Two-dimensional Graphene Paper Supported Flexible Enzymatic Fuel Cell

Shen, Fei; Pankratov, Dmitrii; Halder, Arnab; Xiao, Xinxin; Toscano, Miguel D.; Zhang, Jingdong; Ulstrup, Jens; Gorton, Lo; Chi, Qijin

Published in:
Nanoscale Advances

Link to article, DOI:
10.1039/C9NA00178F

Publication date:
2019

Document Version
Peer reviewed version

Link back to DTU Orbit

Citation (APA):
This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the Information for Authors.

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal’s standard Terms & Conditions and the Ethical guidelines still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.

This article can be cited before page numbers have been issued, to do this please use: F. Shen, D. Pankratov, A. Halder, X. Xiao, M. D. Toscano, J. Zhang, J. Ulstrup, G. Lo and Q. Chi, Nanoscale Adv., 2019, DOI: 10.1039/C9NA00178F.
Two-dimensional Graphene Paper Supported Flexible Enzymatic Fuel Cell

Fei Shen, Dmitry Pankratov, Arnab Halder, Xinxin Xiao, Miguel D. Toscano, Jingdong Zhang, Jens Ulstrup, Lo Gorton, and Qijin Chi

Application of enzymatic biofuel cells (EBFCs) in wearable or implantable biomedical devices requires flexible and biocompatible electrode materials. To this end, freestanding and low-cost graphene paper is emerging among the most promising support materials. In this work, we have exploited the potential of using graphene paper with two-dimensional active surface (2D-GP) as carriers for enzyme immobilization to fabricate EBFCs, which represents the first case of flexible graphene papers directly used in EBFCs. The 2D-GP electrodes were prepared via the assembly of graphene oxide (GO) nanosheets into paper-like architecture, followed by reduction to form layered and cross-linked networks with good mechanical strength, high conductivity and little dependent on the degree of mechanical bending. 2D-GP electrodes served as both a current collector and an enzyme loading substrate that can be used directly as bioanode and biocathode. Pyrroloquinoline quinone dependent glucose dehydrogenase (PQQ-GDH) and bilirubin oxidase (Box) adsorbed on the 2D-GP electrodes both retain their biocatalytic activities. Electron transfer (ET) at the bioanode required Meldola blue (MB) as an ET mediator to shuttle electrons between PQQ-GDH and electrode, but direct electron transfer (DET) at the biocathode was achieved. The resulting glucose/oxygen EBFC displayed a notable mechanical flexibility, with wide open circuit voltage up to 0.665 V and maximum power density of approximately 4 µW/cm$^2$ both fully competitive with reported values for related EBFCs, and with the mechanical flexibility and facile enzyme immobilization as novel merits.

Introduction

Rapid development of portable microelectronics for biomedical purposes has increasingly demanded miniature power sources that facilitate long-term operation under particular environments such as physiological and pseudo-physiological conditions. Such power-source systems are particularly needed for low-power biomedical devices, e.g. cardiac pacemakers, urinary sphincters and integrated biosensing devices for periodic monitoring of diseases.

