A SKIN-MOUNTABLE BACTERIA-POWERED BATTERY SYSTEM FOR SELF-POWERED MEDICAL DEVICES

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ABSTRACT

Biochemical energy harvesting from human sweat is arguably the most underdeveloped because of immature technologies. Nonetheless, excitement is building for scavenging power from sweat, as it is the most suitable energy source for skin-contacting wearable devices. Despite the vast potential and promise of sweat-driven power generation, the technique is limited to unstable and inefficient enzymatic catalysis, which requires fundamental breakthroughs to enable self-sustaining, long-lived power generation. Here, we for the first time demonstrate the ability to generate an innovative, practical, and longstanding power from human sweat by using the metabolisms of human skin-inhabiting bacteria, *Staphylococcus epidermidis*. Our sweat-powered battery was based on microbial fuel cells (MFCs), exploiting the sweat-eating bacteria as a biocatalyst to transform the chemical energy of sweat into electrical power through bacterial metabolism. A DC/DC booster circuit was connected to the stacked devices to increase the operational voltage (~500 mV) to a maximum output of >3 V for powering a thermometer.

KEYWORDS

Sweat-based power generation; skin-inhabiting microorganisms; *Staphylococcus epidermidis*; electromicrobiology; microbial fuel cells

INTRODUCTION

Wearable electronics have recently emerged as a novel platform for electronics, taking on more important roles in health diagnostics, therapeutics, and monitoring [1-3]. However, current wearable technology relies on batteries or other energy storage devices to operate, which causes challenges in realizing compact and long-lived advanced functionality because of their bulky size and finite energy budgets [4-6]. Furthermore, frequent recharging or replacing power devices hinders the practical and sustainable use of wearable devices [7]. Power autonomy is a critical requirement for the next generation wearable devices, so they can work continuously, independently and self-sustainably. Therefore, a realistic and accessible power source will be urgently needed for a next-generation of smart, stand-alone, always-on wearable systems.

Among possible technologies, sweat-based energy harvesting offers the most suitable power-producing technique for wearable, skin-mountable applications because of its efficient, non-invasive energy-harvesting route. Sweat-energy harvesting can use enzymes or microorganisms to scavenge biochemical energy from the wearers' body fluids. The enzyme-based approach catalyzes the oxidation of metabolites from sweat and the reduction of oxygen for energy conversion to electricity [8-10]. However, the promise of this technology has long been limited by its low stability and inefficient electrochemical performance. The redox enzymes easily and rapidly degenerate under nonoptimal environmental conditions, thus negatively affecting their biocatalytic reactions, degrading stability, and reducing power [11-15]. On the other hand, the microbial energy harvesting methods are significantly more resilient than the enzymatic approaches and provide superior self-sustaining features with long-term stability. Microorganisms in the MFCs contain complete enzyme pathways and regenerate biocatalytic enzymes as part of their natural metabolism. As a result, they can provide self-assembling, self-repairing, and self-maintaining operational capabilities [16]. In this work, we created a thin, flexible MFC powered by human skin-inhabiting bacteria (Figure 1).

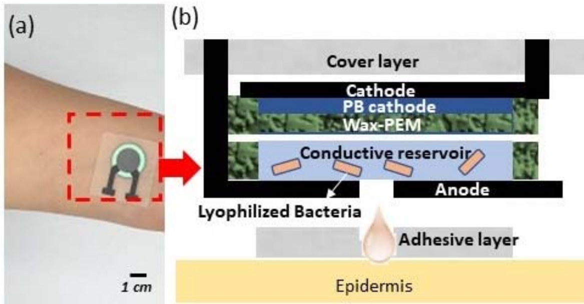

Figure 1: (a) Photo image, and (b) schematic diagram of the wearable skin-bacteria powered biobattery.

