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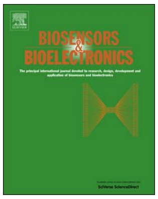

A disposable power source in resource-limited environments: A paper-based biobattery generating electricity from wastewater

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ABSTRACT

We report a novel paper-based biobattery which generates power from microorganism-containing liquid derived from renewable and sustainable wastewater which is readily accessible in the local environment. The device fuses the art of origami and the technology of microbial fuel cells (MFCs) and has the potential to shift the paradigm for flexible and stackable paper-based batteries by enabling exceptional electrical characteristics and functionalities. 3D, modular, and retractable battery stack is created from (i) 2D paper sheets through high degrees of folding and (ii) multifunctional layers sandwiched for MFC device configuration. The stack is based on ninja star-shaped origami design formed by eight MFC modular blades, which is retractable from sharp shuriken (closed) to round frisbee (opened). The microorganism-containing wastewater is added into an inlet of the closed battery stack and it is transported into each MFC module through patterned fluidic pathways in the paper layers. During operation, the battery stack is transformed into the round frisbee to connect eight MFC modules in series for improving the power output and simultaneously expose all air-cathodes to the air for their cathodic reactions. The device generates desired values of electrical current and potential for powering an LED for more than 20 min.

1. Introduction

Disposable lab-on-a-chip (LOC) devices have recently emerged as a new paradigm for clinical diagnostics and monitoring disease states (Ahn et al., 2004; Samel et al., 2007; Choi et al., 2011). The devices incorporate advanced micro-sized biosensors and microfluidics, which require only small reagent volume, reduced size, and minimized power consumption (Choi et al., 2011). They also offer many other advantages including short reaction time, versatile designs, multifunctional system integration, and highly paralleled operation with small footprints, thereby enabling portability and mobility for effective and rapid point-of-care (POC) testing even in challenging field conditions where laboratory infrastructure, equipment and trained personnel, as well as access to clean water are not available (Ahn et al., 2004; Samel et al., 2007; Choi et al., 2011). A recent advance in the LOC devices has greatly enhanced POC diagnostic performance and the technologies have been successfully introduced into the market (Chin et al., 2012; Volpatti and Yetisen, 2014). However, there has been a significant challenge in realizing a truly stand-alone and self-sustainable diagnostic platform that does not rely on a competent laboratory service. The key challenge is to develop a miniaturized power source for powering those POC devices (Choi, 2016). Power autonomy is one of the most critical requirements for the POC diagnostics that can work independently and self-sustainably in limited-resource and remote regions, where the stable electrical supply is not accessible. Even standard batteries can be problematic in those areas in terms of economic and environmental impacts. Also, conventional energy harvesting technologies (e.g. solar, thermal, mechanical, chemical energy) are too overqualified and expensive as a power source for single-use, disposable POC tests, requiring relatively small power consumption only for a couple of minutes. Therefore, there is a need for continuous effort towards the development of such power sources with disposability, low-cost, minimum environmental issues and accessibility in resource-limited settings.

Biomass can be one of the excellent energy harvesting sources readily available even in resource limited environments (Rittmann, 2008). Typically, microbial fuel cells (MFCs) have been used as energy transducers that convert the biological energy in biomass directly into electricity via microbial metabolism (Logan, 2009; Lovley, 2012; Schröder et al., 2015). Microorganisms oxidize organic fuels, completing respiration by transferring electrons to the device electrode (Torres et al., 2010; Borole et al., 2011). The

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organic fuel for microorganisms can be any type of biodegradable substrate including wastewater, urine, or soiled water in a puddle. In addition, river, ocean or pond water generally host various microorganisms that can transfer electrons via metabolism to an external electrode. For this reason, MFCs have been regarded as a promising energy technique in developing countries and the concept of the MFC has been validated by successful demonstration of large-scale system as prototypes of large power sources or energy-efficient wastewater treatment technology (Ewing et al., 2014; Logan, 2010; Li et al., 2014).

Miniaturizing MFC devices is also an interesting approach for potentially powering POC diagnostic tools due to easy accessibility in those regions, low-cost, and environmentally friendly features (Choi, 2015; Lee and Choi, 2015a; Qian and Morse, 2011; Wang et al., 2011; Han et al., 2013). However, the promise of this technology has not yet been translated as practical POC applications, because (i) even small-scale MFCs require a relatively long start-up time to accumulate and acclimate microorganisms on the anodic surface (several hours to days), (ii) their device configuration is complicated with necessary multifunctional parts (anode, cathode, and ion exchange membrane) along with microfluidic tubings for liquid inlets/outlets, and (iii) their operation requires additional power/equipment to continuously inject organic fuels. In order to overcome those limitations, Choi group has recently pioneered the novel micro-sized MFC platform on paper substrate as a potential power source for disposable POC devices (Lee and Choi, 2015b; Fraiwan and Choi, 2014; Fraiwan et al., 2014, 2013; Nguyen et al., 2014; Choi et al., 2015; Fraiwan and Choi, 2016). The paper-based MFC allowed for rapid adsorption of microorganism-containing solution through capillary force of paper and immediate microbial cells' attachment to the electrode, leading to a very short start-up time. Therefore, the device rapidly generated power with a small amount of microorganism-containing liquid. Moreover, the MFC configuration became simplified by using paper substrates because microfluidic channels/chambers can be easily patterned with hydrophobic wax and the 3D device structure can be constructed by applying origami techniques. In addition, no external pump/tubing were necessary to operate the device because paper has the ability to wick fluids through capillary action. If (i) a desired power output for actual applications is obtained through a fundamental device level breakthrough of this conceptual prototype and (ii) wastewater in the local environment can be a real energy source for its operation, then this novel device can be replicated, laying a foundation to explore the viability of this power source as a practical and accessible power supply even in difficult-to-reach, dangerous and/or extremely remote locations.