Enzymatic biofuel cells (EBFCs) constitute a kind of sustainable bioelectrochemical devices that convert chemical energy into electric power using enzymes as highly efficient biological catalysts and remarkably, they can operate under neutral pH conditions with high selectivity towards conversion of targeted chemical fuels. These unique characters make EBFCs promising power systems for implantable biomedical devices, in which low power is sufficient but mechanical flexibility, biocompatibility and implantability are crucial. Furthermore, a rich variety of dissolved fuels and oxidants (e.g., glucose, lactate, urate and oxygen) and intensive flow rate makes human blood the most attractive internal fluid for EBFC operation. The possibility to operating EBFCs in various physiological media of human and other mammals has recently been demonstrated at versatile in vitro, ex vivo and in vivo levels. Electrode materials are central in the development of high-performance EBFCs. Indeed, recent advances in the field of EBFCs have been driven mainly by the design and assembly of three-dimensional (3D) porous and high surface-area electrode materials. However, these bioelectrodes can hardly be integrated into blood or other biological vessels. Additionally, for biological tests they require a membrane to prevent clogging by blood cells and possible formation of cholesterol plaques or other structures that could affect the blood circulation and induce thrombosis or embolism. In many low-power electronics application, the EBFC power density might not be a key factor, since as demonstrated by nanocomposite based EBFCs the power density achieved is far higher than that for practical needs. However, the (re)production of these nanoarchitectures in the centimeter scale is complicated and costly. In addition, intensive consumption of glucose and oxygen by an EBFC needed for generating high current density is very likely to cause local hypoxia and even cell death. The power output from an implanted EBFC should therefore be only as low as needed to power the targeted device. To date, for example, the highest power output achieved for EBFCs in blood mimicking glucose-containing buffer solutions is close to 1000 µW/cm$^2$, i.e. reaching $\sim 130$ µW/cm$^2$ in whole human blood. This value is significantly higher than required to power most modern...
cardiac pacemakers (only 1-10 µW needed) \(^4,17\). In contrast, research efforts toward scalable two-dimensional (2D) materials for potentially implantable bioelectrodes are clearly underplayed, although the advantages of 2D materials as a freestanding support for non-enzymatic sensors \(^{18,19}\), enzyme biosensors \(^{20,21}\), microbial biofuel cells \(^{22,23}\) and others \(^{24,25}\) have been clearly demonstrated.

Graphene based nanocomposites, arguably now the most broadly used 2D materials, have offered new opportunities for the immobilization of various enzymes, mainly because of their high electrical conductivity, high surface area, good mechanical strength, tunable mechanical flexibility, and good biological compatibility \(^{26,27}\). An increasing number of researchers have explored graphene and its composites for enzyme immobilization. For example, Di Bari et al. reported the electrodeposition of graphene oxide (GO) on glassy carbon (GC) electrodes to construct 3D electrodes of high surface-area, which were further functionalized for covalent attachment of multi-copper oxidases (MCOs) \(^{28}\). Inamuddin et al. have developed a bioanode using layer-by-layer assembly of sulfonated graphene/ferritin/glucose oxidase biocomposite films for mediated electron transfer (MET) driving oxidation of glucose \(^{29}\). However, graphene and its hybrids could not self-support (or be freestanding) in this research, but needed to be supported by GC or gold electrodes \(^{32,33}\). These graphene-modified electrodes are therefore largely limited to the lab-level tests and can hardly be used for fabricating practical devices due to their non-scalability and high cost. In order to overcome this limitation, flexible, manoeuvrable or even implantable supporting electrodes are needed to replace the rigid (GC and graphite) or expensive (gold and platinum) working electrodes for design and fabrication of new-generation EBFCs which can favor biomedical applications.

In this work, we have engineered flexible and freestanding graphene papers with a 2D active surface (2D-GP) by a novel low-cost solution-processed procedure. The resulting graphene papers were tested as a support for both biocathode and bioanode to create a flexible, membrane-free and potentially implantable glucose/O\(_2\) EBFC. As illustrated in Scheme 1, the main building blocks include pyrroloquinoline quinone-dependent glucose dehydrogenase (PQQ-GDH), bilirubin oxidase (BOx), GO nanosheets and the ET mediator Meldola blue (MB) (Scheme 1A). Engineered 2D-GP enabled facile immobilization of both enzymes via direct adsorption with their biocatalytic activities fully retained. PQQ-GDH required MB as an ET mediator to act as an anode biocatalyst for electrocatalytic oxidation of glucose, but adsorbed BOx can exchange electrons with the 2D-GP electrode via direct ET (DET) toward electrocatalytic reduction of dioxygen. The assembled EBFCs exhibited high performance and stability. To the best of our knowledge, this work represents the first exploration of graphene paper as a self-supporting electrode material for flexible and membrane-free glucose/O\(_2\) EBFCs.

