Full Paper

Electrochemical Characterization of a Modified Electrode Based on Carbon Nanotubes and a Synthesized Schiff Base: Application for Voltammetric Determination of Epinephrine, Acetaminophen and Folic Acid

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Abstract- The electrochemical behavior of a multiwalled carbon nanotube paste electrode modified with 2-((7-(2, 5-dihydrobenzylideneamino) heptylimino) methyl) benzene-1, 4-diol (DBHB) was studied. The pH dependent, apparent charge transfer rate constant and transfer coefficient were investigated for the electrochemical behavior of DBHB. This electrode showed high electrocatalytic activity toward oxidation of epinephrine (EP) relative to an unmodified carbon paste electrode. Cyclic voltammetry and chronoamperometry were used to study the electro-oxidation of EP at the modified electrode and electrocatalytic mechanism, catalytic rate constant and diffusion coefficient was obtained for oxidation of EP. Using differential pulse voltammetry (DPV) a highly selective and simultaneous determination of EP, acetaminophen (AC) and folic acid (FA) has been obtained at the modified electrode as an electrochemical sensor. The present method provides a simple method for selective detection of EP in biological samples.

1. INTRODUCTION

Electrode reactions of some species at bare electrodes require high overpotential and their voltammetric determinations in the presence of other species are impossible [1]. Also in potentiometric determinations the selectivity is very poor when a common bare electrode used as indicator electrode [2]. So, it is necessary to develop sensitive and selective sensors for simultaneous determination of different important species in mixture of them. A useful approach to overcome these problems is the use of modified electrodes as electrochemical sensor [1-3]. Surface modification of electrodes is a major area in the field of electroanalytical chemistry that lead to significant reduction of overpotential and increases in the electron transfer rate constant for desired electrode reactions at the electrode [4–6].

Epinephrine or adrenaline (EP) is a hormone and a neurotransmitter. Medically, EP has been used as a common emergency healthcare medicine [7]. EP has a significant role in the series of biological performance and nervous chemical processes [8]. Therefore, fast and accurate detection of EP is important not only for identification, but also for pathological research. Several methods have been developed to determine EP such as chemiluminescence [9], capillary electrophoresis [10], spectrophotometry [11], polymer film modified glassy carbon electrode [12], nanoparticles modified carbon paste electrode [13], self-assembled monolayer modified electrode [14], carbon nanotube modified electrode [15].

Acetaminophen or paracetamol (AC) is an antipyretic and analgesic drug commonly used against mild to moderate pain or for reduction of fevers [16,17]. Overdose ingestions of AC lead to accumulation of toxic metabolites, which may cause severe and sometimes fatal hepatotoxicity and nephrotoxicity, which in some cases associate with renal failure [18,19]. The large scale therapeutic use of this drug generated the need for the development of fast, simple and accurate methodologies for the detection of AC [20]. Several methods have been used for the determination of AC including UV–VIS spectrophotometry [21], flow-injection [22] and chromatographic methods [23]. Among different methods, electrochemical methods may be the most widely applied because of high sensitivity, simplicity and reproducibility of this approach [24-27].

Folic acid (FA) is an important component of the hematopoietic system and is the coenzyme that controls the generation of ferroheme [28]. Lack of FA gives rise to gigantocytic anemia and is associated with leucopenia, devolution of mentality and psychosis. Determination of FA is often required in pharmaceutical, clinical and food samples. Different electroanalytical methods were reported for FA determination [29].

EP, AC and FA have close oxidation potential on the bare electrodes. So it is essential to resolve this problem for their simultaneous determination in routine analysis. Modified carbon paste electrodes, among of many approaches, has shown to be a powerful tools for determination of mixture of these compounds in biological samples [30].

Carbon nanotubes (CNTs) have attracted more attention in physical, chemical and material science fields [31] due to their unique electrical conductivity, chemical stability and high mechanical strength and modulus [32,33]. The subtle electronic properties of carbon nanotubes suggest that they have the ability to promote electron transfer when used as the electrode material in electrochemical reactions [34]. These properties provide a new manner of electrode surface modification for designing new electrochemical sensors [35-37] and novel electrocatalytic materials [38,39].