MATERIALS AND METHODS

Materials

Tryptone, yeast extract, sodium chloride (NaCl), dimethyl sulfoxide (DMSO), glutaraldehyde solution, L-Lactic acid (L-6402, 98%) and D-(+)-Glucose were purchased from Sigma-Aldrich. Poly(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) (Clevios PH1000) was purchased from Heraeus. Conductive graphite ink (#E34561000G) was purchased from Fisher Scientific Company, LLC. Whatman™ Grade 3MM chromatography paper was obtained from VWR International, LLC. Prussian Blue (PB) was obtained from Spectrum Chemical. Finally, graphene was purchased from Angstron Materials and artificial sweat was purchased from Quantimetrix.

Bacterial Inoculum

S. epidermidis were grown from -80 ºC glycerol stock cultures by inoculating in a 20 mL of L-broth medium with gentle shaking in air for 24 h at 35 ºC. The L-broth media consisted of 10.0 g tryptone, 5.0 g yeast extract and 5.0 g NaCl per liter. Broth cultures were then centrifuged at 5,000 rpm for 5 min to remove the supernatant. The bacterial cells were re-suspended in a new medium and used as power source for the device. To monitor bacterial growth, we measured the optical density at 600 nm (OD_{600}) of a bacterial culture.

Preparation of skin mountable biobattery

The wearable biobattery consisted of the engineered conductive paper anodic layer, the paper cathodic layer with the wax-based membrane, the adhesive skin-mountable layer and the cover layer (Figure 1). The conductive anodic reservoir was prepared by introducing a 20 µL mixture of 1 wt% PEDOT:PSS and 5 wt% DMSO into paper reservoirs and air-dried for 8 h [17, 18]. To further increase anode reservoir hydrophilicity, 20 µL of 2 wt% 3-glycidoxypropy-trimethoxysilane was added to the reservoir and air-dried [19]. The PEDOT:PSS polymers provided a conductive 3D paper matrix. The addition of graphene removed the need for multiple PEDOT:PSS injection steps for reaching the desired sheet resistance range (> 300 ohm/sq).

The Prussian-Blue (PB)-based cathode electrode was prepared with 8 mg of PB and 3 mg of graphene with a conductive binder solution, followed by ultrasonication for 10 min. The conductive binder solution was prepared with (i) 30 µL of PEDOT:PSS solution, (ii) 5 µL of 5 wt% Nafion, (iii) 100 µL of isopropanol. The mixture was brush coated on the predefined paper-reservoir on the cathodic side of the paper. The cathode electrode was prepared by screen-printing of graphite ink on top of the previously brushed catalyst.

Freeze-drying bacterial cells

After the MFC devices were inoculated with bacterial cells, they were placed in a low freeze drier (FreeZone Plus 2.5 Liter Cascade Benchtop Freeze Dry System, Labconco, MO, USA). The drying operation was performed at a pressure of 0.06 atm for 12 h with freezing and sublimation processes. During the freezing, the chamber temperature dropped to −50 °C and then progressively increased back to room temperature. The device was not affected by the lyophilization processes.

Electrical measurement setup

The voltage difference between the anodes and the cathodes were measured with a data acquisition system (National Instruments, USB-6212), and were recorded every 30s via a customized LabView interface. The current flow through an external resistor was calculated by Ohm's law.

RESULTS AND DISCUSSION

Power generation from *S. epidermidis*

A realistic and accessible power source will be urgently needed for a next-generation of smart, stand-alone, always-on wearable electronic systems. This is by no means a simple challenge because human skin intimately integrated with the system is an extremely harsh environment for power generation. Skin is cool, dry, acidic and lacks potential energy sources. This work is to create the ability to generate an innovative, practical, and longstanding power from human sweat, which is one of the few available energy resources on skin, by using the metabolisms of sweat-eating bacteria including human skin microorganisms. Here, *Staphylococcus epidermidis,* one of the majority of bacteria that inhabit our skin, was used to power a paper-based microbial fuel cell. For the purpose of on-demand power generation and long shelf life of the biobattery, the bacteria cells were pre-loaded and freeze-dried in the anodic chambers. The exoelectrogens covered the conductive paper reservoir for biofilm formation. Then, the cells were freeze-dried through sublimation and desorption processes. We previously demonstrated that freeze-dried bacteria cells can be rehydrated to generates power [20]. Rehydration of freeze-dried exoelectrogens is a critical step that can be highly improved by the content of activation liquid. Here, sweat was used as an organic activation sample.