**Experimental section**

**Chemicals and enzymes**

Meldola blue (MB), i.e. 8-Dimethylamino-2,3-benzophenoxazine hemi(zinc chloride) salt (> 90%), 1,4-Piperazinediethanesulfonic acid (PIPES) (99.5%), D-(+)-glucose (99.5%), uric acid sodium salt and sodium L-ascorbate (> 98%) were from Sigma, potassium dihydrogen phosphate (99.995%) and dipotassium phosphate (99.995%) from Fluka. Sodium hydroxide (99.99%), calcium chloride dihydrate (99%), sodium L-lactate (> 99.0%), hydrazine hydrate, bovine serum albumin (BAS) and Bradford reagent were from Sigma-Aldrich. Potassium hexacyanoferrate(III) (99%) was from Riedel-de Haën. GO powder was either in-house prepared \(^{21}\) or obtained from the Sixth Element Inc. PQQ-GDH (1020 U/mg) from *Acinetobacter calcoaceticus* was purchased from Sorachim SA. BOx from *Myrothecium verrucaria* (167 U/mg) was produced and purified by Novozymes A/S based on a previously reported protocol \(^{32}\). All chemicals were used as received without further purification. Milli-Q water (18.2 MQ cm) was used throughout.

**Graphene paper preparation**

Synthesis of the graphene paper was based on the previously reported producers \(^{18,23,33}\) but with modification regarding particularly conductivity improvement *(vide infra)*, which is crucial for freestanding bioelectrode acting simultaneously as a...
current collector. First, GO powder was dispersed in Milli-Q water and sonicated for 2 h below 30 °C to obtain 1 mg/mL GO dispersion. Then 20 mL of GO dispersion was vacuum filtered through a membrane with the average pore size of 0.2 μm and a diameter of 47 mm. After peeled off from the filter membrane, freestanding GO paper was obtained. The transformation of the GO paper to rGO paper was achieved by placing GO paper in a Teflon container together with a tiny beaker containing 100 μL of hydrazine but no direct contact with the hydrazine solution. The container was sealed in a stainless steel autoclave and heated to 99 °C for 2 h. Upon elevating the temperature, hydrazine evaporated to form steam filling the whole container, and reducing the GO paper to rGO paper. Finally, to remove residual hydrazine and further enhance the conductivity, the rGO paper was annealed at 600 °C for 1 h in a high-temperature oven under Ar flow. For facilitating electrochemical measurements, graphene paper was cut to rectangular pieces (typically 0.5 cm × 1 cm) with an effective geometric surface area of 0.25 cm².

**Morphology, surface resistance and elemental composition of graphene paper**

The morphology of dispersed GO was probed by tapping mode atomic force microscopy (AFM, Agilent) with a Tap300Al-G tip from Budget Sensors. The topography of the GO and rGO paper was further characterized by scanning electron microscopy (SEM) using Quanta FEG 200 ESEM electron microscope from FEI with TX microscope Control Software. The surface resistance of the graphene paper was characterized by a four-point probe (FFP) from a Jandel Model RM3 test station. The elemental composition of GO paper and rGO paper before and after annealing was analyzed by X-ray photoelectron spectroscopy (XPS), using the Thermo Scientific XPS System with the FEI with TX microscope Control Software. The surface resistance of the graphene paper was characterized by a four-point probe (FFP) from a Jandel Model RM3 test station. The elemental composition of GO paper and rGO paper before and after annealing was analyzed by X-ray photoelectron spectroscopy (XPS), using the Thermo Scientific XPS System with the FEI with TX microscope Control Software.

**Bioanode preparation**

Bioanodes were fabricated by physical adsorption of PQQ-GDH onto as-prepared 2D-GP electrodes. For the immobilization of MB mediator, the 2D-GP electrode was immersed in a 10 mM MB aqueous solution and left overnight. The MB modified 2D-GP electrode was then rinsed with Milli-Q water at least three times to remove unbound MB. PQQ-GDH solution in a 20 mM PIPES buffer (pH 7.0 adjusted by NaOH solution) containing 3 mM CaCl₂ as stabilizer was prepared. 10 μL of 4 mg/mL PQQ-GDH was drop-cast onto the MB modified 2D-GP electrode and then kept in a moisture chamber at 4 °C for 30 min. Before use, the bioanode was rinsed copiously with phosphate buffer.

**Biocathode preparation**

The enzyme immobilization for biocathodes was similar to that for the bioanodes but without mediators. 10 μL of 3.61 mg/mL Box solution (in 20 mM Tris buffer, containing 100 mM Na₂SO₄, pH 8.0) was spread on 2D-GP electrode surface and kept in a moisture chamber at 4 °C for 30-40 min. After enzyme adsorption, the electrodes were rinsed with buffer solution to remove loosely bound enzyme.

