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Short communication

Flexible and transparent gastric battery: Energy harvesting from gastric acid for endoscopy application

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ABSTRACT

In this paper, we present the potential to harvest energy directly from the digestive system for powering a future wireless endoscopy capsule. A microfabricated electrochemical cell on flexible parylene film is proposed as a gastric battery. This electrochemical cell uses gastric juice as a source of unlimited electrolyte. Planar fabricated zinc [Zn] and palladium [Pd] electrodes serve as anode and cathode respectively. Due to planar geometry, no separator is needed. Moreover the annular structure of the electrodes provides lower distance between cathode and anode reducing the internal resistance. Both electrodes are biocompatible and parylene provides flexibility to the system. For a surface area of 15 mm^2, 1.25 mW is generated which is sufficient for most implantable endoscopy applications. Open circuit output voltage of this battery is 0.75 V. Since this gastric battery does not require any external electrolyte, it has low intrinsic weight, and since it is flexible and is made of biocompatible materials, it offers a promising solution for power in implantable applications.

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1. Introduction

Endoscopy provides a powerful tool for the treatment and diagnosis of various diseases such as stomach ulcers (Kobayashi et al., 2012), stomach cancer (Ahn et al., 2009), and acid-reflux disease (Shaheen et al., 2012). Recently, the development of a pill-sized capsule with an integrated camera, battery, sensors and actuators has provided a painless wireless alternative to the traditional tethered version. These capsules have the potential to image even the small intestine (Lewis and Swain, 2002) and measure temperature, pH (Hung et al., 2012), and other critical physiochemical parameters in the digestive system which conventional endoscopy tools may not be able to perform. The endoscopy capsule is swallowed easily through the mouth into the stomach and does not require any pushing force.

The battery is one of the key components of any wireless endoscopy capsule; it is typically quite bulky and occupies a lot of space inside the capsule. There are several studies focusing on making a small light weight yet an efficient source of energy for powering biomedical devices. Energy harvesting from the environment *in vivo* provides a sustainable solution for long-term operation. Recently many approaches for energy harvesting have been proposed, ranging from muscle motion (Li et al., 2010), vibration (e.g. heart beat, breathing) (Karami and Inman, 2012; Sodano et al., 2005), microbial fuel cell (Wilkinson, 2000) and glucose in biological fluids (Lenka. et al., 2012; Liu and Dong, 2007).

Most available devices and batteries are rigid, non-conformal, and therefore not suitable for *in vivo* applications. Since devices in the digestive system are often in motion, flexibility is one of the most important factors for building these devices. Moreover one expects the substrate for endoscopy to be transparent to facilitate imaging. Parylene-C is one such promising substrate for flexible biomedical devices (Stieglitz et al., 2005; Wright et al., 2007). It is a highly-crystalline polymer made from poly-para-xylylene modified only by the substitution of a chlorine atom for one of the aromatic hydrogens. Moreover it is a low weight, transparent, flexible, FDA approved, and biocompatible material. It can be extremely stable in different chemicals and temperatures making it an ideal candidate for biocompatible substrate.

Most portable, low cost, efficient, and implantable power sources are designed based on electrochemical approaches. Recently different types of biofuel cells (BFCs) with various performances have been developed (Mano et al., 2002; Osman et al., 2011). Most batteries are simple galvanic cells composed of two electrodes and electrolyte. The important issues to consider are the provision of electrolyte, which is a source of redox species, and integration issues for implantable applications. Glucose is an abundant available biochemical inside the body and is typically used in biological fuel cells (Kerzenmacher et al., 2008; Zebda et al., 2012). Since oxidation of glucose at the anode is not very spontaneous, glucose oxidase is used as an enzyme to support charge transfer (Zhou et al., 2010).

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However, stability of enzymes in long-term operation is limited. In many conventional electrochemical batteries, not limited to implantable applications, hydrogen ions are used as oxidizing species.

The stomach is an abundant source of hydrogen ions because gastric juice, which is composed of mucus, pepsin, and hydrochloric acid is highly acidic. Stomach epithelium cells secret the contents of gastric juice through the stomach and provide a suitable environment for digestion of foods. Normally two liters of gastric juice are generated daily, but the precise value depends on many factors such as diet (Campbell, 2012).

In this study we suggest the potential of gastric juice in the digestive tract as a source of energy for powering a wireless endoscopy capsule. The battery is essentially a spontaneous electrochemical cell with two microfabricated electrodes on parylene serving as a flexible substrate. Gastric juice inside the stomach serves as the only source of electrolyte that is automatically replenishable. Flexibility, miniturization and planar structure, in adition to the fact that higher power can be generated makes the proposed battery distinct from an only previous known effort on using gastric juice for battery (Jimbo and Miki, 2008) which had a relatively high 200 Ω internal resistance and output power of 1 mW. It also utilized a vertical structure that needed a physical separator between its electrodes making it more bulky. In this paper, we showcase a solution that is planar where no separator is needed. It also uses nafion which is a known proton exchange membrane. The internal resistance is much lower while the power generated is higher. We provide preliminary investigations on this battery and recommend its use for medical diagnostics of a digestive tract owing to its simplicity, flexibility, biocompatibility and low cost.

