

Voltammetric paracetamol sensor using a gold electrode made from a digital versatile disc chip and modified with a hybrid material consisting of carbon nanotubes and copper nanoparticles

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Abstract A composite consisting of carbon nanotubes (CNT) and copper nanoparticles (CuNPs) was prepared by a chemical reduction method, and its structure characterized by scanning electron microscopy, transmission electron microscopy energy dispersive spectroscopy and FT-IR spectrometry. The hybrid composite was deposited on the surface of a disposable gold electrode that was manufactured from a commercial digital versatile gold disc by a drop casting method. The electrochemical properties of the modified electrode were investigated by cyclic voltammetry and differential pulse voltammetry. The sensor showed an excellent electrocatalytic activity towards oxidation of paracetamol (PA). The calibration plot (with current typically measured at 0.41 V vs. Ag/AgCl) is linear in the 0.5 to 80 μ M concentration range, and the detection limit is as low as 10 nM. The sensor was successfully applied to the determination of PA in spiked water and tablet samples where it gave recoveries ranging between 95.25 and 100.5 %.

Keywords DVD · Gold disc · Carbon nanomaterial · Metal nanoparticle · Cyclic voltammetry · Differential pulse voltammetry · Scanning electron microscopy · Transmission electron microscopy

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Introduction

Paracetamol (N-acetyl-p-aminophenol), also known as acetaminophen is an important antipyretic and analgesic drug widely used for pain and fever all over the world [1, 2]. Generally, normal use of paracetamol does is safe and it has not any side effects. However, overdoses of paracetamol, exhibit harmful effects on kidney and liver [3]. Due to high consumption of PA, development of a fast, simple, sensitive and economic method for detection of PA in pharmaceutical formulations, biological samples and environmental is vital [4]. Since PA is considered as one of the pollutants monitored in surface waters, determination of trace amount of this drug in water bodies is of great interest [5].

A variety of methods have been employed for PA analysis in various type of samples. These include spectrophotometry [6], chromatography [7] and capillary electrophoresis [8].

It is well known that paracetamol is an electroactive compound and, therefore, the electrochemical techniques which are selective, sensitive, inexpensive, and also simple, are suitable methods for PA quantification in solutions compared with the above mentioned methods [9, 10].

Since the discovery of carbon nanotubes (CNTs) by Iijima in 1991 [11], they have increasingly been used as an ideal electrode materials for electrochemical sensing due to their unique properties, such as high electrical conductivity, mechanical strength, extraordinary thermal conductivity and chemical stability [12, 13]. Metal nanoparticles (MNPs) including gold (Au), platinum (Pt), palladium (Pd), copper (Cu), nickel (Ni), and silver (Ag), play a crucial role in the construction of modified sensors and they exhibit a high electrocatalytic activity because of their small size and excellent conductivity [14, 15]. Recently, CNT/metal nanoparticle composites have attracted great attention for construction of electrochemical sensors. Combination of the properties of both CNTs and MNPs exceptionally increases the surface-to-

volume ratio of the electrode and, therefore, enhances the mass transport characteristics [16, 17]. Carbon nanotube (CNT)-copper nanoparticle (CuNP) hybrid composite is used in analysis of some important analytes such as glucose sensing [18] and sensing of carbohydrates [19].

Gold electrodes are the most widely used for electrochemical purposes [20]. However, electrodes made from gold can be quite expensive. Angnes and co-workers was first reported a method to produce a disposable gold electrode obtained from compact discs (CDs) [21].

These electrodes have shown comparable performance to commercial gold electrodes with many advantages such as superior versatility, low cost, easy handling, and disposable surface. The applications of CD and also digital versatile disc (DVD) electrodes have been reported in some literature [22, 23].

We propose a disposable gold electrode manufactured from commercial digital versatile disc (DVD), without further pretreatment. A CNT-CuNP hybrid composite was prepared then the suspension of the composite easily drop cast at the surface of the electrode and the modified electrode used for electrochemical sensing of paracetamol in solutions. To our knowledge, there is no any report about the fabrication of paracetamol sensors based on the CNT/CuNP hybrid modified DVD-gold electrode.

