

Design of a Novel Nano-Sensor for Determination of Acetaminophen

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Received: November 11 2013

Accepted: December 21 2013

ABSTRACT

The Fe₃O₄ nanoparticles coated with silica nanoparticles were prepared, the obtained Fe₃O₄@SiO₂ have uniform spherical morphology with a mean diameter of about 30 nm. Then an electrochemical sensor based on with Fe₃O₄@SiO₂ nanoparticles –coated poly (diallyldimethylammonium chloride) (PDDA)- carbon nanotube (Fe₃O₄@SiO₂ -PDDA-CNT) nanocomposite was fabricated for sensitive detection of acetaminophen. The samples were characterized by means of transmission electron microscopy (TEM) and Fourier transform infrared spectroscopy (FT-IR). Cyclic voltammetry (CV) was used to investigate the electrocatalytic ability of acetaminophen on the Fe₃O₄@SiO₂- PDDA-CNT/ GCE, and differential pulse voltammetry (DPV) was used for the quantification of acetaminophen.

KEYWORDS: Nano-Sensor, Nanoparticle, Acetaminophen, Cyclic voltammetry, differential pulse voltammetry.

1. INTRODUCTION

In recent years, there has been intense research directed to use Nano Science in a wide range of fundamental studies and technological applications. Furthermore, there is a considerable effort toward the use of nano-materials in electrochemistry due to their unique physicochemical and electrochemical properties that are not represented by the corresponding bulk forms [1]. Different types of nano-structured materials, including noble metals, oxides and composite nanoparticles, have often been used in electrochemical studies including electrocatalysts, fuel cells, photonic processes and electroanalytical techniques [2- 5]. Nanomaterials have received much interest by virtue of their excellent properties suited for applications in various fields such as electronic, pharmaceutical, biomedical, cosmetic, energy, and catalysis [6– 8]. Biosensors are becoming increasingly important due to their applications in biological and chemical analyses, clinical detection, and environmental monitoring. Acetaminophen (N-acetyl-p-aminophenol or paracetamol) is one of the most commonly used analgesics in pharmaceutical formulations. It is used to reduce fever and as a pain-killer for backache, headache, and arthritis [9, 10]. Acetaminophen is a non-carcinogenic and effective aspirin substitute for patients who are sensitive to acetylsalicylic acid. Even though the normal concentration range of acetaminophen for therapeutic purposes may vary and can be affected by sex, age, general health, synergism with other compounds, and individual response, the plasma concentration of acetaminophen in humans follows a standard drug dose range from 50 to 100 µM [11, 12]. Thus, it is necessary to develop efficient, sensitive, simple and accurate analytical techniques for the determination of acetaminophen. The discovery of carbon nanotubes (CNTs) has attracted much attention due to their structural uniqueness, chemical and physical properties and potential applications [13, 14]. The subtle electronic behavior of CNTs reveals that they have the ability to mediate electron transfer reactions of electroactive species in solution when used as an electrode modifier. Additionally, transition-metal nanoparticles, in different forms, have emerged as a novel family of catalysts able to promote more efficiently a variety of organic transformations because of their small size and extremely large surface-to-volume ratio [15, 16]. Recently several different types of nanoparticles have been successfully introduced onto CNTs, such as CdTe [17], Au [18], Cu [19], Ag [20] and Ni (OH)₂ [21] for fabrication of sensors. Ni, NiO, Ni (OH)₂ particles and nanoparticles have also been used to modify traditional electrode surfaces such as diamond [22], gold [23], carbon or graphite [24].

In this work, a sensor based on the silica coated Fe₂O₃ magnetic nanoparticles (Fe₃O₄@SiO₂) Poly (dimethyldiallylammonium chloride) (PDDA) Nano composite film modified glassy carbon electrode (GCE) was fabricated for sensitive detection of acetaminophen in 0.1 mol L⁻¹ Britton–Robinson (BR) buffer solution (pH 7.0). Cyclic voltammetry (CV) was used to investigate the electrocatalytic ability of acetaminophen on the Fe₃O₄@SiO₂- PDDA- GCE, and differential pulse voltammetry (DPV) was used for the quantification of acetaminophen. The fabricated electrode showed excellent electrocatalytic activity towards acetaminophen, and could be used for the detection of acetaminophen in real samples with satisfactory results.