To the best of our knowledge, no any study has been reported on the simultaneous determination of EP, AC and FA using carbon paste electrode (CPE) modified with carbon nanotubes (CNT) and DBHB. So, in the present work, we described initially the preparation of a CPE modified with both DBHB and CNT (DCNPE) as a new sensor in the electrocatalysis and determination of EP. Then, we evaluated the analytical performance of the proposed method in quantification of EP in the presence of AC and FA. The method is fast, simple, and enough sensitive to measure those species in real sample.

2. EXPERIMENTAL

2.1. Apparatus and chemicals

The electrochemical measurements were performed with as potentiostat/galvanostat (SAMA 500, electroanalyzer, system, I.R. Iran). The experimental condition were controlled at $25\pm1°C$. A three-electrode cell including a platinum wire, a saturated calomel electrode and the DCNPE were used as the auxiliary, reference and working electrodes, respectively. A pH meter Metrohm 691 was used for adjusting the pH of solutions. EP, AC, FA and all other reagents were of analytical grade from Merck (Darmstadt, Germany). Graphite fine powder and paraffin oil (DC 350, density=0.88 g Cm^{-3}, Merck), were used for preparing the pastes. Multiwalled carbon nanotubes (purity more than 95%) with o.d. between 5 and 20 nm, i.d. between 2 and 6 nm, and tube length 1–10 µm were purchased from plasma Chem. Buffer solutions were prepared from phosphoric acid, and its salts in the pH range of 4.0–9.0. The one mg mL^{-1} EP ampoule (from Darou Pakhsh pharmaceutical manufacturing company) was purchased from local pharmacy.

2.2. A typical procedure for synthesis of 2,2'-[1,7–heptanediylbis(nitrilomethylidene)]-bis(4-hydroxyphenol)

To a mixture of 2,5-dihydroxybenzaldehyde (0.35 g, 2.5 mmol) in MeOH was added 1,7-diaminoheptane (0.18 g, 1.4 mmol) and stirring for 30 min. The progress of the reaction was monitored by TLC. After the reaction completion, yellow solid product was filtered off and washed with cold MeOH and pure Schiff base, 2,2'-[1,7–heptanediyl bis(nitrilomethylidene)]-bis(4-hydroxyphenol) was obtained in 90% yield, m.p.=215–217 °C.

The chemical structure of this compound (abbreviated as DBHB) is shown at Scheme 1. The Schiff base product was identified by physical and spectroscopic data as following;

2,2'-[1,7–heptanediyl-bis(nitrilomethylidene)]-bis(4-hydroxyphenol):   Yellow   solid; Yield: 90 %; M.p: 215–217 °C. Anal. Calcd.: C, 68.1; H, 7.02; N, 7.6. Found: C, 68.1; H, 6.9; N, 7.4. IR (KBr)/υ(Cm^{-1}): 3373–3500 (s, br, 2OH), 1646 (s, C=N), 1503, 1457 (Ar), 1239 (s, C-O). ^{1}H NMR (400 MHz/DMSO-d6)/δ ppm: 12.7 (br, 2OH, Intramolecular hydrogen bonding), 8.90 (br, 2OH), 8.42 (s, 2CH Imine), 6.78 (d, 2H, Ar, J= 4 Hz), 6.76 (dd, 2H, Ar, J_1= 8.2 Hz, J_2= 2.2 Hz), 6.69 (d, 2H, Ar, J= 8.4 Hz), 3.54 (t, 4H, 2CH$_2$, J= 12.8Hz), 1.58 (m, 8H, 4CH$_2$), 1.33 (m, 2H, CH$_2$). ^{13}C NMR(100 MHz/DMSO-d6)/δ ppm: 165.77, 153.62, 149.70, 120.12, 119.01, 117.25, 116.90, 59.02, 30.83, 28.88, 27.03. MS: m/z=370 (M$^+$, 4), 235 (6), 220 (22), 206 (28), 193 (90), 179 (32), 150 (68), 137 (92), 126(100). UV/λ_{max}: 340 (s), 240 (w).
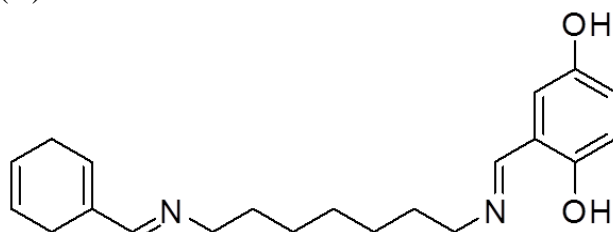
Scheme 1. Chemical structure of DBHB