**Im mobilized enzyme concentration tests**

The enzyme concentration was tested according to the Bradford protein assay. A standard curve was prepared by testing the absorbance (595 nm) of various concentrations of BSA (50 μL) mixing with Bradford reagent (1.5 mL). The amount of immobilized enzyme on the 2D-GP electrodes was calculated from the difference between the initial and rinsed enzyme amounts.

**Electrochemical measurements**

All electrochemical measurements were performed at room temperature (23 ± 2°C) using a PalmSens3 electrochemical interface controlled by the PSTrace software. For half-cell tests, a three-electrode system consisting of functionalized graphene electrodes as working electrode, a platinum wire as a counter electrode and Ag/AgCl (KCl sat) as a reference electrode was used. The EBFC performance was evaluated by using a two-electrode system with bioanode and biocathode immersed in the same electrolyte solution without a separate membrane. The distance between two bioanode and biocathode was controlled at 1 cm. A 10 mM phosphate buffer (PB) solution with pH 7.0 was used as the electrolyte for electrochemical experiments unless stated otherwise. All presented data were obtained on at least three independent measurements for each experiment.

**Results and discussion**

**Morphology, microscopic structures and conductivity of rGO papers**

A self-supporting and flexible GO film was prepared by flow-directed assembly of GO nanosheets. AFM images show the morphology of dispersed GO and an average height of GO of about 1 nm (Fig. S1). Assembling GO flakes formed a paper-like film, which showed a flat surface and a compact layered cross section, Fig. 1A, C and E. However, the internal resistance of the GO film is relatively high, owing to the disruption of its sp² bonding networks. In order to operate as a supporting electrode, the GO film must be reduced to recover high conductivity. The GO paper prepared by vacuum filtration was reduced by hydrazine vapor. Hydrazine was chosen because of its strong reducing capacity and easily removable reduction products. Water molecular layers remained in the GO layers providing channels for reductant molecules to spread into the interior of the films. Release of the gaseous products (H₂ and CO₂) formed during chemical reduction expanded the compact layers. The resulting rGO paper therefore possesses a rough surface and a continuously crosslinked architecture (Fig. 1D and 1F). The contacts between graphene sheets lower significantly the resistance of whole rGO paper (48.33 Ω/sq). The hydrazine reduced GO paper subsequently underwent thermal annealing to remove the remaining reagents and to enhance the conductivity further. As a result, the resistance of rGO paper formed was as low as 25.86 Ω/sq. Furthermore, this rGO paper remains flexible (Fig. 1B) and surface and cross sectional structures are largely unchanged.
Chemical composition of rGO papers

The elemental composition of the rGO paper during the reductive process was investigated by XPS. Fig. 2A compares the general survey spectra of GO film, hydrazine reduced GO paper and thermally annealed rGO paper. The O1s peak intensity (around 530 eV) had significantly decreased following the hydrazine treatment, and continued to decrease after the 600 °C annealing, indicating loss of oxygen. The atomic ratios of carbon to oxygen were 2.57, 7.62 and 11.70 for GO films before and after treatments, respectively. A new peak around 400 eV (magnified in dash circle,) appeared after hydrazine exposure, which indicated that nitrogen was introduced. The weak intensity of this peak suggested that only a trace amount of nitrogen was incorporated, according with reported observations. A slight reduction of this peak occurred after thermal treatment.

The detailed C1s spectra of the graphene papers before and after treatments are shown in Fig. 2B-D, respectively, along with the curve fitting using the Thermo Advantage software with a fixed Gaussian/Lorentzian (G/L) ratio. The untreated GO paper had a main peak at 284.5 eV (53.48%) assigned to the aromatic sp² structures, and another broad peak with a tail towards higher binding energy attributed to the overlap of various carbon bonding configurations. The second peak can be assigned to C-O single bonds at 286.6 eV (35.83%) and carbon doubly bonded to oxygen at 287.8 eV (10.69%). After chemical treatment, the fraction of carbon contributing to C-O and C=O bonds had decreased significantly to 10.57% and 2.11%, respectively. Conversely, the main peak at 284.5 eV had increased to 70.42% and a new component at 258.4 eV (16.90%) corresponding to C-C single bond appeared. The change of various carbon functional groups retained the previous tendency but slowed down after thermal treatment, indicative of further reduction of GO. A small percentage of C-O groups was still present (4.41%), but the C=O peak had completely disappeared, whereas the C>C and C-C group signals had increased slightly, to 73.53% and 22.06%, respectively. These results support the observed recovery of conductivity of the 2D-GP electrodes.