Experimental

Chemicals

PA was obtained from Borhan Darou Co. (Mashhad Iran) (www.borhandarou.com). A 1.0×10^{-2} M stock standard solution of PA was prepared and stored at 4 °C. The working standard solutions were prepared by appropriate dilution of the aqueous stock standard solution with a phosphate buffer. A 0.1 M phosphate buffer was prepared using Na_2HPO_4 and NaH_2PO_4 . The pH of phosphate buffer was adjusted using dilute solutions of HCl or NaOH. MWCNTs with >95 % purity, 20–30 nm outer diameter, 10–30 μm length, 5–10 nm inner diameter; were purchased from US research nanomaterial (<http://www.us-nano.com/>), and were pretreated by refluxing in concentrated nitric acid at 60 °C for 12 h prior to use. Cupric sulfate pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$), potassium borohydride (KBH_4), potassium hydroxide, ethylenediaminetetraacetic acid disodium salt ($\text{EDTA} \cdot 2\text{Na} \cdot 2\text{H}_2\text{O}$), all obtained from Merck chemical company (<http://www.merck.com>). All of the other reagents were of analytical grade and used without further purification. Deionized distilled water was used throughout the work.

Preparation of CNT-CuNP hybrid composite

The carbon nanotube-copper nanoparticle hybrid was prepared by chemical reduction method according to

the reported procedure in reference [19]. Briefly, 65 mg MWCNTs was sonicated in 20 mL aqueous solution containing 499.2 mg $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ (2 mmol) and 0.16 g $\text{EDTA} \cdot 2\text{Na} \cdot 2\text{H}_2\text{O}$ for 10 min. While the mixture was stirred vigorously, 10 mL aqueous solution containing 448 mg KOH and 53.9 mg KBH_4 (1 mmol) was gradually added to the above solution and keep stirring for 30 min. The black precipitate was collected by filtrating and washed with distilled water and absolute ethanol and finally dried in vacuum. The copper nanoparticles were prepared by describing method without adding CNT.

Construction of the modified electrode

The DVD gold disc (EMTEC) (www.emtec-international.com) was used as received. The DVDs were cut into several slices then by applying a bending pressure by hand, the upper layer of them was peeled away. Each slice of the gold film was covered with galvanoplastic adhesive tape with a 5 mm diameter hole and used as the working electrode. A copper strip was used as a conductor (Fig. 1). 2.0 mg of CNT-CuNP hybrid was mixed well in 1.0 mL DMF with ultrasonic agitation to form a homogenous mixture. Then 10 μL of the mixture was added on the surface of the DVD gold electrode. The solvent was then evaporated in air at room temperature.

Apparatus

The voltammetric measurements were performed using a $\mu\text{Autolab}$ electrochemical system (Metrohm) (www.metrohm.com) equipped with a NOVA software. All electrochemical measurements were carried out in a three-electrode measuring cell containing; an Ag/AgCl/KCl (3.5 M) as reference electrode, a platinum wire as a counter electrode were purchased from Azar Electrode Company, Urmia Iran and 5.0 mm diameter modified DVD gold as a working electrode.

