Journal of Applied Chemistry
JAC
http://chemistry.journals.semnan.ac.ir

Synthesis of NiO nanoparticle and application of its in the preparation of electrochemical sensor for voltammetric determination of Nalbuphine

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Article history:
Received: 17/Jun/2014
Received in revised form: 8/Jul/2014
Accepted: 3/Aug/2014

Abstract

In this study we report synthesis and application of NiO nanoparticle (NiO/NPs) carbon paste electrode (NiO/NPs/CPE) as high sensitive sensors for voltammetric determination of Nalbuphine (NB). The NiO/NPs was characterized with different methods such as SEM and XRD. The cyclic voltammogram showed an irreversible oxidation peak at 0.57 V (vs. Ag/AgClsat), which corresponded to the oxidation of NB. Compared to common carbon paste electrode, the electrochemical response was greatly improved. The electro-oxidation of NB occurred in a pH-dependent 1e− and $1H^+$ process, and the electrode reaction followed a diffusion-controlled pathway. Under the optimum conditions, the voltammetric oxidation peak current of NB showed linear dynamic ranges with a detection limit of 0.5 μM for NB. The novel sensor has been found selective and successfully implemented for the determination of NB in water, serum and urine samples.

Keywords: Nalbuphine, Modified electrode, Voltammetric determination, NiO nanoparticle.

1. Introduction

Nalbuphine is a semi-synthetic opioid used commercially as an analgesic under a variety of trade names, including Nubain. Nalbuphine is a semi-synthetic opioid agonist-antagonist analgesic of the phenanthrene series [1]. It is chemically related to the widely used opioid antagonists, naloxone and naltrexone, and the potent opioid analgesic, oxymorphone. It is available in two concentrations, 10 mg and 20 mg of nalbuphine hydrochloride per mL. Both strengths contain 0.94% sodium citrate hydrous, 1.26% citric acid anhydrous, 0.1% sodium metabisulfite, and 0.2% of a 9:1 mixture of methylparaben and propylparaben as preservatives; pH is adjusted, if necessary, with hydrochloric acid. The 10 mg/mL strength contains 0.1% sodium chloride. So, determination of NB is very important in pharmaceutical and biological samples [2].

Nanoscience represent new and enabling platforms that promise to provide a broad range of novel uses and

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improved technologies for environmental, biological and other scientific applications [3]. One of the reasons behind the intense interest is that nanotechnology permits the controlled synthesis of materials where at least one dimension of the structure is less than 100 nm. Recently, nanostructured materials have also been incorporated into electrochemical sensors for biological and pharmaceutical analyses [4–6]. While they have many properties similar to other types of carbon, they offer unique advantages including enhanced electron transfer, large edge plane/basal plane ratios and rapid kinetics of the electrode processes. In between, NiO/NPs is an important multifunctional material with applications such as varistors, gas sensors, SAW devices, transparent electrodes and catalysts. The various applications of NiO/NPs are due to the specific chemical, surface and microstructural properties of this material [7-9].

In continuation of our studies on chemically modified electrodes [10–17], we describe the synthesis and application of NiO/NPS as a novel nanosensor in a carbon paste matrix for the voltammetric determination of NB. We also evaluate the analytical performance of the modified electrode for the voltammetric determination of NB in real samples such as drug, urine and serum.

2. Experimental

2.1. *Chemicals*

All chemicals used were of analytical reagent grade purchased from Merck (Darmstadt, Germany) unless otherwise stated. Doubly distilled water was used throughout. Phosphate buffer (sodium dihydrogen phosphate and disodium monohydrogen phosphate plus sodium hydroxide, 0.1 mol L^{-1}) solutions (PBS) with different pH values were used. High viscosity paraffin (d = 0.88 kg L^{-1}) and pure graphite powder (particle size<50 µm) from Merck was used for the preparation of the carbon paste electrodes.

2.2. Apparatus

Cyclic voltammetry, chronoamperometry, and square wave voltammetry were performed in an analytical system, Autolab with PGSTAT 302N (Eco Chemie, the Netherlands). A conventional three-electrode cell assembly consisting of a platinum wire as an auxiliary electrode and an $Ag/AgCl/KCl_{sat}$ electrode as a reference electrode was used. The working electrode was either a NiO/NPs/CPE.