2.3. Preparation of the electrodes

The DCNPE was prepared by hand mixing 0.01 g of DBHB with 0.96 g graphite powder and 0.03 g of CNT with a mortar and pestle. Then ~0.7mL of paraffin was added to the above mixture and mixed for 20 min until a uniformly wetted paste was obtained. The paste was then packed into the end of a glass tube (ca. 3.7 mm i.d. and 10 Cm long). A copper wire inserted, into the carbon paste provided the electrical contact. When necessary a new surface was obtained by pushing an excess of the paste out of the tube and polishing with a weighing paper. For comparison, modified CPE electrode without CNTs (DCPE), CNT paste electrode without DBHB (CNPE), and unmodified CPE in the absence of both DBHB and CNT were also prepared in the same way. After all the thoroughly above steps, the electrode was rinsed with deionized water.

3. RESULTS AND DISCUSSION

3.1. Electrochemical characterization of DCNPE

The DBHB is insoluble in aqueous solution, so its electrochemical behavior was investigated at DCNPE. A redox pair were observed for DCNPE in 0.1 M phosphate buffer solutions pH 7.0, with E_{pa} = 0.283 V and E_{pc}= 0.182 V *vs*. SCE and ΔE_p= (E_{pa}-E_{pc}) of 0.101

V which was greater than prevised value for a reversible system. The influence of pH was studied on the electrochemical behavior of DBHB. Cyclic voltammetry response of DCNPE was recorded in 0.1M phosphate buffer solutions with different pHs. The formal potential $E^{0'}=E_{pa}-\alpha(E_{pa}-E_{pc})$ of the surface redox pair was plotted versus pH. The results represented that the slope ($E^{0'}$/pH) is 47.0 mv/pH over a pH range from 4.0 to 9.0 which is very close to the predicted Nernst value for the process with two electrons and two protons transfer [40].