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2. EXPERIMENTAL

2.1. Chemicals and Reagents

Poly (dimethyldiallylammonium chloride) (PDDA) (MW < 200,000) was obtained from Aldrich. Carbon nanotube (CNT) was purchased from Sigma Aldrich Co. (outer diameter from 20 nm to 30 nm, wall thickness from 1 nm to 2 nm). Graphite flake (nature, -325 mesh) was from Alfa Aesar. BR buffer solution was prepared by mixing definite weights of boric acid, acetic acid and phosphoric acid and the desired pH was adjusted using 0.20 mol L⁻¹ sodium hydroxide. All other reagents and solvents were of analytical grade and used without further purification. All chemicals were prepared with deionized water purified via Milli-Q unit. Acetaminophen tablets were purchased from a local pharmacy (made in Hakim and Shafa pharmaceutical Co., Tehran, Iran).

2.2. Instrumentation

All the voltammetric measurements were carried out using a nanocomposite modified glassy carbon electrode (Fe₃O₄@ SiO₂- PDDA- CNT/GCE) as a working electrode, A silver/silver chloride electrode (Ag|AgCl, KCl 3M) and a platinum wire were used as reference and auxiliary electrodes, respectively. DPV, CV experiments were carried out using an Autolab PGSTAT 30 Potentiostat Galvanostat (EcoChemie, The Netherlands) coupled with a 663 VA stand (Metrohm Switzerland). All of the potential were measured with respect to the reference electrode. Fourier transform infrared (FT-IR) spectra were recorded on a FT-IR spectrometer (Perkin Elmer) with a spectral resolution of 4 cm⁻¹ in the wave number range of 500–3500 cm⁻¹. The samples and KBr were fully dried before the FT-IR analyses to exclude the influence of water. Transmission electron microscopy (TEM) images were taken with a Tecnai 20 (FEI-Philips) instrument with a field emission gun operating at 200 kV. pH measurements were performed with a Metrohm 744 pH meter using a combination glass electrode.

2.3. Synthesis of Fe₃O₄@SiO₂- PDDA- CNT Nanocomposite

Fe₃O₄ nanoparticles were achieved by a typical procedure [6]. Next, the silica was grown on Fe₃O₄ cores [7–9] to form the Fe₃O₄@SiO₂ nanoparticles. A stock solution of 0.50 wt% PDDA solution was prepared by dissolving 5 mg of PDDA in solution and stirred for 30 min. With the aid of ultrasonic agitation for 30 min, 2.0 mg CNT were dissolved in 1 mL of 0.5 wt% PDDA. Then, solution was mixed with 5 mL Fe₃O₄@SiO₂ (5 mg/mL) hydrosol prepared above (the pH value of Fe₃O₄@SiO₂ hydrosol was adjusted to about 11–12 with NaOH solution) and stirred for 1 h. The resulting mixture was further treated with 2.5 mL hydrazine hydrate and allowed to react for 12 h at 60 °C. Finally, the obtained Fe₃O₄@SiO₂- PDDA- CNT nanocomposite was separated by centrifugation and further washed with water. Pre Dried samples with Freeze dryer FD-10(Pishtaz Engineering Co, Iran)) were weighed for the dry weight.

2.4. Preparation of Fe₃O₄@SiO₂-PDDA-CNT/GCE Sensor

Before modification, the bare GCE was polished to obtain a mirror-like surface with 1.0 and 0.05 µm γ -alumina, then cleaned ultrasonically in deionized water for 2 min and finally cleaned in turn in an ultrasonic cleaner with 1:1 nitric acid solution, alcohol and doubly deionized water. 1.0 mg Fe₃O₄@SiO₂-PDDA-CNT nanocomposite was added into 1 mL deionized water, followed by ultrasonication for 2 h to form a homogenous mixture. Then, 5 µL of the mixture was dropped on the pretreated GCE and dried in a desiccator.