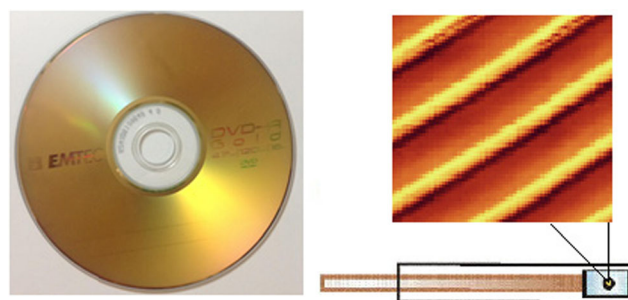
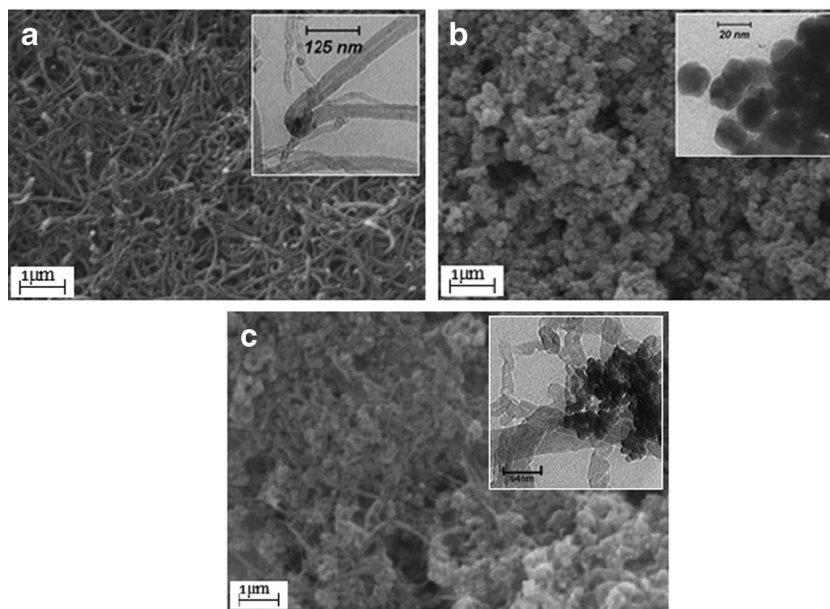


Fig. 1 Schematic of electrode construction. Inserted figure: AFM image of gold film surface

Fig. 2 SEM images of (a) CNTs, (b) CuNPs and (c) CNT-CuNP. Inset shows TEM images



Results and discussion

Choice of materials

Nanomaterials, such as carbon nanotubes (CNTs) and transition metallic nanoparticles, are widely applied in sensor construction. CNTs are a unique form of carbon which is a promising alternative support material owing to their intrinsic properties such as high surface area, unique electronic properties and chemical inertness, thermal stability and high mechanical strength. It has been confirmed that CNTs are suitable supports for many kinds of metal catalysts. The higher signal enhancement by CNTs may be due to their larger surface area, which leads to higher analyte loading. So, CNTs served as a better electrode material compared to the other carbon nanomaterials such as graphene. Transition metallic nanoparticles, including gold, platinum, palladium, copper, and silver can be used to increase the electrochemical activities. Copper (Cu) nanoparticles increase the response current and they are relatively inexpensive with respect to the other transition metals, and they also have good biocompatibility.

Characterization

The surface morphologies of CNTs, CuNPs and CNT-CuNP hybrid were investigated using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The results are shown in Fig. 2. As can be seen in Fig. 2c, a great amount of well dispersed CuNPs are embedded in the CNT matrix and a hybrid network is formed. This conductive copper-CNT network may establish electrical conduction pathways throughout the whole hybrid, which is responsible for the electric conductivity and electrochemical sensing.

Figure S1 shows the Fourier transform infrared (FT-IR) spectrum of (a) CNTs, (b) CNT-CuNP and (c) CuNP. In Fig. S1a the peaks at 3400, 1709, 1565 cm^{-1} , correspond to O–H, C = O, and C = C stretching vibrations, respectively. The peaks at 1640, 1200 and 1090 cm^{-1} correspond to the vibration of the carboxylic acid groups [24]. The FT-IR spectrum of CNT-CuNP hybrid (Fig. S1b) is similar to that of the CNTs, and the peak at 620 cm^{-1} can be assigned to CuNPs [19] (Fig. S1c). The obtained results indicate that the CNT-CuNP is a simple hybrid of CNTs