The cyclic voltammograms of DCNPE was recorded at different scan rates which shown in Fig. 1. A linear relation was existed between peak currents and scan rate (v) in the range of 20-1600 mV s^{-1} (Fig.1A) showing that the redox process of DCNPE was occurred in diffusion-less manner. Fig. 2B shows variation of E_p *vs.* logarithm of the scan rate. At scan rates higher than 90mV s^{-1} there is a linear relation between E_p and logarithm of the scan rate (Fig. 2C) and the slopes of the related lines are equal to -2.303RT/(1-α) nF and 2.3RT/αnF for cathodic and anodic peaks, respectively. Therefore the obtained value for α is 0.32.
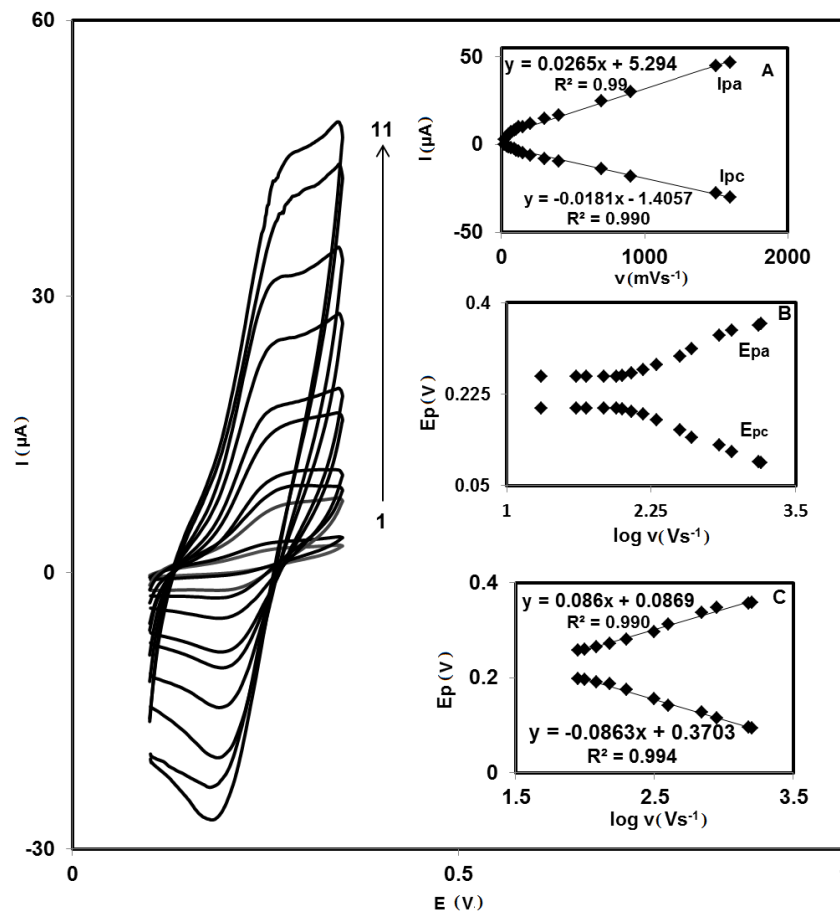
Fig. 1. Cyclic voltamograms of DCNPE in 0.1 M phosphate buffer solution pH 7.0 at various scan rates, the numbers 1-11 correspond to 20, 40, 100, 120, 150, 300, 400, 700, 900, 1500 and 1600 mVs^{-1}; (**A**) plot of I_p *vs.* scan rate (**B**) plot of E_p *vs.* log v, (**C**) plot of E_p *vs.* log v for high scan rates

Also the Laviron equation can be used to demonstrate the electron transfer rate constant for the surface confined electroactive species with $\Delta E_p > 200/n$ mV [41]:

$$\log k_s = \alpha \log (1 - \alpha) + (1 - \alpha) \log \alpha - \log (RT/n_\alpha F\upsilon) - \alpha (1 - \alpha) n_\alpha F\Delta E_p/2.3RT \tag{1}$$

Using this equation the value of apparent charge transfer rate constant (k_s) was calculated as 5.7 s^{-1} for the DBHB at DCNPE in 0.1M phosphate buffer pH 7.0.

An approximate estimate of the surface coverage of the electrode was made by adopting the method used by sharp et al [42]. According to this method the peak current is related to the surface concentration of electroactive species, Γ, by the following equation:

$$I_p = n^2 F^2 A\Gamma\upsilon/4RT \tag{2}$$

Where n represents the number of electrons involved in reaction, A is the surface area of the DCNPE, Γ (mol cm^{-2}) is the surface coverage and other symbols have their usual meanings. From the slope of anodic peak currents versus scan rate (Fig. 1A), the value of Γ obtained as 7.0×10^{-8} mol cm^{-2} for n=2.