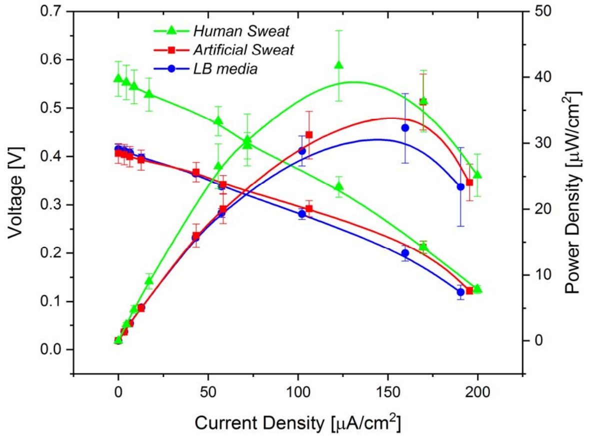

Figure 2: Power outputs & polarization curves of the biobatteries with lyophilized S. epidermidis activated by human sweat, artificial sweat & LB media.

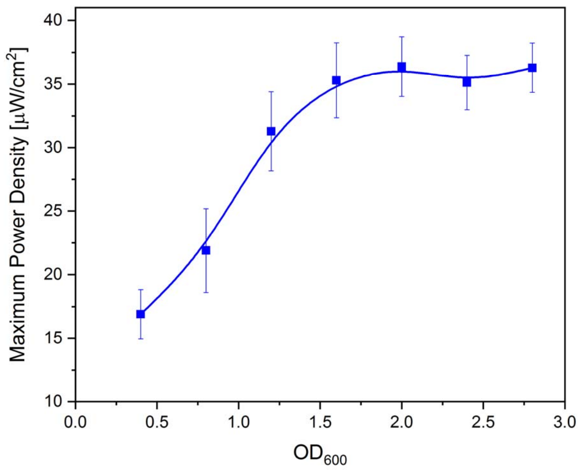

Figure 3: Power generation as a function of bacterial cell concentration inoculated in the anodic reservoir.

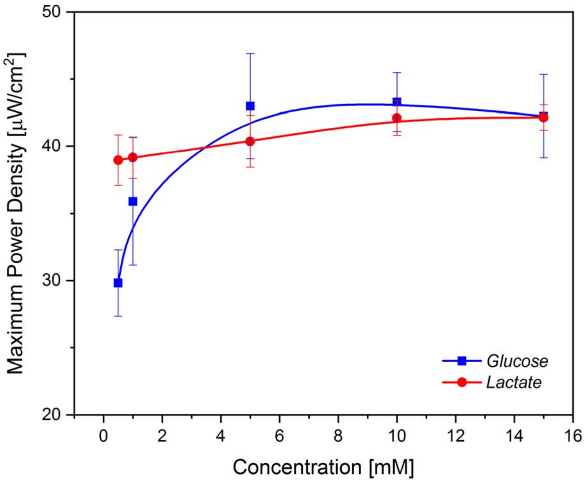

Figure 4: Power generation with response to different concentration of lactate and glucose in sweat

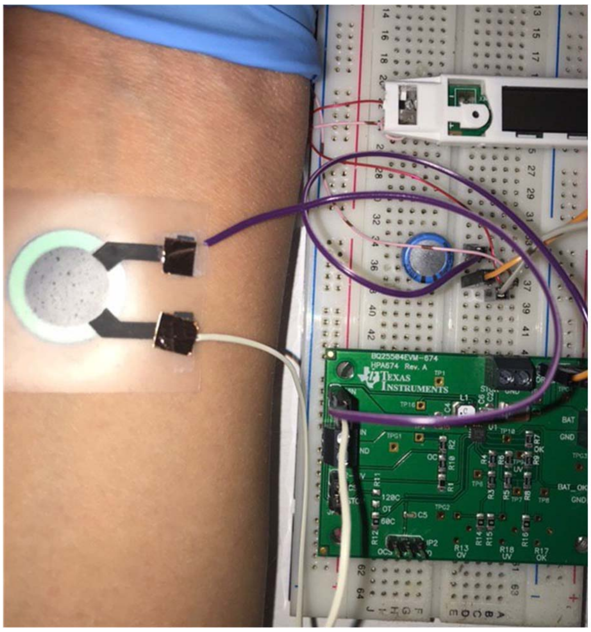

Figure 5: A sweat-driven microbial energy harvesting system connecting a DC-DC booster circuit to power a thermometer.