2.3. Synthesis of NiO/NPs

To prepare the NiO/NPs, in a typical experiment, a 0.6 M aqueous solution of nickel nitrate $Ni\ (NO_3)_2$ and a 0.4 M aqueous solution of sodium hydroxide (NaOH) were prepared in distilled water. Then, the beaker containing NaOH solution was heated at the temperature of about 60 °C. The $Ni\ (NO_3)_2$ solutions were added drop wise (slowly for 2.0 h) to the above heated solution under high-speed stirring. The beaker was sealed at this condition for 2 h. The precipitated $Ni(OH)_2$ were cleaned with deionized water and ethanol then calcined at 350 °C for 2.0 hours for synthesis of NiO/NPs.

2.4. Preparation of the modified electrode

NiO/NPs/CPE was prepared by mixing 0.5 g of liquid paraffin, 0.2 g of NiO/NPs and 0.8 g of graphite powder. Then the mixture was mixed well for 45 min until a uniformly wetted paste was obtained. A portion of the paste was filled firmly into a glass tube (geometrical area; 0.09 cm^2) as described above to prepare NiO/NPs/CPE. When necessary, a new surface was obtained by pushing an excess of the paste out of the tube and polishing it on a weighing paper.

2.5. Preparation of real samples

Urine samples were stored in a refrigerator immediately after collection. Ten milliliters of the sample was centrifuged for 45 min at 2000 rpm. The supernatant was filtered using a 0.45 µm filter and then diluted 5 times with the phosphate buffer, pH 7.0. The solution was transferred into the voltammetric cell to be analyzed without any further pretreatment. The standard addition method was used for NB determination in real samples. Also, water and serum samples were directly subjected to the voltammetric measurement after filtered using a 0.45 µm filter.

2. Results and discussion

The X-ray diffraction (XRD) data were recorded using Cu K_α radiation (1.5406 Å) (Fig. 1A). The intensity data were collected over a 2θ range of 10–80°. The average grain size of the samples was estimated with the help of Scherrer equation using the diffraction intensity of (200) peak. XRD studies confirmed that the synthesised materials were NiO, and all the diffraction peaks agreed with the reported Joint Committee on Powder Diffraction Standards (JCPDS) data, and no characteristic peaks were observed other than NiO [18]. The mean grain size (D = 23 nm) of the particles was determined from the XRD line broadening measurement using Scherrer equation:

$$D=K\lambda/(\beta \cos\theta) \qquad (1)$$

where λ is the wavelength (Cu Kα), β is the full width at the half-maximum (FWHM) of the NiO (200) line and θ is the diffraction angle. A definite line broadening of the diffraction peaks is an indication that the synthesised materials are in the nanometre range**.** The morphology of the as-grown nanostructures was characterized by scanning electron microscopy (SEM) technique. Figure 2 shows the SEM image of the synthesized product. It is clear that in this case, a NiO nanoparticle was successfully prepared.

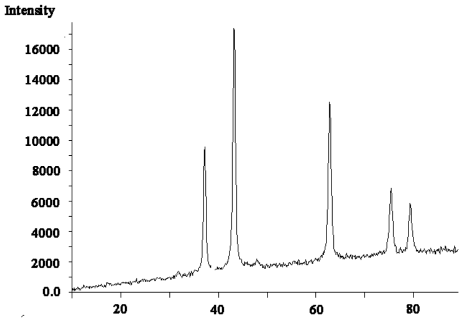


Figure 1. XRD patterns of as-synthesized NiO nanoparticle.

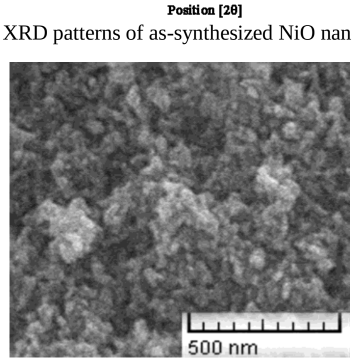


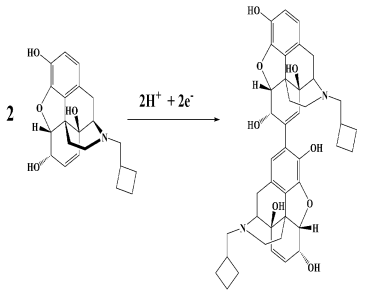
Figure 2. SEM image of NiO/NPs.