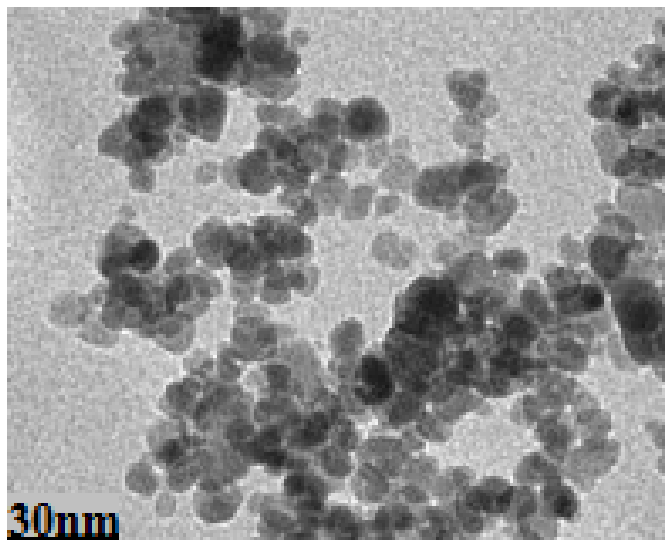
2.5. Electrochemical Measurements

About 10 mL of the BR buffer solution containing an appropriate amount of acetaminophen standard solution or sample was added into the electrochemical cell and then the three-electrode system was installed on it. The CVs were recorded in the potential range from 0.0 to 0.80 V after 200 s (supplementary content) accumulation under stirring with a scan rate of 50 mV s⁻¹. The DPV was carried out with the parameters of increment potential, 0.004 V; pulse amplitude, 0.05 V; pulse width, 0.05 s; sample width, 0.0167s; pulse period, 0.2 s; and quiet time, 2 s.

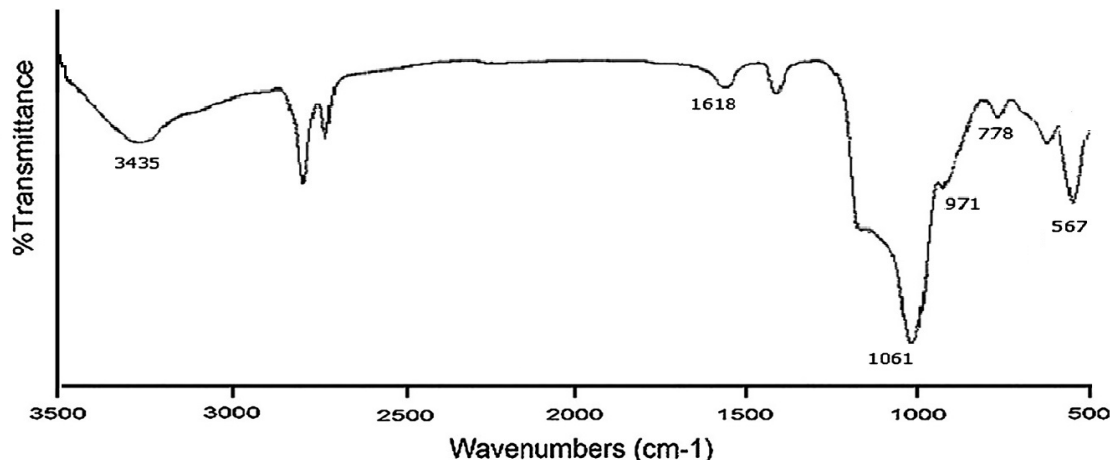
3. RESULTS AND DISCUSSION

3.1. Characterization of Fe₃O₄@SiO₂ Nanoparticles

Fig. 1 shows the transmission electron microscopy (TEM) images of the Fe₃O₄@SiO₂ microspheres. We can clearly see that the Fe₃O₄@SiO₂ particles are spherical with a smooth surface. The average particle size is about 30 nm.