2. Materials and methods

2.1. Methodology

The approach of using a gastric battery in the stomach is demonstrated in Fig. 1. While many applications for the proposed battery is possible, we use the wireless endoscopy capsule as a primary application; a typical wireless endoscopy capsule consists of a camera, sensors and electronic circuits for navigation, communication, and sensing and a battery. In the approach demonstrated in Fig. 1, the proposed gastric battery can be used as a power source; since the voltage and power output is expected to fluctuate due to variations in the acidic environment of the stomach, a power management circuitry with integrated buck/boost converters and a voltage regulator will be needed to provide a stable power supply. The design of the battery in the proposed design is expected to be on the surface of the capsule to harvest the gastric juice. Electrodes for this gastric battery can be fabricated on the surface of the capsule; this is achieved by using a flexible substrate like parylene which is also optically transparent so as not to interfere with the imaging.

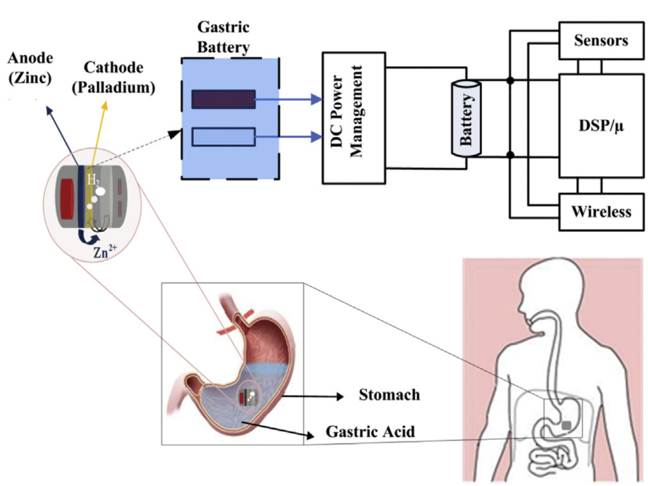

Fig. 1. Schematic of proposed battery using gastric juice inside the stomach as an electrolyte for the galvanic cell.

Gastric battery proposed in this paper is essentially an electrochemical galvanic cell with gastric juice as an electrolyte (and a source of hydrogen ions). Reduction and oxidation on the microfabricated cathode and anode results in ion transfer in solution and generates electron flow at the electrodes that powers the external circuit. The overall electrochemical charge transfer can be explained as follows: Zn as an anode easily oxidizes and dissolves in gastric solution leaving behind two electrons in the metal anode (reaction 1 below); hydrogen ions coming from the gastric juice are reduced at the cathode (Pd), and the generated hydrogen gas evolves as a bubble from this electrode (reaction 2 below). Overall reaction (3) below shows the final relationship between Zn consumption and hydrogen gas generation.

$$\text{Anodes}: \ Zn \rightarrow Zn^{2+}\ (aq) + 2e^- \tag{1}$$

$$\text{Cathode}: \ 2H^+ + 2e^- \rightarrow H_2(g) \tag{2}$$

$$\text{Overall reaction}: \ Zn(s) + 2H^+ \rightarrow H_2(g) + Zn^{2+}(aq) \tag{3}$$

For determination of total voltage between anode and cathode in the proposed electrochemical cell, Nernst Eq. (4) can be used,

$$E_{cell} = E^{\varnothing}_{cell} - (RT/nF)\ \ln([H_2]_{aq}[Zn^{2+}_{aq}]/[H^+]^2_{aq}) \tag{4}$$

where E_{cell} is the cell potential (electromotive force), $E^{\varnothing}_{cell}$ is the standard cell potential, R is the universal gas constant: $R=8.314472(15)$ JK/mol, T is the absolute temperature, n is the number of moles of electrons transferred in the cell reaction or half-reaction: $n=2$, and F is faraday constant: $F=96\ 485.3415$ C/mol.

Standard cell voltage can be derived from the cell's equilibrium condition when there is no net ion flux and cell voltage is zero; standard cell voltage is then given by

$$E^{\varnothing}_{cell} = (RT/nF)\ \ln([H_2]_{aq}[Zn^{2+}_{aq}]/[H^+]^2_{aq}) \tag{5}$$

This gives the cell voltage in standard conditions as 0.76 V. If conditions change, the Nernst equation shown in (4) can be used to calculate the output voltage. Since there is a strong dependency on the concentration of hydrogen ions, which is expected to fluctuate, the output voltage is not steady and electronic means through buck/boost conversion and voltage regulation is employed to provide a stable output power supply. Design of these circuit elements is not the focus of this research article and can be found elsewhere (Sarpeshkar, 2010).

2.2. Fabrication

The flexible gastric battery was fabricated using standard microfabrication methods for the creation of electrodes followed by electrodeposition. The structure of the gastric battery is shown in Fig. 2a, parylene-C was chosen as a substrate; Zn and Pd were subsequently employed as the anode and cathode; nafion as ion exchange membrane, and a protective filter are the various components of the gastric battery.

The entire fabrication process is detailed in Fig. 2b. First, a silicon wafer is covered by 12 µm of parylene-C; this is achieved using PDS2010 parylene coater with 20 g of dimer at furnace temperature of 690 °C, chamber temperature of 135 °C and vaporizer at 175 °C. In the next step, SPR photoresist is spun on parylene at 3000 rpm for 30 s. After UV lithography for patterning the desired shape of the electrodes, 20 nm chromium as an adhesion layer and 250 nm Pd are sputtered. Lift off with acetone leaves Pd

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