Journal of Electroanalytical Chemistry 644 (2010) 1–6

Contents lists available at ScienceDirect

Journal of Electroanalytical Chemistry

journal homepage: www.elsevier.com/locate/jelechem

Selective voltammetric determination of D-penicillamine in the presence of tryptophan at a modified carbon paste electrode incorporating TiO_2 nanoparticles and quinizarine

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ARTICLE INFO

Article history:
Received 13 September 2009
Received in revised form 18 February 2010
Accepted 28 February 2010
Available online 25 March 2010

Keywords:
D-Penicillamine
Tryptophan
Quinizarine
TiO_2 nanoparticles

ABSTRACT

A carbon paste electrode (CPE) chemically modified with TiO_2 nanoparticles and quinizarine (QZ) was used as a selective electrochemical sensor for the simultaneous determination of minor amounts of D-penicillamine (D-PA) and tryptophan (Trp). This modified electrode showed very efficient electrocatalytic activity for anodic oxidation of both D-PA and Trp. Substantial decreases of anodic overpotentials for both compounds made this analysis possible. Results of square wave voltammetry (SWV) using this modified electrode showed two well-resolved anodic waves for the oxidation of D-PA and Trp, which makes the simultaneous determination of both compounds possible. The peak potential for the oxidation of D-PA was lowered by at least 220 mV compared with that obtained for an unmodified CPE. In optimal conditions, linear ranges spanned a D-PA concentration from 0.8 μM to 140.0 μM and the detection limit was 0.76 μM at a signal-to-noise ratio of 2. In addition, the sensor had good stability and reproducibility.

1. Introduction

Nanotechnology has recently become one of the most exciting fields in sciences. A wide variety of nanomaterials, especially nanoparticles with different properties, have physical properties due to collective phenomena and environment effects that are interesting to study in their own right [1]. Owing to their small size (normally in the range of 1–100 nm), nanoparticles exhibit unique chemical, physical and electronic properties those are different from those of bulk materials. Nanoparticles can therefore be used to construct novel and improved sensing devices, such as electrochemical sensors and biosensors. Many types of nanoparticles of different sizes and compositions are now available, which facilitates their application in electroanalysis. Different kinds of nanoparticles, and sometimes the same kind of nanoparticles, can play different roles in different electrochemical sensing systems, such as enzyme sensors, immunosensors and DNA sensors [2–5]. Generally, metal nanoparticles have excellent conductivity and catalytic properties, which make them suitable for acting as “electronic wires” to enhance the electron transfer between redox centers in proteins and electrode surfaces and as catalysts to increase electrochemical reactions. Oxide nanoparticles are often used to immobilize biomolecules due to their biocompatibility, while semiconductor nanoparticles are often used as labels or tracers for electrochemical analysis.

Penicillamine (PA) is a strong chelating agent and can react with the majority of heavy metal ions. The outstanding metal binding capability is reflected in the pharmaceutical importance of PA [6]. Therefore, PA is the drug of choice in the treatment of hepatolenticular degeneration (Wilson’s disease) and is also effective for the treatment of several disorders including rheumatoid arthritis, primary biliary cirrhosis, scleroderma, fibrotic lung diseases, cystinuria, heavy element poisoning and progressive systemic sclerosis [7–9]. The typical therapeutic dose administered to humans is in the range of 0.5–2.0 g daily. While the D-enantiomer of PA is therapeutic, the L-enantiomer is highly toxic; since it possesses the same configuration as L-amino acids (which are the constituents of proteins) and can interfere with amino acid metabolism [10].

Several different methods have been proposed for the determination of PA in biological specimens and pharmaceutical formulations. Up until now, PA has been determined by HPLC with fluorescence [11], chemiluminescence [12] and mercury-based electrochemical [13] detection. Various spectrophotometric methods [14,15] and electrochemical methods [16–20] have also been proposed for the determination of PA. Although these methods have been successfully employed, some of them suffer interference from the pharmaceutical or biological matrix, and others are time-consuming or require expensive equipment and, consequently, are

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doi:10.1016/j.jelechem.2010.02.034

not suitable for routine analysis in most laboratories. Therefore, the development of a simple, rapid and sensitive determination of PA in pharmaceutical formulations and biological specimens is of great importance.

Tryptophan (Trp) is an essential amino acid, meaning that humans must consume it in their diet to survive. This compound is a precursor for the important biological molecules serotonin (a neurotransmitter), melatonin (a neurohormone), and niacin. It has also been implicated as a possible cause of schizophrenia in people who cannot metabolize it properly. When improperly metabolized, it creates a byproduct in the brain that is toxic, causing hallucination and delusions [21]. Due to its low abundance in vegetables, this compound is sometimes added to staple food products and pharmaceutical formulas [22]. The electroanalytical methods, with respect to their sensitivity, accuracy, lower cost and simplicity, have been more attractive in recent years for Trp determination [23–26]. It is well known that the direct electrochemical oxidation of Trp at the surface of a bare electrode is irreversible and therefore requires high overpotential [8]. The electrochemical detection of Trp, therefore, has proven to be facilitated by electrode chemical modification. Significant effort has been devoted to the goal of finding new mediators for the preparation of chemically modified electrodes (CMEs) that will create the overpotential for the oxidation of Trp [27–30].