Sweat-activated power generation

A microfluidic channel was integrated into the system to collect sweat from the skin and sufficient number of well-cultured exoelectrogenic skin bacteria (*Staphylococcus epidermidis*) were pre-inoculated and lyophilized in the engineered reservoir. Human sweat, artificial sweat and LB media samples were tested for the biobattery as activation liquid to rehydrate the freeze-dried bacteria and generate bioelectricity (Figure 2). A bacterial concentration with an OD_{600} of 2.0 was used to saturate the 10 μL volume of the anodic reservoir (Figure 3). The biobattery's response to lactate and glucose concentration in the sweat sample was measured (Figure 4). Sweat includes biodegradable organic substrates such as lactate and glucose, which contain chemical energy convertible to electrical energy by the biobattery.

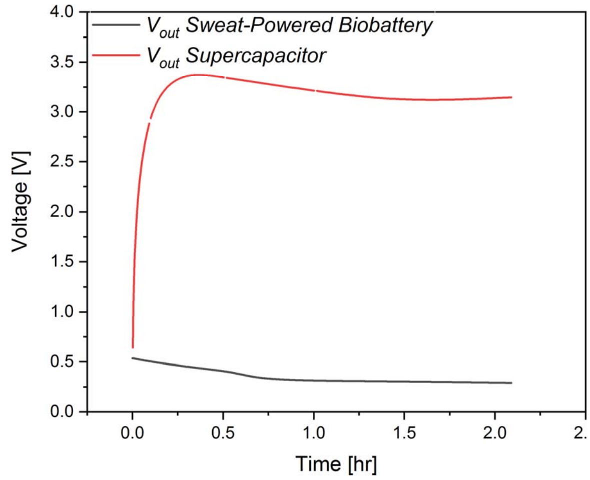

Figure 6: Plot of time versus voltage of sweat-powered biobattery and DC-DC booster circuit.

Battery system with DC-DC booster circuit

The microwatt-scale power generation of the proposed skin mounted biobattery, though still considerably lower than conventional batteries, indicates the feasibility of self-sustainable wearable biobatteries for low-power applications. With current advances in nano-scale supercapacitors and emergence of ultra-low power DC-DC convertors with start voltages as low as 0.2 V and operation currents in nano- or even pico-ampere scale, a single miniaturized biobattery will be able to fulfill the 3.3 V input voltage that is required by most commercial electronic circuits.

In this work, we connected the biobattery to a low input voltage booster, BQ255504 (Texas instruments), that is well-suited to operate within the miniaturized biobatteries (Figure 5). The voltage boost converter can start operation with input voltage of 300 mV~ 600 mV. Once started, it can continuously generate energy with only 150 mV of input voltage and ultra-low quiescent current of 0.33 μA. As shown in Figure 5 & 6, The DC-DC booster circuit was capable of converting the relatively low DC voltage of the biobattery (0.5 V) to a more practical range for a thermometer of >3.0 V.

CONCLUSION

A stable power supply is the most critical factor in developing practical wearable devices because the performance of their potential applications depends significantly on power availability. Among possible technologies, sweat-based energy harvesting offers the most suitable power-producing technique for wearable, skin-mountable applications because of its efficient, non-invasive energy-harvesting route. This report demonstrated a wearable skin bacteria-powered biobattery for use in wearable electronics. The bacterial energy harvesting methods are significantly more resilient than the enzymatic approaches and provide superior self-sustaining features with long-term stability. This work will establish an innovative strategy to revolutionize power generation on human skin, delivering on-chip energy to the next generation of wearable electronic paradigm.

ACKNOWLEDGEMENTS

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