Selective response of dopamine on 3-thienylphosphonic acid modified gold electrode with high antifouling capability and long-term stability

Xinchun Wu[a], Ping Li[b], Yongfeng Zhang[a], De Yao[c],*

[a] School of Chemical Engineering, Inner Mongolia University of Technology, Hohhot 010051, China
[b] Jining Teachers College, Department of Chemistry, Wulanchabu 012000, China
[c] Erdos Institute of Applied Technology, Erdos 017000, China

A B S T R A C T

In this work, an Au electrode modified with self-assembled monolayers (SAMs) of 3-thienylphosphonic acid (TPA) was used as a novel functional interface to selectively sense dopamine (DA) in the presence of excess ascorbic acid (AA). Ellipsometry, X-ray photoelectron spectroscopic (XPS) and electrochemical measurements proved the immobilization of TPA on the gold surface. Interestingly, the Au electrode modified with TPA substantially improved the antifouling and renewal capabilities towards the oxidation of dopamine (DA) after 15 days of storage in undeoxygenated phosphate buffer solution (PBS pH 7.4). Moreover, the TPA-SAMs modified Au electrode could afford a selective electrochemical response for the DA oxidation in the presence of ascorbic acid (AA). Based on this result, a high sensitive detection limit of 2.0×10^{-7} M for DA could be obtained in the presence of high concentration of AA.

1. Introduction

Dopamine (DA) is an important class of neurotransmitters and is involved in a variety of central nervous system functions. High DA levels are known to be cardiotoxic, leading to rapid heart rate, high blood pressure, and possible death of the heart muscles. On the contrary, a loss of DA-containing neurons may result in some serious diseases such as Parkinson's disease [1,2]. Therefore, DA is directly related to biologically relevant events. Due to its crucial role in neurochemistry, determination of the concentration of DA has been a considerable interesting research field [3,4]. Up to now, several traditional methods [5–9] (such as spectrometric, fluorometric, radioenzymatic, electrochemistry and chromatographic methods) have been used for the determination of DA. Among those, electrochemical methods have proved to be significantly advantageous to the biosciences because electrochemical instrumentation is inexpensive, robust, sensitive, rapid and relatively simple to operate [10–13]. In addition, electrochemical methods are easy for miniaturization, thus, they can be used for in vitro [14] and in vivo [15] studies of DA, which have produced considerable information over DA level in real biological systems. Nevertheless, one of the major problems of electrochemical detection of DA in real biological matrixes is the presence of a high concentration of ascorbic acid (AA), which is oxidized at nearly the same potential as DA on bare electrodes, and results in overlapped voltammetric response [16–18]. In addition, the bare electrodes easily suffer from a fouling effect due to the polymerization of the oxidation product of DA, which inhibiting electron transfer reaction of DA oxidation, and consequently resulting in rather poor selectivity and sensitivity for DA determination [19–22].

Up to now, various approaches have been suggested to overcome all these problems in the selective and sensitive measurement of DA. One promising approach is the use of chemically modified electrodes [23–27]. Modification of Au electrodes with self-assembled monolayers (SAMs) of functionalized organosulfur compounds have attracted much attention in the field of biosensors due to the well-defined structures of SAMs, tunable specific functional terminal groups and rapid response of the electrode [28–32]. The SAMs modified electrodes carrying charges have been successfully used to separate the oxidation waves of DA and AA via the electrostatic interaction between the charged groups of SAMs and the analytes [33–36]. For example, for detection of target DA, the interference from AA can be eliminated by modifying the Au electrode surface with carboxylic terminated SAMs due to the electrostatic repellence between negatively charged carboxylic groups at the electrode and the negatively charged AA ion in solution.

Recently, SAMs of thiophene and its derivatives immobilized on Au electrode have attracted considerable interest due to their rigid structure, high stability, high order and high electron conductivity [37,38]. In the present paper, we designed and synthesized 3-thienylphosphonic acid (TPA, shown in Scheme 1) in which the phosphonic acid group
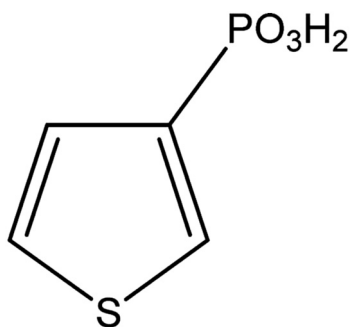
* Corresponding author.
  E-mail address: ydimut@163.com (D. Yao).

Scheme 1. The structure of 3-thienylphosphonic acid (TPA).

carrying two unit negative charges. Obviously, TPA SAMs on Au electrode have the higher interfacial charge density than carboxylic acid terminated SAMs on Au electrode due to dibasic acids property of phosphonic acid group, which can effectively electrochemically discriminate between DA and AA via the electrostatic interactions. Meanwhile, the thienyl group on TPA has high electron conductivity, which can accelerate the electron communication between DA and the gold electrode. As a result, DA can be determined electrochemically in the presence of concentrated AA at the TPA-SAMs modified Au electrode with high selectivity. Interestingly, the fouling effect of DA oxidation almost can be eliminated at the TPA-SAMs modified Au electrode. In addition, the TPA-SAMs modified Au electrode shows excellent renewal capability for DA oxidation and long-term stability in PBS. At the end, possible interpretations to the observed interesting phenomena are discussed.