The chemical modification of electrodes using electron transfer mediators is an interesting field in analytical chemistry. One of the most important effects of any mediator is a reduction of the overpotential required for electrochemical reaction, which enhances the sensitivity (current) and selectivity of the method. Electrochemical detection using mercury-based electrodes, for example, has been used for the determination of thiols and disulfides in complex matrices, including biological fluids [31].

Carbon-based electrodes are among the most commonly used electrodes in voltammetric techniques because of their low cost, wide potential windows, low electrical resistances and versatility of chemical modification. Many types of carbon-based electrodes, such as glassy carbon [32–35], carbon composites [35] and carbon pastes [36–41], are used as modified electrodes.

Penicillamine is an active molecule related to natural amino acids that in contrast to the protein-forming amino acids (such as tryptophan) which are present in the L form, the natural form is D-penicillamine, the L and DL forms being both toxic and non-active. Therefore, determination of this amino acid same structure and tryptophan as an amino acid is important, thus in the present work, we describe the initial preparation and suitability of a QZ modified TiO_2 nanoparticles carbon paste electrode (QZMNCPE) as a new electrode in the electrocatalysis and determination of D-PA in an aqueous buffer solution. We then evaluated the analytical performance of this modified electrode in the quantification of D-PA in the presence of Trp.

2. Experimental

2.1. Apparatus and chemicals

Electrochemical experiments were carried out using a computerized potentiostat/galvanostat μAutolab type III (Eco Chemie B.V.A) controlled with General Purpose Electrochemical System (GPES) software. A conventional three-electrode cell was used with an Ag/AgCl/KCl 3.0 M system, platinum wire, and QZMNCPE, which were used as the reference, auxiliary and working electrodes, respectively. A Metrohm model 691 pH/mV meter was also used for pH measurements.

All solutions were freshly prepared with doubly distilled water. The D-PA and Trp were from Fluka and were used as received. Other reagents were analytical grade (Merck). Graphite fine powder (Merck) and paraffin oil (DC 350, Merck, density = 0.88 g cm^{-3}) were used as binding agents for graphite pastes. Buffer solutions were prepared from orthophosphoric acid and its salts in the pH range of 2.0–11.0. TiO_2 nanoparticles (surface area = 84 m^2 g^{-1} and particle size = 6.7 nm) and QZ were synthesized in our laboratory.

2.2. Preparation of the electrode

Modified carbon paste electrodes were prepared by dissolving 0.01 g of QZ in CH_3Cl and hand mixing with 95 times its weight of graphite powder and four times its mass of TiO_2 nanoparticles using a mortar and pestle. Paraffin (Dc 350, Merck) was added to the above mixture and mixed for 20 min until a uniformly moist paste was obtained, which was then packed into the end of a glass tube (ca. 3.4 mm i.d. and 10 cm long). A copper wire inserted into the carbon paste provided an electrical contact. When necessary, a new surface was obtained by pushing an excess of paste out of the tube and then polishing the freshly exposed paste with weighing paper.

The QZ-modified CPE (QZMCPE) and TiO_2 nanoparticles CPE (NCPE) were prepared in the same way but without adding TiO_2 nanoparticles and QZ, respectively. Also, unmodified carbon paste was prepared in the same way but without adding QZ and TiO_2 nanoparticles to the mixture. These pastes were then used for comparison to the modified pastes.

3. Results and discussion

3.1. Electrochemistry of QZMNCPE

The QZ is insoluble in aqueous solutions, and can be easily incorporated into the carbon paste without much concern of its leaching from the electrode surface. Therefore, QZ can be fabricated reproducibly by a chemically modified electrode.

The electrochemical behavior of the QZMNCPE was first investigated using cyclic voltammetry (Fig. 1A). Experimental results show that well defined and reproducible anodic and cathodic peaks with $E_{pa} = 0.560$ V, $E_{pc} = 0.400$ V, $E^{0'} = 0.480$ V vs. Ag/AgCl/KCl 3.0 M and $\Delta E_p = 160$ mV. The electrode process was quasi-reversible, with ΔE_p greater than the $(59/n)$ mV expected for a reversible system.

The capability of the electrode to generate a reproducible surface was examined using cyclic voltammetric data that were obtained in an optimum solution (pH 7.0) from five separately prepared QZMNCPEs. The calculated RSDs for various parameters were accepted as the criteria for satisfactory surface reproducibility (about 1–4%). This is virtually the same as that expected for renewal or ordinary carbon paste surfaces. However, we still regenerated the QZMNCPE surface before each experiment according to our previous result [37,41].

Cyclic voltammograms of the QZMNCPE were recorded at different scan rates (from 25 to 900 mV s^{-1}). Fig. 1B illustrates that the anodic and cathodic peak currents (I_p) were linearly dependent on υ at scan rates of 25–500 mV s^{-1}. A linear correlation was also obtained between peak currents and the scan rate, indicating that the redox process is not controlled by diffusion. Fig. 1C shows the anodic peak potentials, E_{pa}, as a function of the potential sweep rate. We found that for scan rates above 200 mV s^{-1}, the values of E_p were proportional to the logarithm of the scan rate. Under these conditions, the k_s can be calculated according to the following equation [42]:

$$\mathrm{Log}(k_s) = \alpha \log(1-\alpha) + (1-\alpha)\log\alpha - \log(RT/nF\upsilon) - \alpha(1-\alpha)n\alpha F\Delta E_p/2.3RT \qquad (1)$$