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Generation of electrical power under human skin by subdermal solar cell arrays for implantable bioelectronic devices

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A B S T R A C T

Medical electronic implants can significantly improve people's health and quality of life. These implants are typically powered by batteries, which usually have a finite lifetime and therefore must be replaced periodically using surgical procedures. Recently, subdermal solar cells that can generate electricity by absorbing light transmitted through skin have been proposed as a sustainable electricity source to power medical electronic implants in bodies. However, the results to date have been obtained with animal models. To apply the technology to human beings, electrical performance should be characterized using human skin covering the subdermal solar cells. In this paper, we present electrical performance results (up to 9.05 mW/cm^2) of the implantable solar cell array under 59 human skin samples isolated from 10 cadavers. The results indicate that the power densities depend on the thickness and tone of the human skin, e.g., higher power was generated under thinner and brighter skin. The generated power density is high enough to operate currently available medical electronic implants such as pacemakers that require tens of microwatt.

1. Introduction

As the average human lifespan continues to gradually increase, diverse medical electronic implants are becoming more important, to functionally assist internal organs, and to help maintain quality of life by treating chronic diseases. Cardiovascular, neurological and gastroenteric disorders are now being treated by implants, using devices such as cardiac pacemakers (Kurtz et al., 2010), deep brain stimulators (Mayberg et al., 2005), gastric stimulators (Cigaina, 2004) and diaphragmatic stimulators (Sardarzadeh, 2012). However, since the electrical capacity of the batteries which provide power to these medical electronic implants is finite, the batteries are usually large, occupying about half of the volume of the implants (Romero et al., 2009). In addition, the entire implant, including the battery, needs to be periodically replaced every 2–8 years through surgical intervention (Reese et al., 2011; Wood and Ellenbogen, 2002), which creates psychological, physical and financial burdens to patients (Kurtz et al., 2010). At the same time, the finite electrical capacity that can be implanted in human bodies limits not only the practical use of mechanically sophisticated flexible and stretchable electronics (Kim et al., 2010; Ko et al., 2012; Labroo and Cui, 2013; Manunza and Bonfiglio, 2007; Reeder et al., 2014) for biomedical applications but is also insufficient for more advanced functionalities, such as real-time communication. Such devices require sustainable high electric power, for example, in advanced therapeutic and diagnostic medical implants including real-time glucose or blood pressure monitors (Fassbender et al., 2008; Yu et al., 2006), bio-signal sensors (Xu et al., 2015), drug delivery systems (Minev et al., 2015), artificial hearts (Copeland et al., 2004) and many others (Chow et al., 2004; Kuzum et al., 2014; Tahir et al., 2005; Wang, 2006). Recently, various energy harvesting strategies have been designed to make use of energy sources in the human body, including electrochemical reactions (Agnes et al., 2014; Katz and MacVittie, 2013; Liu et al., 2010), mechanical motion (Bai et al., 2013; Zhao et al., 2014), wireless energy transmission (Kim et al., 2012) and

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others (Carmo et al., 2010; Torres and Rincón-Mora, 2009). Some of these methods require further development to improve durability, biocompatibility or electric power output.

Another alternative approach involves producing electricity from light transmitted through the skin by photoelectric effect (Amar et al., 2015; Goto et al., 2001; Hannan et al., 2014; Murakawa et al., 1999). Rigid solar cells, implanted into pig models, were found capable of supplying enough power to operate custom-built implants (Haeberlin et al., 2015, 2014). Subdermal flexible solar microcell arrays designed to be mechanically more compatible with skin also generated electricity to power electronic implants in mouse models (Song et al., 2016). Although these studies demonstrated the feasibility of the concept in animal models, the actual electrical characteristics under human skin must be considered in order to further develop the technology for human beings, since the performance of the device can depend on various features of the skin covering the solar cells. Here, we present the electrical performance of flexible implantable photovoltaic (IPV) devices under isolated human skin samples, whose results improve the chances for more realistic use of the implantable power source for human beings. Experiments conducted with skin samples from 6 locations of 10 human cadavers provide quantitative data for the factors (such as skin thickness and tone) that affect the amount of power generation under skin. Results indicate that the IPV devices under the human skin generate around 0.51–9.05 mW/cm^2 depending on the thickness and tone of the skin. These results should be very important consideration in designing the sustainable power source for functional medical electronic implants.