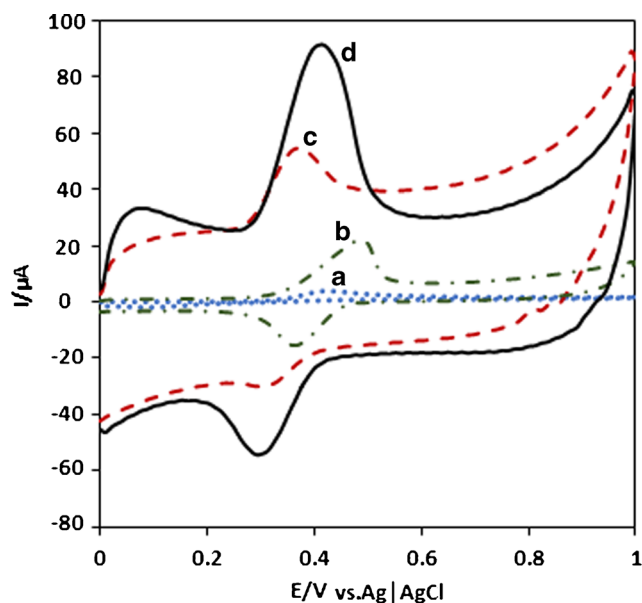


Fig. 3 Cyclic voltammograms of 100.0 μM of PA in phosphate buffer (pH 9) at (a) bare DVD-gold electrode (dotted line), (b) CuNPs-DVD-gold (dashed dotted line), (c) CNTs-DVD-gold (dashed line) and (d) CNT-CuNP-DVD-gold (solid line). In all cases, the scan rate is 100mVs^{-1}

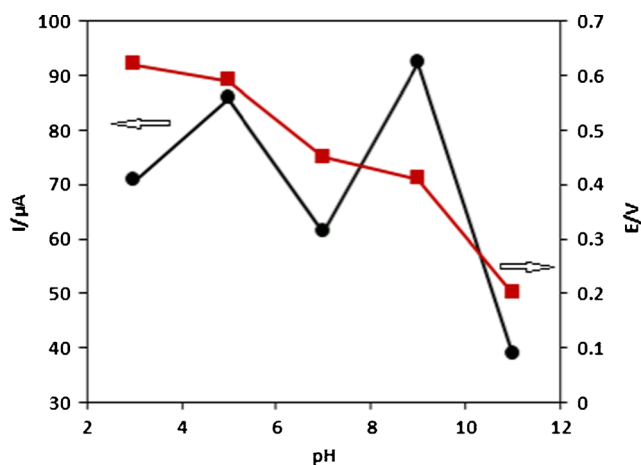


Fig. 4 Influence of pH on the oxidation peak current and peak potential

and CuNPs because all the characteristic peaks of these materials can be seen in their FT-IR spectra.

The chemical composition of the hybrid was checked by using the energy dispersion spectroscopy (EDS). The EDS results in Fig. S2, clearly show that the main elements in CNT-Cu NP hybrid are C, Cu and O atoms. The presence of oxygen atoms in the hybrid is related to the CNTs functional groups. Fig. S3 also shows the XRD pattern of the CuNPs.

Cyclic voltammetric study of PA

The electrochemical behaviors of PA at different fabricated electrodes were characterized by cyclic voltammetry. The cyclic voltammograms of PA obtained at bare DVD-gold, CuNPs-DVD-gold, CNTs-DVD-gold and CNT-CuNP-DVD-gold are shown in Fig. 3. In all cases, the PA molecules show a pair of well-defined redox peaks, with a quasi-reversible behavior with a lowest anodic peak potential. As is evident in Fig. 3a (dotted line) for 100 μM solution of PA, a broad and weak oxidation peak, around 0.42 V with 3.89 μA peak current is observed at bare DVD-gold. But in the case of CuNPs-DVD-gold electrode, as shown in Fig. 3b (dashed dotted line), the oxidation peak is located at 0.49 V with the peak current (I_p) at 21.7 μA . As is seen in Fig. 3c (dashed line), in the case of CNTs-DVD-gold electrode, the oxidation peak is appeared at 0.37 V with a peak current at 54.8 μA , but in the case of CNT-CuNP-DVD-gold electrode, the oxidation peak is located at 0.41 V with a peak current at 90.8 μA (Fig. 3d solid line). The experimental results,

reveal that the oxidation process of PA molecules shows the highest peak current at CNT-CuNP-DVD-gold modify electrode with respect to the other constructed electrodes. This can be attributed to the excellent electrocatalytic activity of the CNTs and CuNPs towards the paracetamol oxidation process.