Electrochemical behavior of MB modified rGO papers

Fig. 2 XPS of GO and rGO papers: (A) comparison of the general survey spectra of GO paper, hydrazine reduced GO paper and thermally annealed GO paper. (B), (C) and (D) Corresponding C1s spectra, respectively analyzed in detail; the solid red curves are the measured data, the dashed blue curves are the overall fitting. The curves in other colors are deconvoluted spectra.

Fig. 1 Morphology and microscopic structures of graphene papers: digital photographs of GO (A) and rGO (B) papers at the centimeter scale; SEM images of the surface structures of GO (C) and rGO (D) papers; and cross-section SEM images of the layered assembly of GO (E) and rGO (F) papers.
Before any modification, the bare 2D-GP electrode was characterized electrochemically in the presence of the electroactive species \(K_2[Fe(CN)_{6}]\) at different scan rates. As shown in Fig. S2, well-defined redox peaks at \(E_{1/2}=0.23\) V vs Ag/AgCl, KCl sat were observed. The peak current follows closely a square root dependence of scan rate, according with diffusion control. The 2D-GP electrodes with MB molecules adsorbed via noncovalent bonding was investigated next (Fig. S3A). As a phenoxyazine salt, MB contains several aromatic rings, and can adsorb onto carbon materials by π-π stacking. Cyclic voltammograms (CVs) of MB modified graphene electrode are shown in Fig. S3B. Well-defined two-electron redox peaks at \(E_{1/2} \approx -0.15\) V, equation (1) were observed caused by reversible oxidation/reduction of the two nitrogenic moieties (Fig. S3C). The peak current retained the same intensity after 20 scans, verifying the stable MB adsorption on the electrodes.

\[
MB^+ + H^+ + 2e^- \leftrightarrow MBH
\]  

(1)

Ideally, the anodic and cathodic peaks should be symmetric. However, peak separation remained right down to 53 mV at 0.1 V/s probably due to the rough surface of the graphene electrodes, and diffusing protons. Although there should be no mass transport constraints of oxidized and reduced reactants since both are present on the electrode surface, protons involved in the redox reaction (equation 1) still have to be exchanged with the electrolyte. This could give rise to peak separation, e.g. due to a concentration gradient. The surface coverage of MB \(\Gamma_{MB}\) could be determined from the CVs according to the Laviron equation 30:

\[
i_p = \frac{n^2F^2}{4R \Delta E_p} \Gamma_{MB} \Delta v
\]

(2)

where \(n\) is the number of electrons transferred during the process. \(F\) and \(R\) are Faraday’s constant and the gas constant, respectively, \(T\) the temperature, and \(\Delta v\) the electrode surface area. The coverage \(\Gamma_{MB}\) was estimated as \(1.76 \times 10^{-10}\) mol/cm². A dense monolayer of Meldola Blue in planar adsorption holds a surface coverage of \(2.40 \times 10^{-10}\) mol/cm² 37. The observed \(\Gamma_{MB}\) thus corresponds to about 75 % coverage.

CVs of MB modified electrodes with different scan rates (e.g., 0.005-0.5 V/s) showed a linear relationship between \(i_p\) and \(v\) (up to 0.4 V/s), Fig. S4, according with diffusion-less voltammetry, but the \(i_p/v\) correlation begins to deviate from linearity at higher scan rate. This could result from similar “non-ideality” as for the observed peak separation, such as rough surface, fast scan rate and proton transport. The standard apparent interfacial electrochemical electron transfer rate constant \(k_{app}\) of MB was calculated by Laviron’s method 40 using the following equations:

\[
\Delta E_p = \left(\frac{RT}{nF}\right) \ln \left(\frac{1}{m}\right)
\]

(3)

\[
1/m = \frac{nF \Delta v}{RT \Delta E_p}
\]

(4)

where \(m\) was determined from the peak separation \(\Delta E_p\). The rate constant was calculated as 8.6 s⁻¹ from the slope of the plot of \(1/m\) vs \(v\) (Fig. S5). This value reflects efficient interfacial electron transfer between MB and the graphene electrodes.