2. Material and methods

2.1. Fabrication of flexible IPV device

We prepared dual junction solar microcells (GaInP/GaAs), epitaxially grown on GaAs wafers as reported previously (Song et al., 2016). In short, solar microcells (size: 760 µm×760 µm, thickness: 5.7 µm) were fabricated on wafers by the wet etching process (H_2O_2 30%, H_3PO_4 85%, HCl 35%, OCI), followed by deposition of electrodes (Ti: 20 nm/ Au: 60 nm). The microcells on the wafers were separated and transferred to a flexible polyimide film (thickness: 12.5 µm) where SU-8 photoresist (thickness: ~2 µm, Microchemicals) was spin-coated to serve as an adhesion layer. The flexible solar microcells array, expected to have long lifetime (~30 years) (Núñez et al., 2013), was encapsulated with multiple transparent layers such as SU-8 (thickness: ~2 µm) and NOA61 (thickness: ~23 µm, Norland Products), also known to be biocompatible (Nemani et al., 2013; Norland product, 2014), to prevent interaction between the solar materials and biological substances, after interconnecting the solar microcells in series (×2) and parallel (×7) with sputtered metal layers (Ti: 50 nm/Au: 300 nm). The encapsulation layers isolate the IPV devices from substances in tissues but transmit light to the devices, thus enabling power generation by photoelectric effect without chemical interactions between the IPV devices and tissue substances.

2.2. Preparation of human cadavers

A total of 10 human cadavers (race: Asian, age: 43–95, male: 5, female: 5) were selected for the analysis of solar cell arrays under human skin (Fig. S1). The cadavers were all of Korean descent and had been bequeathed to Chonnam National University Medical School under the acquisition terms described in the Human Tissue Act 1964. The cadavers had been preserved by anatomical embalming using formalin.

2.3. Measuring thickness of human skin

The thickness of isolated human skin samples from the cadavers was measured under constant pressure on a motorized translational microstage equipped with a force sensor (transducer techniques) and top vacuum holder. To accomplish this, first, we adjusted the parallel alignment of the microstage and the top vacuum holder by using a two-axis tilting stage. The force sensor and a square plate (size: 6 mm×6 mm) were installed on the motorized microstage and the top vacuum holder, respectively. After mounting a skin sample on the flat sensing plate of the force sensor, we slowly moved the microstage (resolution of z-axis: ~0.037 µm) vertically while monitoring the pressure in real time. We measured the thickness of the human skin sample when the applied pressure to the skin was 81.6 mN/cm^2.

2.4. Measuring optical properties of human skin

We measured the optical properties of the isolated human skin samples with a fiber-optic spectrometer (Avantes) integrated with double integrating spheres. The double integrating spheres collect scattering light transmitted through translucent skin. We measured the amount of light transmitted (M_s) through human skin placed between the double integrating spheres, for wavelengths of 400–900 nm. After removing the skin from between the spheres, we repeated the measurements with the light source on (M_w) and off (M_d). The transmittance of the human (T_s) skin was calculated using the following equation: $T_s=(M_s-M_d)/(M_w-M_d)$. We averaged 20 sets of measurements for each skin sample.

3. Results and discussion

3.1. Concept of the subcutaneously implantable solar cell for power generation in human body

Fig. 1 illustrates the concepts involved in the subcutaneous implantation of solar microcells for electric power generation in human bodies. Since human skin (Fig. 1a) protects our bodies from bacteria, viruses and many other unwanted substances, delivering electrical power to medical electronic implants through electrical wires penetrating the skin may put the body at risk of infection. Generating the necessary electrical power under the skin can avoid that risk. Fig. 1b shows a histological microscope image of shoulder skin, separated from a human cadaver (race: Asian, ages: 82, male) that was preserved by an embalming solution composed of ethanol, glycerin, formalin, phenol and distilled water, and stained with Accustain trichrome stain (Masson) kit (Sigma-Aldrich). The shoulder skin consists of three primary layers: the epidermis (~32 µm), dermis (~1.8 mm) and subcutaneous fat. Although human skin is not optically transparent, a fraction of light (700–1000 nm) penetrates through human skin up to about 4 mm (Barolet, 2008). Fig. 1c shows a demonstration of the light transmitted through an isolated hand dorsum skin (thickness: ~0.94 mm) from an embalmed human cadaver (race: Asian, ages: 61, male). When the light source (wavelength: 360–2500 nm, Avalight-HAL, Avantes) is shined on a spot of the isolated hand dorsum skin, a certain amount of light is transmitted through the skin as can be seen on the white paper (Fig. 1c). By absorbing the transmitted light an implantable photovoltaic (IPV) device can generate electrical power under the skin, and can supply electricity to an implanted medical electronic device, as illustrated in Fig. 1d.

3.2. Characteristic of electrical parameters of flexible IPV device under the human skin

The current-voltage characteristics of the solar microcells under the human skin are evaluated using a flexible IPV device (Fig. 2a) prepared by transfer-printing and interconnecting thin solar microcells (14 cells, 2 in series and 7 in parallel, thickness: ~5.7 µm) on a flexible polyimide (PI) film (12.5 µm), followed by encapsulating the devices as reported elsewhere (Song et al., 2016). See more details in Material and