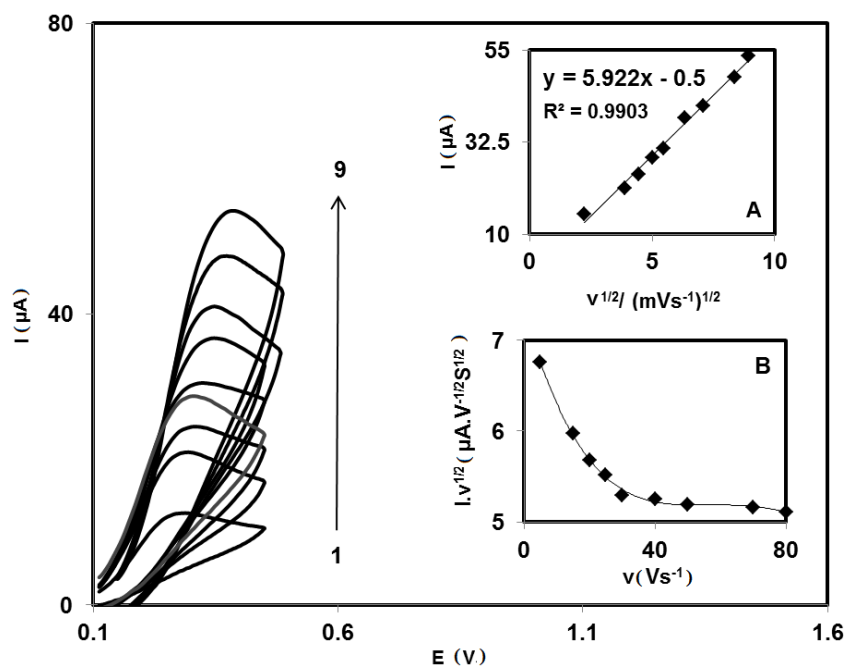### 3.2. Electrocatalytic oxidation of EP at DCNPE

Fig. 2 explains the cyclic voltammetry results for the electrochemical oxidation of 0.5 mM EP at the unmodified CPE (curve b), CNPE (curve d), DCPE (curve e), and DCNPE (curve f). The oxidation of EP at CPE (curve b) and CNPE (curve d) is about 440 mV whereas the oxidation of EP at DBHB modified electrodes (curves e and f) is about 290 mV. The oxidation peak potential of EP at modified electrodes with DBHB is shifted by about 150 mV toward negative values, with respect to electrodes without DBHB.
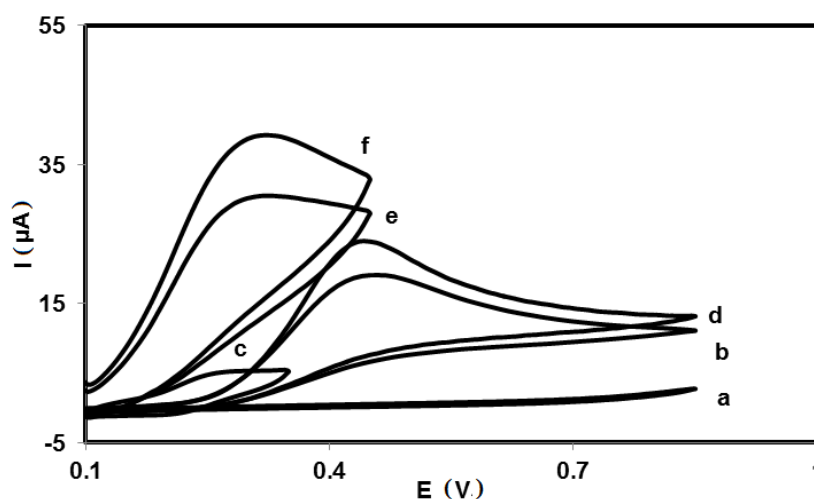
Fig. 2. Cyclic voltammograms of (a) unmodified CPE in 0.1 M phosphate buffer solution (pH 7.0) at scan rate of 40 mV s^{-1}; (b) as (a) +0.5 mM EP; (c) as (a) at the surface of DCNPE; (d), (e) and (f) as (b) at the surface of CNPE, DCPE and DCNPE, respectively

The DCNPE, in a solution without EP, exhibited a well-behaved redox reaction (curve c), upon addition of EP there was a dramatic enhancement of the anodic peak current (curve e) indicating a strong electrocatalytic effect of DCNPE for oxidation of EP [40]. Also when comparing the oxidation of EP at the DCPE (curve e) and DCNPE (curve f), an enhancement of the anodic peak current at the DCNPE relative to that obtained at the DCPE was observed. Therefore, the combination of carbon nanotube and DBHB definitely improve the characteristics of EP oxidation.