**Electrocatalytic oxidation of glucose at the 2D-GP bioanode**

PQQ-GDH was physically adsorbed onto the MB modified electrode and then employed as the biocatalyst for glucose oxidation at the anode. The amount of immobilized PQQ-GDH on the electrode was determined to be around \(4.78 \times 10^{-10}\) mol/cm². MB has been widely used as a mediator for NADH or NADPH based dehydrogenases due to its fairly low redox potential and photo-insensitivity 37,41. Here, we show that physically adsorbed MB can establish an electron transfer pathway between the redox center of PQQ-GDH and the graphene paper. Fig. 3A displays the sigmoidal bioelectrocatalytic curves in the presence of glucose. The biocatalytic current starts from a potential of about -0.15 ± 0.02 V and rises to a limiting value around 0.05 V. The onset potential towards glucose achieved herein is close to most PQQ-GDH bioelectrodes 16,42-45, and even 0.33 V lower compared to that of mediator-free PQQ-GDH linked to carbon fiber electrodes functionalized with graphene nanosheets 46, testifying to robust and competitive operation of the new graphene paper bioanode. Control experiments without enzyme showed no...
catalytic signals in this potential range (Fig. S6), verifying that the glucose oxidation resulted from PQQ-GDH. The catalytic current of the as-prepared bioanode increases with increasing concentrations of glucose (Fig. S7). When the concentration of glucose reaches 5 mM, the enzyme response towards glucose is close to the saturation value. It is worth noting that this glucose concentration is well matched with the average value of glucose in human blood 47, indicating the potential for implantable application. The catalytic processes can be described by the following equations:

\[
PQQ - \text{GDH} + D - \text{glucose} \rightarrow \text{PQQH}_2
\]
\[-\text{GDH} + D - \text{gluco} - 1.5 - \text{lactone}
\]

(5)

\[
\text{PQQH}_2 - \text{GDH} + \text{MB}^+ \rightarrow \text{PQQ} - \text{GDH} + \text{MBH} + \text{H}^+
\]

(6)

PQQ-GDH oxidizes dextroglucose to gluconolactone and itself is reduced to \(\text{PQQH}_2\)-GHD, which then transfers electrons to MB\(^+\) (the oxidized form of MB) to recover catalytic ability. The MBH formation (the reduced form of MB) was followed by electrooxidation on the electrode, equation (1). The low catalytic potential of this bioanode towards glucose oxidation is very attractive for EBFCs.

Electrocatalytic reduction of dioxygen at the 2D-GP biocathode

The multicopper oxidase, BOx, was chosen as the biocatalyst for the dioxygen reduction reaction (ORR) at the cathode without using mediators. The biocathode was again fabricated by facile direct adsorption of the enzyme onto the bare 2D-GP electrode. The amount of immobilized BOx on the electrode was approximate \(3.02 \times 10^{10}\) mol/cm\(^2\). The reduction current of BOx biocathode in air-saturated PB was recorded by cyclic voltammetry (Fig. 3B). The reduction reaction started around 0.50 ± 0.02 V and reached a limiting current density of 11.78 \(\mu\)A/cm\(^2\) at 0.20 V, which is similar to the reported results of BOx immobilized on other carbon electrodes 48. No reduction on bare graphene electrode between 0.1-0.6 V was observed, confirming that dioxygen reduction was in fact catalyzed by BOx. Since no mediator was introduced in this system, dioxygen reduction was effected by direct ET between the enzyme and graphene paper, as described by equations (7) and (8).

\[
\text{BOx}_{\text{ox}} + 4e^- \rightarrow \text{BOx}_{\text{red}}
\]

(7)

\[
\text{BOx}_{\text{red}} + \text{O}_2 + 4\text{H}^+ \rightarrow \text{BOx}_{\text{ox}} + 2\text{H}_2\text{O}
\]