In this work, we created an origami battery in which eight paper-based MFC modules were stacked in series (Fig. 1). The device was based on ninja star-shaped design formed by eight modular blades, which is retractable from sharp shuriken (closed) (Fig. 1a) to round frisbee (opened) (Fig. 1b). Each blade had 3D MFC structure (i.e. anode, proton exchange membrane, and air-cathode) created from 2D sheets through high degrees of folding along predefined creases. The microorganism-containing solution was added into an inlet of the closed battery stack (sharp shuriken), through which it was transported into each MFC module. During operation, the battery stack was transformed into the round frisbee to connect eight MFC modules in series for improving power output and simultaneously expose all air-cathodes to the air for their cathodic reactions. The battery stack generated desired values of electrical current and potential for powering a red LED even with readily prepared wastewater sample available for on-site operation in low resource settings and economically challenged regions of the world.

2. Experimental

We created a three-dimensionally folded paper MFC stack which was capable of transforming its shape from the sharp shuriken to the round frisbee or vise-versa. The stack was composed of the eight MFC modules. With the shuriken shape, individual MFCs were disconnected and their inlets were positioned in the center for easy sample introduction. When the stack was opened for the round frisbee shape, all MFCs were connected in series and their cathodic parts were maximally exposed to the air. This miniaturized paper-based power source could lead to a very practical application by using wastewater in the local environment as the electron donor and allowing the use of freely-available oxygen in the air as the electron acceptor.

2.1. Paper-based MFC modules

Each MFC module was fabricated by sandwiching five

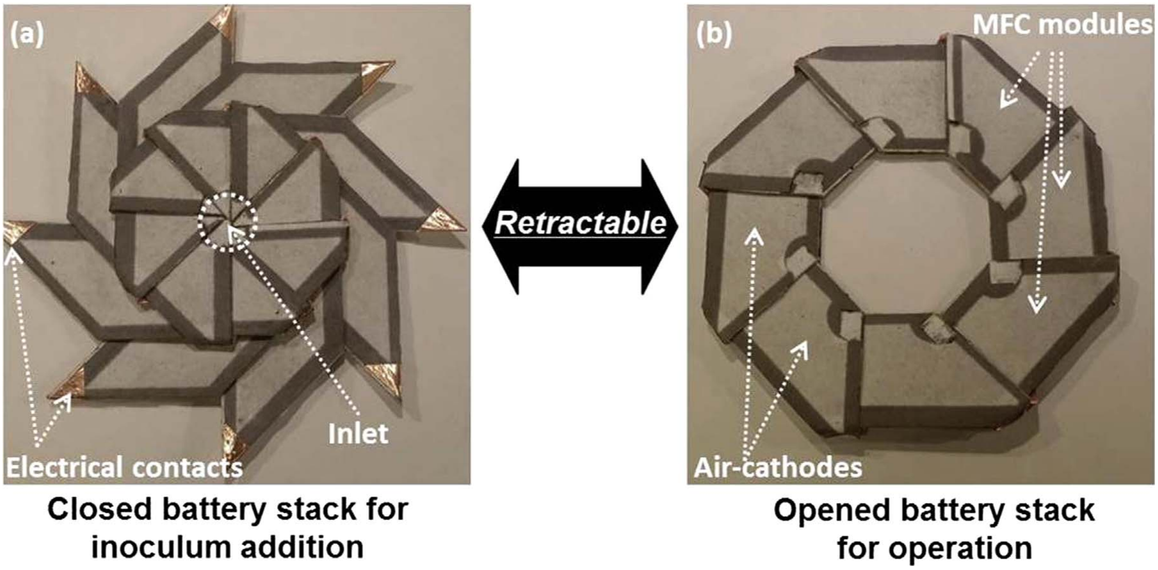

Fig. 1. Conceptual device photo-images of the origami paper-MFC stack. Each MFC module is prepared as a blade for the eight point ninja star. The sharp shuriken (a) can be transformed into the round frisbee (b) for operation as a power source.