The active surface areas of the working electrodes are estimated according to the slope of the IP versus $\nu^{1/2}$ plot for a known concentration of $K_4Fe(CN)_6$, based on the Randles–Sevcik equation:

$$I_p = 2.69\times105n^{3/2}AD^{1/2}\nu^{1/2}\,C_O \quad (2)$$

where I_{pa} refers to the anodic peak current, n the electron transfer number, A the surface area of the electrode, D_R the diffusion coefficient, C_0 the concentration of $K_4Fe(CN)_6$ and ν is the scan rate. For 1.0 mmol L^{-1} $K_4Fe(CN)_6$ in 0.10 mol L^{-1} KCl electrolyte with n = 1 and DR = 7.6 × 10^{-6} cm s^{-1} and from the slope of the I_{pa}–$\nu^{1/2}$ relation, the microscopic areas were calculated. They were 0.15 and 0.09 cm^2 for NiO/NPs/CPE and CPE, respectively.

Scheme 1 shows the electrooxidation reaction of NB. According to Scheme 1, we anticipated that the oxidation of NB would be pH dependent. The effect of pH was investigated using cyclic voltammetry technique for electrooxidation of NB at a surface of NiO/NPs/CPE. It was found that the oxidation peak current increased gradually from pH 5.0 to 7.0, and then the current conversely decreased when the pH value increased from 7.0 to 8.0 (Fig. 3). According to the above point that pH 7.0 was chosen as the optimal experimental condition.



Scheme 1: Mechanism for electrooxidation of NB.

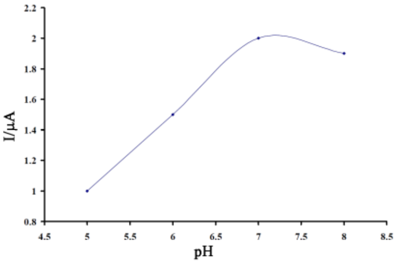


Figure 3. Current–pH curve for electrooxidation of 100.0 μM NB at NiO/NPs/CPE with a scan rate of 50 mV s^{-1}.

Fig. 4 (curves a & b) showed the electrochemical responses of NiO/NPs/CPE, and CPE in 100 μM NB in PBS solution (pH 7.0), respectively. At NiO/NPs/CPE, and CPE, NB showed an irreversible oxidation peak, with oxidation peak potential (E_{pa}) of 0.57 V, and 0.60 V, respectively. However, the peak current of NB at NiO/NPs/CPE was much larger than that at the CPE; it was about 1.7 times larger than CPE by cyclic voltammetry. Thus, the modified electrode exhibited a catalytic activity toward the oxidation of NB. This further testified the superiority of NiO/NPs/CPE to CPE and indicated that the use of NiO/NPs as modifier facilitated the electron transfer between NB and electrode.

To obtain information about the rate-determining step, the Tafel plot was drawn, as derived from points in the Tafel region of the cyclic voltammogram. The slope of the Tafel plot was equal to $2.3\ RT/n(1-\alpha)F$, which came up to 0.3064 V decade^{-1} for scan rate 50 mV s^{-1} (Fig. 5). Therefore, we obtained the mean value of α, which is equal to 0.8.

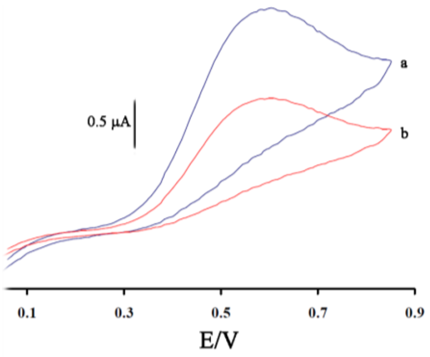


Fig. 4. Cyclic voltammograms of (a) NiO/NPs/CPE, and (b) CPE in the presence of 100 µM NB at pH 7.0, respectively.

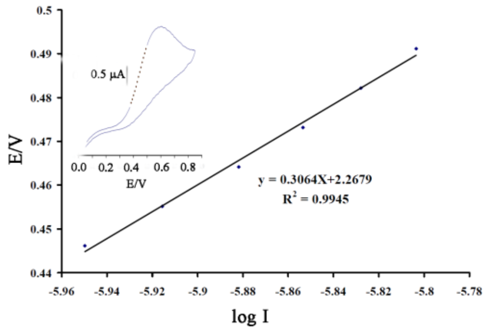


Figure 5. Tafel plot for NiO/NPs/CPE in 0.1 MPBS (pH 7.0) at the scan rateof 50 mV s^{-1}in the presence of 100.0 µM NB.