(8)

In the detailed catalytic mechanism, four electrons sequentially tunnel from the electrode to the fully oxidized enzyme. The four electrons are transferred via the type I copper center of BOx. One electron is left at the type I center and three electrons transferred further to the type II/III center by intramolecular ET, forming the fully reduced enzyme 49. Subsequently, \(\text{O}_2\) reacts with the reduced trinuclear copper center forming a peroxy intermediate (PI), in which two copper ions are oxidized. A second intramolecular two-electron transfer step then occurs along with the cleavage of the O-O bond in the PI, resulting in a fully oxidized intermediate enzyme form (NI) 50. With electrons from the electrode and protons from the electrolyte, the fully oxidized NI is rapidly reduced to the fully reduced form of BOx along with liberation of water. Efficient electron tunneling between the electrode and T1 site of BOx requires a short surface-type I distance and a proper orientation of enzyme 51. The rough surface of the graphene electrode seemingly provides such appropriate biocompatible binding sites and short BOx ET distances, leading to an effective biocathode with DET towards the ORR.

Electrochemical performance of as-constructed EBFCs

The prepared new graphene paper based PQQ-GDH bioanode and BOx biocathode were assembled to a complete EBFC. The performance of this biofuel cell was investigated by linear sweep voltammetry (LSV) in air-saturated PB containing 6.4 mM glucose (Fig. 4A). Glucose was oxidized at the anode and donated electrons, which traveled through the external circuit to the cathode and were subsequently accepted by \(\text{O}_2\). As shown in the individual polarization curves of the bioanode and biocathode, the anodic catalytic current was around two times higher than that for the cathode, indicating that the EBFC performance is mainly limited by activity of the cathode (Fig. S8). The open circuit voltage (OCV) of the assembled EBFC was ca. 0.665 V, which is similar to other reported PQQ-GDH/MCOs EBFCs 16,43 operating in PB, and 0.255 V higher than that of

![Graph showing the electrochemical performance of as-constructed EBFCs](image-url)
graphene functionalized EBFC. A maximum power density of 4.03 µW/cm² was obtained at a voltage of 0.42 V, which is significantly higher compared to the recently reported EBFC based on spectrographic graphite as the electrode support. Table 1 compares the performance of graphene materials based bioelectrochemical systems with different kinds of biocatalysts. The peak power output in this work is comparable with the recently reported results. Other reports show 5–7 times higher power density than that achieved in this work, but they consume much higher concentration of glucose, which is far beyond the glucose concentration in normal human blood. The stability of the new EBFC was further tested by continuously recording the current at the maximum power density and found to be comparable with that of a recently reported mediated EBFC with the highest performance ever achieved for whole human blood (Fig. S9).  

Table 1. Performance of graphene materials based bioelectrochemical systems.

<table>
<thead>
<tr>
<th>Anodic enzyme</th>
<th>Fuel concentration</th>
<th>Cathodic enzyme</th>
<th>Electrode architecture</th>
<th>OCV (V)</th>
<th>Power density (µW/cm²)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>PQQ-GDH</td>
<td>20 mM glucose</td>
<td>Laccase</td>
<td>3D graphene nanoflakes</td>
<td>0.410</td>
<td>5.50</td>
<td>46</td>
</tr>
<tr>
<td>Cellulose dehydrogenase</td>
<td>5 mM glucose</td>
<td>Laccase</td>
<td>Gold nanoparticles /graphene</td>
<td>0.740</td>
<td>5.16</td>
<td>52</td>
</tr>
<tr>
<td>Thylakoid membranes</td>
<td>Light</td>
<td>BOx</td>
<td>3D graphene matrix</td>
<td>0.500</td>
<td>1.79</td>
<td>53</td>
</tr>
<tr>
<td>NADH-GDH</td>
<td>30 mM</td>
<td>Laccase</td>
<td>Graphene/carbon nanotubes</td>
<td>0.690</td>
<td>22.5</td>
<td>57</td>
</tr>
<tr>
<td>Glucose oxidase</td>
<td>200 mM glucose</td>
<td>BOx</td>
<td>3D graphene coated carbon fiber cloth</td>
<td>0.620</td>
<td>34.3</td>
<td>58</td>
</tr>
<tr>
<td>PQQ-GDH</td>
<td>6.4 mM glucose</td>
<td>BOx</td>
<td>2D graphene paper</td>
<td>0.665</td>
<td>4.03</td>
<td>this work</td>
</tr>
</tbody>
</table>