The effect of scan rate on the electrocatalytic oxidation of EP at the DCNPE was investigated (Fig. 3). As can be seen in Fig. 3A, there is a linear correlation between plots of peak height (I_p) against the square root of scan rate ($v^{1/2}$) in the range of 5-80 mVs^{-1}, which indicate the process was diffusion controlled. A plot of the sweep rate normalized current ($I_p/v^{1/2}$) versus scan rate (Fig. 3B) exhibits the characteristic shape typical of an EC$'_{cat}$ process.


Fig. 3. Cyclic voltammograms of DCNPE in 0.1 M phosphate buffer pH 7.0 containing 0.5 mM EP at different scan rates; the numbers 1–9 correspond to 5, 10, 15, 20, 25, 30, 40, 70 and 80 mVs^{-1}, Insets: **(A)** variation of the electrocatalytic currents *vs.* the square root of scan rate and **(B)** variation of the scan rate normalized current ($I_p/v^{1/2}$) with scan rate

3.3. Chronoamperometric investigation

The chronoamperometry, with a potential step of 350 mV, was employed for the catalytic oxidation of EP at DCNPE (Fig. 4). The diffusion coefficient (D) of EP was determined at DCNPE based on the Cottrell equation [40]. Inset (A) of Figure 4 shows the plot of I versus

$t^{-1/2}$ with the best fits for different concentration of EP. The slopes of the resulting straight lines were plotted versus the EP concentration (Fig. 4B). By the slope of this curve, the value of the D was found to be 3.14×10^{-5} cm^2 s^{-1}.
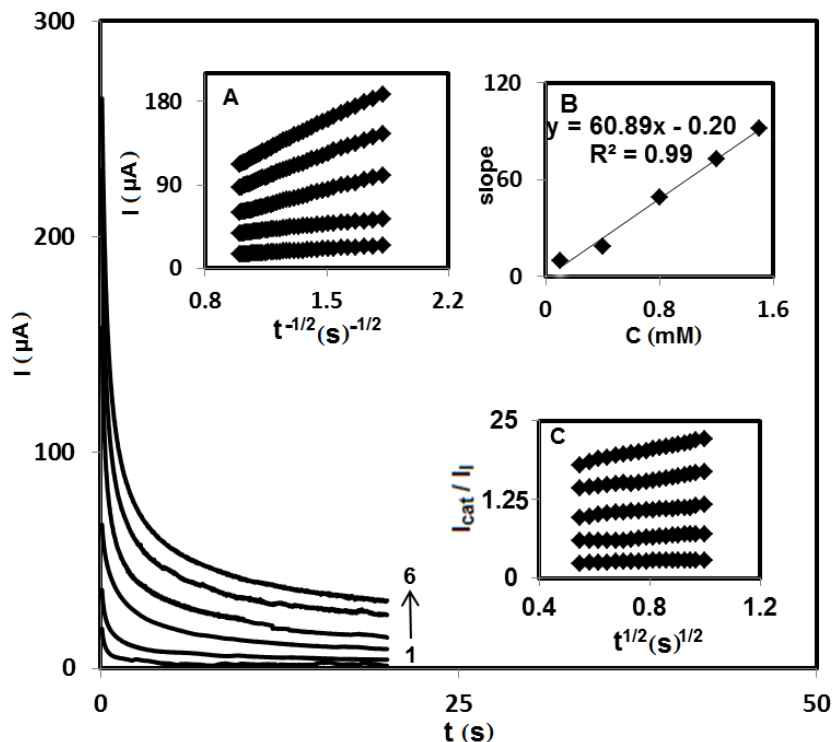
Fig. 4. Chronoamperograms obtained at DCNPE in 0.1 M phosphate buffer solution pH 7.0 for different concentrations of EP. The numbers 1–6 correspond to 0, 0.1, 0.4, 0.8, 1.2 and 1.5 mM of EP. Insets: **(A)** plots of I *vs.* $t^{-1/2}$ obtained from chronoamperograms 2-6, **(B)** plot of the slope of the straight lines against the EP concentration, **(C)** Dependence of I_{cat}/I_L on $t^{1/2}$ derived from the data of chronoamperograms

