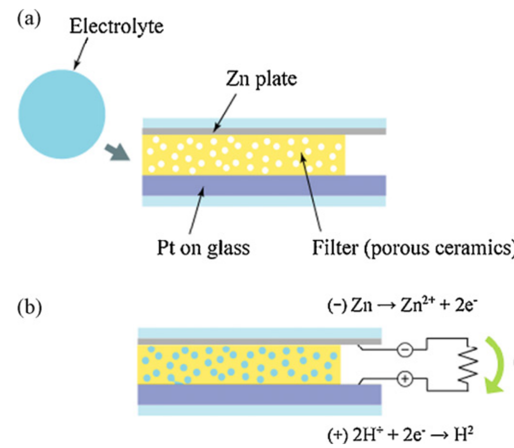

Fig. 2. Working principle of GMB: (a) liquid electrolyte, such as gastric fluid, is absorbed by porous filter by capillary attraction: (b) GMB generates electricity as zinc dissolves (amount of dissolving zinc is too small to be toxic).

The simple structure of the GMB facilitates miniaturization. It is designed to have a volume approximately one third that of a commercially available capsule endoscope, as depicted in Fig. 1. The area of the electrode is 10 mm × 8 mm. The contact pads to provide electrical connection to the outside circuitry are 10 mm × 2 mm.

3. Experiments

3.1. Fabrication

The GMB consists of positive and negative electrodes, a filter, and a casing. Titanium (Ti) and then Pt are evaporated on a 1-mm thick glass plate to form the positive electrode. The Ti acts as a contact metal to enhance the adhesion between the Pt and the glass. The metals cannot be deposited directly onto the PDMS because the heat involved generates cracks in the PDMS and thus, in the Pt layer. A 0.3-mm thick Zn plate is used as the negative electrode. For the porous ceramic filter, we used Fine Porous Ceramics F-type FSA-40 from Kurosaki Harima Corporation, which is made of alumina and contains an average of 1600 pores per square inch. PDMS, which is a thermosetting polymer, is molded to form the top and bottom casing. The PDMS structures are bonded via surface activation by oxygen plasma. The process is completed by inserting the electrodes and the filter into the casing. The size of the fabricated GMB (Fig. 3) is 10 mm × 8 mm × 4 mm.

3.2. Results and discussion

When used in the human body, the GMB utilizes gastric fluid as an electrolyte. Gastric fluid consists of hydrochloric acid (HCl), potassium chloride, sodium chloride (NaCl), and pepsin. We measured the quantity of electric power generated by the GMB utilizing simulated gastric fluid (SGF) (pH 1.2) as an electrolyte. The SGF consists of 80-mM HCl, 34-mM NaCl, and 10-μM digestive enzyme pepsin [26]. The output voltages and currents were acquired using external load resistors from 100 Ω to 5 kΩ while the GMB was immersed in the SGF solution. When a 5-kΩ load resistor was used, the GMB successfully generated an output voltage of more than 0.6 V for 90 min, as shown in Fig. 4. However, unstable output voltages were observed when low load resistors, such as 100 Ω and 200 Ω, were used. This instability is thought to originate from hydrogen bubbles generated on the positive electrode. The gen-