The chronoamperometry as well as the other electrochemical methods was employed for the investigation of electro-oxidation of NB at NiO/NPs/CPE. Chronoamperometric measurements of NB at NiO/NPs/CPE were done (not shown) for various concentrations of NB. For an electroactive material (NB in this case) with a diffusion coefficient of D, the current for the electrochemical reaction (at a mass transport limited rate) is described by the Cottrell equation [19]:

$$I = nFAD^{1/2}\, C_b\, \pi^{-1/2}\, t^{-1/2} \qquad (3)$$

Under diffusion control, a plot of I versus $t^{-1/2}$ will be linear, and from the slope the value of D can be obtained. The mean value of the D was found to be 1.0×10^{-4} cm^2/s.

The repeatability and stability of NiO/NPs/CPE were investigated by linear sweep voltammetric measurements of 10.0 µM NB. The relative standard deviation (RSD%) for six successive assays was 0.95%. When using five different electrodes, the RSD% for five measurements was 1.6%. When the electrode stored in the laboratory, the modified electrode retains 96% of its initial response after a week and 93% after 35 days. These results indicate that NiO/NPs/CPE has a good stability and reproducibility, and could be used for NB analysis.

The influence of various substances as potentially interfering compounds for the determination of NB was studied under the optimum conditions with 10.0 µM NB at pH 7.0. The potential interfering substances were chosen from the group of substances commonly found with NB in pharmaceuticals and/or in biological fluids. The tolerance limit was defined as the maximum concentration of the interfering substance that caused an error of less than ±5% for the determination of NB. After the experiments, we found that neither 1000-fold of glucose, sucrose, lactose and fructose, nor 750-fold of K^+, Li^+, Ca^{2+}, Mg^{2+}, Al^{3+}, NH_4^+, SO_4^{2-}, Cl^- and ClO_4^-, nor 500-fold phenylalanine, valine, tryptophan, histidine and glycine affected the selectivity. Nor did saturation solution of starch; neither 400-fold of urea and thiourea were interfered with the determination of NB.

Since square wave voltammetry has a much higher current sensitivity than linear sweep voltammetry, it was used for the determination of nb (Fig. 6 inset). The SW voltammograms clearly show that the plot of peak current vs. NB concentration is linear for 0.8–400 µM of NB with slope of 0.1835 µA μM^{-1} (Figure 6). According to the method mentioned in Ref. [20], the lower detection limit, C_m, was obtained by using the equation Cm = 3sb/m, where s_b is the standard deviation of the blank response (µA) and m is the slope of the calibration plot. The data analysis presents the value of lower limit detection of NB to be 0.5 µM.

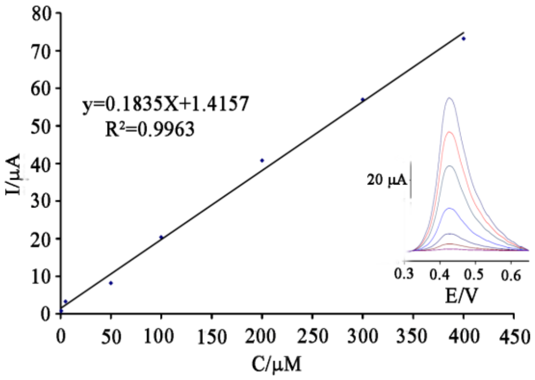


Figure 6. The plots of the electrocatalytic peak current as a function of NB concentration. Inset shows the SWVs of NiO/NPs/CPE in 0.1 M phosphate buffer solution (pH 7.0) containing different concentrations of NB. From inner to outer correspond to 0.8, 5.0, 50.0, 10.0, 20.0, 300.0 and 400.0 µM of NB.

In order to demonstrate the ability of the modified electrode to the determination of NB in real samples, determinations of NB in pharmaceutical and in urine samples were examined. The results are given in Table 1. These results demonstrated the ability of NiO/NPs/CPE for voltammetric determination of NB with high selectivity and good reproducibility.

Table 1: Ability of propose sensor for determination of NB in real samples

Sample	Added (µM)	Expected (µM)	Founded (µM)	Recovery %
Urine	---	---	<LOD	---
	5.00	5.00	4.87±0.62	97.40
Serum	---	---	<LOD	---
	10.00	10.00	10.45±0.55	104.50
Water	---	---	<LOD	---
	20.00	20.00	20.65±0.75	103.25

3. Conclusions

This work describes the ability of the modified NiO/NPs carbon paste electrode for determination of NB. The voltammetric investigation demonstrates that electrooxidation of NB at the surface of NiO/NPs/CPE showed very distinct characteristics which due to the presence of NiO/NPs layer on the surface of electrode. The proposed modified electrode presented a low detection limit and good linear range and reproducibility which make it a suitable NB sensor for practical applications.

4. Acknowledgements

The authors wish to thank Graduate University of Advanced Technology, Kerman, Iran, for their support

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