The effect of scan rate on the anodic and cathodic peak currents of paracetamol was investigated in the range of 25–200 $\text{mV}\cdot\text{s}^{-1}$ (Fig. S4). As is evident in Fig. S5, there is a linear relationship between the anodic and cathodic peak currents and the square root of the scan rate which indicates the electrode process is controlled by a diffusion process [25].

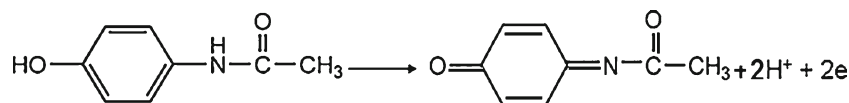
The effect of pH on the electrochemical response of PA, was investigated in phosphate buffer over the pH range of 3–11 (Fig. S6). As is evident in Fig. 4, the peak potential is shifted toward less positive values with increasing the pH, and maximum performance of the electrode response is obtained at pH 9, therefore, all of the experiments carried out in phosphate buffer at pH 9.

The possible reaction pathways for electrooxidation of PA on CNT-CuNP-DVD-gold modified electrode in 0.1 M solution of phosphate buffer (pH 9) shown in Scheme 1. PA oxidizes to N-acetyl-p-quinoneimine in a mechanism involving two protons and two electrons in the oxidation reaction.

Calibration plots and limits of detection

The determination of PA by CNT-CuNP-DVD-gold electrode was carried out in 0.1 M solution of phosphate buffer (pH 9.0) by differential pulse voltammetry (DPV). The differential pulse voltammograms are shown in Fig. 5 and the calibration graph is presented in inset of Fig. 5. The obtained results, show that the peak currents increases linearly upon increasing the concentration of PA in solution. The calibration curve has two linear regions in the range of 0.5 to 80 μM . The limit of detection (LOD) (3 Sb/m) and the limit of quantification (LOQ) (10 Sb/m) were found to be 0.010 μM and 0.037 μM , respectively. Table 1, shows the detection limits which are reported by the other research groups for PA determination at different modified electrodes with nanocomposite material. As is evident in this table, the value of LOD obtained in this work is lower or comparable with those obtained in the other electrochemical determination of PA.

Scheme 1 Possible reaction pathways for electrooxidation of PA



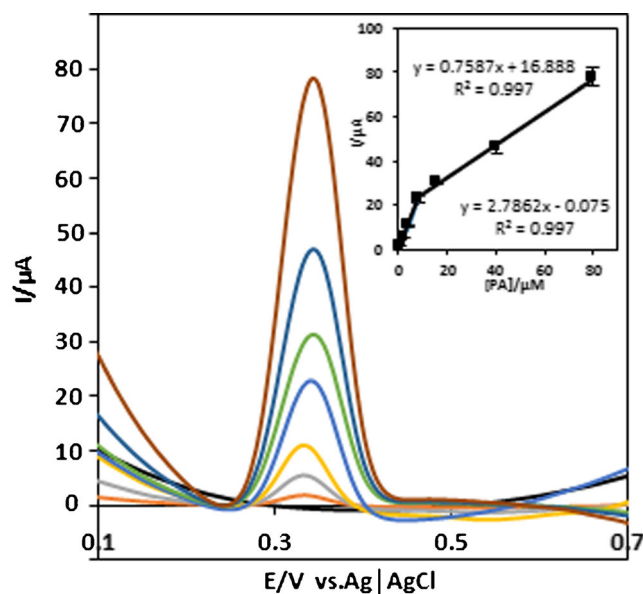


Fig. 5 Differential pulse voltammograms for various concentrations of PA in the range of 0.5–80 μM . In 0.1 M phosphate buffer (pH 9). Inset shows linear calibration curve of peak current vs. PA concentration (0.5–80 μM) at CNT-CuNP-DVD-gold electrode