Fig. 1. TEM images of $\text{Fe}_3\text{O}_4@\text{SiO}_2$ nanoparticles

The Fourier transform infrared (FTIR) spectra of $\text{Fe}_3\text{O}_4@\text{SiO}_2$ nanoparticles is shown in Fig. 2. The bands at around 1618 and 3435 cm^{-1} can be assigned to the H-O-H stretching modes and bending vibration of the free or adsorbed water, respectively. The peaks at 583 , 521 , and 602 cm^{-1} were absorption of Fe-O stretching that stated clearly the existence of non-porous silica protected magnetite particles. The broad high-intensity band at 1061 cm^{-1} is associated with the motion of oxygen in Si-O-Si anti symmetric stretch, due to the asymmetric stretching bonds of Si-O-Si in SiO_2 . The band at 778 cm^{-1} is assigned to the Si-O-Si symmetric stretch. The band at 971 cm^{-1} is assigned to the Si-O symmetric stretch. The band at 567 cm^{-1} is an indication of the presence of Si-O-Fe.

Fig. 2. FT-IR spectra of $\text{Fe}_3\text{O}_4@\text{SiO}_2$ nanoparticles

3.2. Electrochemical Behaviors of Acetaminophen

CVs were used to investigate the electrochemical behavior of 0.1 mmol L^{-1} acetaminophen in 0.1 mol L^{-1} BR buffer solution (pH 7.0) at a scan rate of 50 mV s^{-1} . Fig. 3 shows the different pulse voltammetric behaviors of $\text{Fe}_3\text{O}_4@\text{SiO}_2$ -PDDA-CNT electrodes during electrocatalysis of acetaminophen. At the bare GCE (Fig. 3 A), acetaminophen shows an irreversible behavior with relatively weak redox current peaks at $E_{\text{pa}} = 0.565\text{ V}$ and $E_{\text{pc}} = 0.463\text{ V}$. In contrast, on the $\text{Fe}_3\text{O}_4@\text{SiO}_2/\text{GCE}$ (Fig. 3 B) and PDDA-CNT/GCE (Fig. 3 C), the redox peak currents are significantly increased respectively.

However, in the case of $\text{Fe}_3\text{O}_4@\text{SiO}_2$ -PDDA-CNT/GCE (Fig. 3 D), a pair of well-defined and quasi-reversible redox peaks of acetaminophen was obtained, with $E_{\text{pa}} = 0.551\text{ V}$ and $E_{\text{pc}} = 0.501\text{ V}$. Since smaller potential difference between the anodic and cathodic peaks responds to larger electron transfer rate. The $\text{Fe}_3\text{O}_4@\text{SiO}_2$ -PDDA-CNT/GCE shows the largest redox peak currents compare to other electrodes.

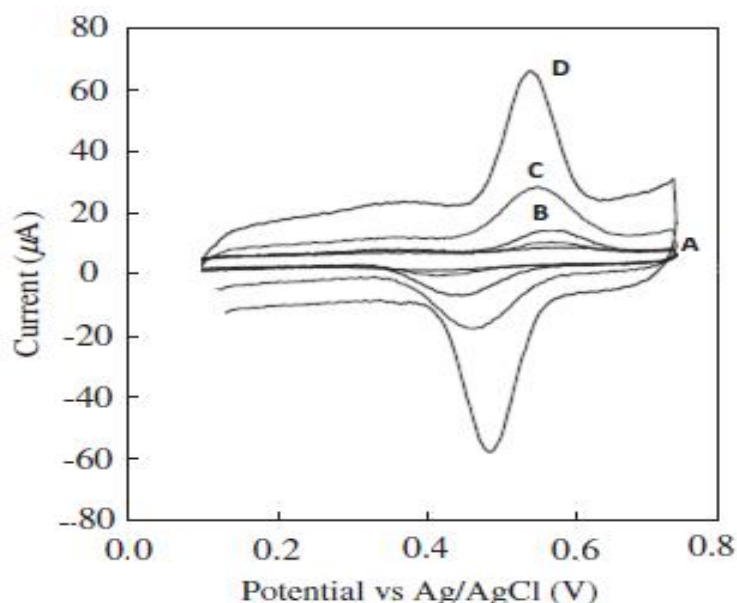


Fig.3. CVs on the (A) bare GCE, (B) $\text{Fe}_3\text{O}_4@\text{SiO}_2/\text{GCE}$, (C) PDDA-CNT/ GCE, and (D) $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-PDDA-CNT/GCE}$ in 0.1 mol L^{-1} BR buffer solution (pH 7.0) with 0.1 mmol L^{-1} acetaminophen at scan rate of 50 mV s^{-1} . Inset: the CV on the $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-PDDA-CNT/GCE}$ in 0.1 M BR buffer solution (pH 7.0) without acetaminophen.