To investigate the influence of mechanical deformation of the electrodes on the performance of the assembled EBFC, the power density of the EBFCs employing electrodes bent to various angles was tested. To eliminate the deviation between different electrodes, the power density of each EBFC was first recorded at the planar angle (P_initial), and then recorded at selected angles (P_x°). The ratio of P_x/P_initial was calculated and normalized for comparison. Table S1 and Fig. 4B show that the EBFC has good tolerance for bending to different angles without obvious changes in power output and internal resistance, similar to graphene-protein layer-by-layer assembled electrodes. The OCV and power output of the assembled EBFC are comparable with that of carbon nanotube based flexible EBFCs.

In order to evaluate the power output of the EBFC operating in human blood, the EBFC performance was tested in blood mimicking buffer (BMB, pH 7.4), which was found to fully simulate the EBFC behavior in whole blood. BMB contained the main plasma electrolytes (including 4.05 mM K⁺, 141.4 mM Na⁺, and 105.4 mM Cl⁻) and redox active components (0.045 mM ascorbate, 0.425 mM urate, 1.92 mM lactate) at their physiological concentrations. Although the OCV value in BMB expectedly dropped to 0.418 V due to parasitic reactions occurring on exposed patches of the biomodified 2D-GP, the observed decrease in OCV was only 50 mV lower compared to the EBFC based on the tubular spectrographic graphite, which indicated more uniform enzymatic coverage of the 2D-GP surface obtained in the present work. The maximum power density achieved in BMB was 30 % lower than that in the pure PB buffer (2.83 and 4.03 µW/cm², respectively), which is still sufficient to drive a cardiac pacemaker or as a self-powered biosensor.

Conclusions

EBFCs based on graphene, nanotube, and other nanoscale carbon materials have been reported and are in increasing focus. In the present study, we have introduced a novel graphene-based EBFC that offers several merits compared with reported related systems. First, the electrode material is freestanding graphene paper – as opposed to carbon or gold supported graphene electrode materials prepared by optimized chemical synthesis. Being of paper design, the mechanically flexible, freestanding, and low cost graphene electrodes hold favorable properties regarding implantation in biological environment. Secondly, the graphene electrode material was characterized comprehensively by SEM, XPS, AFM and four-point conductivity ascertaining that optimal conductivity and other physical properties are achieved. Thirdly, the bioanode and biocathode are based on PQQ-GDH and BOx, respectively and can be prepared by facile direct physical adsorption on the new flexible graphene paper electrodes.

The electrochemical and electrocatalytic properties of the new PQQ-GDH bioanode and BOx biocathode were tested comprehensively by cyclic voltammetry and found to display robust monolayer voltammetry and efficient electrocatalysis towards glucose oxidation and dioxygen reduction. PQQ-GDH needs the MB mediator for facile electrocatalysis, whereas direct electron transfer between enzyme and graphene paper electrode could be effected for the BOx biocathode. The EBFCs were tested particularly for solutions that mimic real blood samples. The new electrodes were finally used to design and build a working EBFC, merits of which are membrane-less construction, mechanical flexibility, biocompatibility, low cost, and facile...
engineering. The peak power output and stability are broadly comparable with reported results for other carbon based EBFCs, but must be help up against the facile electrode and bioelectrode preparation, and the meritorious mechanically flexible structure of the free-standing graphene paper electrodes. Bending was found not to compromise core electronic properties of the electrodes such as the conductivity in particular. The latter offers perspectives for implantable or wearable application, where the power output of the developed EBFCs holds the potential to drive low-power biomedical and bioanalytical microelectronics. Reducing the power requirement of portable medical devices will be an issue of their future development. Further performance enhancement of the biocathode, which seems to be the limiting factor in efficient performance, and long-term stability of the EBFC could therefore be the focus for ongoing efforts.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements


References