Reproducibility and stability of the CNT-CuNP-DVD gold electrode

The reproducibility of the electrode was estimated and the relative standard deviation (RSD) for five measurements was found to be 3.8 % for 50 μM solution of PA. The repeatability of the electrode was also investigated, where the RSD was 3.2 % ($n = 5$) using the same electrode. When the electrode was not in use, it was stored at room

Table 1 Comparison of detection limits (LOD) for determination of PA in some electrochemical measurement with nanocomposite material

Electrode	Method	LOD (μM)	Ref
Graphite–polystyrene composite film modified electrode	DPV	0.034	[26]
G/GCE	SWV	0.032	[27]
Cs/CPE	SWV	0.508	[28]
SWNT/EPPGE	SWV	0.0029	[29]
AuNPs/GCE	DPV	0.13	[30]
GO/MIP/GCE	DPV	0.2	[31]
MWCNTs/AuNPs/DNS	DPV	0.5	[32]
MWCNT-BPVC/M/GCE	CV	3.5	[33]
MWCNTs/CTS-Cu	DPV	0.024	[34]
PtMWCNTs/CPE	Amperometry	0.017	[9]
AuNPs/PGA/CPE	DPASV	0.01	[10]
CNTs-CuNP/DVD-goldE	DPV	0.01	This work

temperature in a desiccator. No apparent change in peak current was observed after storage for 15 days. After storing for 1 month, the peak currents maintained 98 % of initial values. The results, indicate that the electrode has an acceptable reproducibility and stability.

Interference study

The effect of some potential interferences on determination of PA such as ascorbic acid, uric acid and dopamine and common inorganic ions such as Na^+ , K^+ , Cl^- , CH_3COO^- and CO_3^{2-} was investigated by analyzing a standard solution of 5 μM PA under the optimum experimental conditions. The results are given in Table S1. According to the obtained results, the presence of a 100 fold concentration of the interferences in solution, does not show any significant interference with the determination of PA using the modified sensor and the change of the peak current caused by them was less than 5 %. Therefore, the constructed sensor could be used for determination of paracetamol with excellent selectivity.

Analytical application

The practical feasibility of the electrode was investigated for determination of PA in commercially available tablet and in spiked water samples by standard addition method. The paracetamol tablet (500 mg) was grinded in a mortar with pestle and the obtained powders was dissolved in 100 mL water solution by ultrasonication, then, different amount of prepared solutions was diluted to 5 mL with 0.1 M phosphate buffer (pH 9) and transferred to the voltammetric cell for the voltammetric determinations. For preparing the water samples, 10 mL of the sample was centrifuged for 15 min at 1500 rpm. The supernatant was filtered out and then 1 mL of the filtered solution was diluted to 5 mL with 0.1 M phosphate buffer (pH 9). The results are listed in Table 2. As is evident in this Table, the good recovery results, confirm that the constructed CNT-CuNP-DVD-gold modified electrode, is a precise

Table 2 Voltammetric determination of PA in tablet and water samples

Sample	Spiked (μM)	Found (μM)	Recovery (%)
Tablet ^a	40	38.1	95.25
Waste water	40	40.2	100.5
River water	40	39.6	99

The RSD for the determination of PA in tablet and water samples was less than 5 % for $n = 5$

^a 500 mg tablet of PA, Sobhan Darou Co. Iran

and sensitive electrochemical sensor for determination of PA in both pharmaceutical and water samples.

Conclusions

We successfully fabricated a CNT-CuNP-DVD-gold modified electrode as a sensor for voltammetric determination of paracetamol (PA) in solutions. The combination of CNTs and CuNPs on the surface of the DVD-gold electrode, exhibits a promising electrocatalytic activity towards the PA oxidation. The electrode shows good characteristics such as a large dynamic range, good sensitivity and also high stability. The sensor can effectively resist the effect of interferents such as uric acid, ascorbic acid and dopamine. With the above excellent performance, the electrode could be used for efficient determination of paracetamol in real samples.

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Compliance with ethical standard The author(s) declare that they have no competing interests.

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