3.3. Determination of Acetaminophen

Under the optimal conditions, DPV was performed to investigate the relationship between the peak current and concentration of acetaminophen due to its higher sensitivity than CV. As can be seen in Fig. 4, the oxidation peak current was proportional to acetaminophen concentration in the range from 10 to $110 \mu\text{mol L}^{-1}$ with the regression equation of $I_{\text{pa}} (\mu\text{A}) = 0.6089C (\mu\text{mol L}^{-1}) + 2.023$ ($R = 0.9994$). The detection limit was $3.9 \times 10^{-8} \text{ mol L}^{-1}$ ($S/N = 3$). This lower detection limit could be attributed to the combination of $\text{Fe}_3\text{O}_4@\text{SiO}_2$ and PDDA-CNT, in which the $\text{Fe}_3\text{O}_4@\text{SiO}_2$ can increase the electrochemically adsorptive site and the PDDA-CNT could also provide the large specific surface area to increase the loading of acetaminophen. Meanwhile, the electron transfer on the electrode surface could be accelerated and the electrochemical signal was amplified due to the outstanding electric conductivity of $\text{Fe}_3\text{O}_4@\text{SiO}_2$ and PDDA-CNT. Therefore, sensitive detection of acetaminophen was achieved.

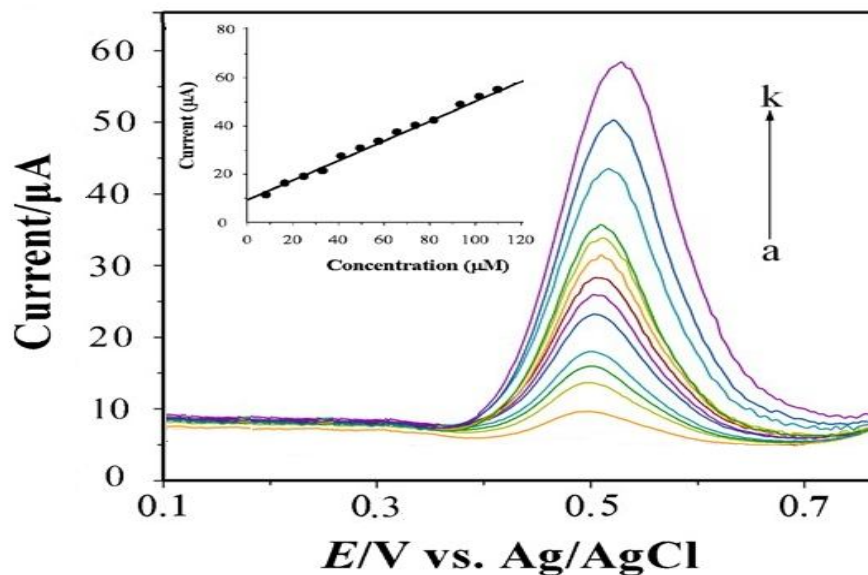


Fig. 4. DPVs of (a-k) 0, 0.1, 1.0, 5.0, 10, 20, 30, 50, 70, 80 and $100 \mu\text{mol L}^{-1}$ acetaminophen on $\text{Fe}_3\text{O}_4@\text{SiO}_2\text{-PDDA-CNT/GCE}$ in 0.1 mol L^{-1} BR buffer solution (pH 7.0).

4. CONCLUSIONS

In this paper, a novel acetaminophen electrochemical sensor based on Fe₃O₄@SiO₂-PDDA-CNT nanocomposite was introduced, and the sensor exhibited an excellent electrochemical activity of acetaminophen. Under the optimized conditions, the nanocomposite film modified GCE was successfully employed for the voltammetric determination of acetaminophen with low detection limit, a wide linear range and good selectivity. The proposed method provides a way to Fe₃O₄@SiO₂ coated functionalized graphene nanocomposite with good compatibility, thus providing promising application in drug analysis.

Acknowledgment

The authors declare that they have no conflicts of interest in the research.

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