2. Experimental

2.1. Materials

All the chemical reagents were of analytical grade (AR). Dopamine, ascorbic acid, ethanethiol ($HSCH_2CH_3$) and 11-mercaptoundecanoic acid [$HS(CH_2)_{10}COOH$] were purchased from Sigma-Aldrich (St. Louis, U.S.A.) and used without further purification. Thiophene (C_4H_4S) was purchased from Beijing Chemical Corporation (Beijing, China) and was freshly distilled twice prior to use. Phosphate buffer solution (PBS 7.4, a physiological solution pH) was made up from Na_2HPO_4 and NaH_2PO_4. Freshly prepared solutions of DA and AA were used in all experiments. All the aqueous solutions were prepared with Millipore water having a resistivity of $18.2\,M\Omega$ (Purelab Classic Corp., USA). 3-Thienylphosphonic acid (TPA) was synthesized under nitrogen atmosphere according to the literature procedure [39]. The purity of the product was affirmed by ^1H NMR. ^1H NMR (D_2O): δ 7.22–7.23 (m, 1H, 5-Th-*H*), 7.44–7.45 (m, 1H, 4-Th-*H*), 7.83–7.84 (m, 1H, 2-Th-*H*).

2.2. Pretreatment of Au substrates

Two types of Au substrates were used. Gold sheet (1.0 cm in diameter, 99.99%) was used for XPS characterizations and gold disk electrode (CHI, 2 mm in diameter) sealed in polymer shell was used for electrochemical measurements. Before deposition of TPA-SAMs, the Au substrates were polished with Al_2O_3 powders (0.3 and $0.05\,\mu M$) and then sonicated in absolute ethanol and Millipore water (each for ~3–5 min). After rinsed with Millipore water, they were immersed into a concentrated HNO_3 aqueous solution for 10 min followed by thoroughly rinsing with Millipore water. Finally, the Au electrodes was subjected to electrochemical pretreatment by consecutive potential cycling in a $0.5\,M\ H_2SO_4$ solution within a potential window between -0.30 and $+1.60\,V$ at a scan rate of $50\,mV\,s^{-1}$. The potential cycling was continued until a reproducible voltammogram showing the presence of gold oxide formation and reduction was obtained [40–42].

2.3. Modification of Au electrode

The pretreated Au electrode was immersed in a 0.1 M KOH solution containing 4 mM TPA in the dark for 72 h. After the electrode was rinsed carefully with Millipore water, 0.1 M KOH solution, 0.1 M $HClO_4$ solution and Millipore water consecutively, the TPA modified Au electrode (TPA/Au) was obtained.

The pretreated Au electrode was placed in ethanol with 4 mM ethanethiol (ET) or 11-mercaptoundecanoic acid (MUA) in the dark for 20 h or 4 mM thiophene (TP) in the dark for 72 h. After these electrodes were rinsed carefully with ethanol for 1 min and Millipore water for another 1 min consecutively, the ethanethiol modified Au electrode (ET/Au), 11-mercaptoundecanoic acid modified Au electrode (MUA/Au) and thiophene modified Au electrode (TP/Au) was obtained, respectively.

2.4. Apparatus

X-ray photoelectron spectroscopy (XPS) measurements were carried out on a Thermo VG Scientific ESCALAB 250 spectrometer using a monochromatic Al $K\alpha$ x-ray source. The single curves were fitted by using XPSPEAK41 software. The thickness of TPA-SAMs was measured using a VAS ellipsometer (M-2000FTM, J.A. Wollam, Inc., Lincoln, NE). The data were evaluated using the software WVASE32 (WexTech Systems, Inc., New York), assuming an isotropic, transparent organic layer with the refractive index of n = 1.5. Cyclic voltammetry (CV), linear sweep voltammetry (LSV) and differential pulse voltammetry (DPV) were performed in a conventional three-electrode electrochemical cell using a CHI 660C electrochemical analyzer (CH Instruments, Shanghai Chenghua Co.). A Pt plate auxiliary electrode and the saturated calomel reference electrode (SCE) were used. All potentials refer to the SCE. The electrolyte was purged with high-purity nitrogen for at least 10 min prior to measurements to remove the dissolved oxygen. All experiments were performed at room temperature ($25\ \pm\ 2\ ^\circ C$).

3. Results and discussion

3.1. Surface characterization of the TPA/Au electrode

Optical ellipsometry was applied as a convenient and precise means of determining the average thicknesses of the SAMs. Thickness values estimated by ellipsometry were 5.95 Å for the TPA-SAMs. The tilted angle of TPA was defined as the dihedral angle between the surface of thienyl-ring and the gold surface. From the ellipsometric thicknesses and the molecular lengths (6.38 Å), the tilted angle of TPA was estimated to be 69°. XPS scan of the P(2p) region shows a peak that is fitted as a spin doublet at 133.3 and 134.2 eV (Fig. S1 in Supporting information), corresponding to $P_{2p3/2}$ and $P_{2p1/2}$, also showing the evidence that the TPA has been successfully immobilized on the Au surface. We further confirmed the existence of TPA SAMs by the aqueous contact angle patterns (Fig. S2 in Supporting information). The TPA modified electrode surface is almost completely hydrophilic with a low static contact angle of 45.05°, whereas the substrate surface of Au electrode without covered TPA is almost hydrophobic which contact angle dramatically increases to 100.72°. The change of the surface structure provides good evidence for existence of TPA SAMs. In the electrochemical desorption experiment (Fig. 1A), the appearance of strong cathodic wave indicates the formation of S—Au bond between TPA and gold surface. In addition, no redox peak of $Fe(CN)_6^{3-}$ ions is observed in cyclic voltammetry measurement (Fig. 1B), indicating the TPA-SAMs significantly block the mass transport of the negatively charged species and result in little electrochemical reaction on the electrode due to electrostatic repulsion.