The catalytic rate constant, k, for the reaction between EP and DCNPE was obtained according to the reduced form of Galus equation [43]:

$$I_C/I_L = \pi^{1/2}\gamma^{1/2} = \pi^{1/2}(kC_bt)^{1/2} \qquad (3)$$

Where I_C is the catalytic current of EP at the DCNPE, I_L is the limited current in the absence of EP, t is the time elapsed (s) and C_b is the bulk concentration of EP. The above equation can be used to calculate the rate constant of the catalytic process (k). Based on the slope of the I_C/I_L versus $t^{1/2}$ plot; *k* can be obtained for a given EP concentration. Such plots obtained from the chronoamperograms in Fig. 4 are shown in inset (c). From the values of the slopes an average value of k was found to be k=7.5×10^4 M^{-1}s^{-1}. The value of k explains the sharp feature of the catalytic peak observed for catalytic oxidation of EP at the surface of DCNPE.

3.4. Differential pulse voltammetry studies

Differential pulse voltammetry (DPV) was used to obtain the calibration plot and detection limit of EP. DP voltammograms was obtained for the oxidation of different concentrations of EP at the DCNPE. The plot of DPV peak current *vs*. EP concentration consisted of two linear segments with slopes of 0.0499 and 0.0132 μA μM^{-1} in the concentration ranges of 10.0-400.0 and 400.0-6000.0, respectively. The decrease in sensitivity (slope) in the second linear rang is likely to be due to kinetic limitation. The detection limit (3σ) for EP in the lower range region was found to be 2.8 μM. Results in this work are comparable with results reported by other research groups for electrocatalytic oxidation of EP at the surface of modified electrodes (Table 1).

3.5. Simultaneous determination of EP, AC and FA

The ability for resolution of the electrochemical responses of different analysts is one of important parameters of the modified electrodes. DPVs are recorded for solutions with different concentration of EP, AC and FA at DCNPE. Obtained DPVs show oxidations peaks of these three analysts are exactly separated at potentials of 0.25, 0.44 and 0.73 V for EP, AC and FA, respectively (Fig. 5). While, the bare electrode could not separate the voltammetric signals of these substances and an overlapped voltammogram was obtained for the analytes. Also it is very interesting to note that the sensitivities of the modified electrode toward EP in the absence and presence of AC and FA were virtually the same, which indicates the oxidation processes of EP, AC and FA at DCNPE were independent. Therefore, simultaneous or independent measurements of these analytes are possible without any interference.

3.6. Interference study

The influence of various foreign species on the determination of EP was investigated. The tolerance limit was taken as the maximum concentration of the foreign substances which caused an approximately 5% relative error in the determination. Ascorbic acid, dopamine, uric acid, levodopa, N-acetyl and captopril at concentration 5 times higher than EP did not show interference in the determination of EP.

3.7. Real sample analysis

To evaluate the applicability of the proposed electrode, voltammetric determination of EP was examined in an EP ampoule that contains 1.0 mg mL^{-1} of EP. A solution with concentration of 200 μM of EP were prepared form this ampoule. Then this sample was transferred into the electrochemical cell and DPV was recorded between 0 and 0.8 V. This process was repeated 5 times and the average recovery percent for EP were obtained using DPV peak current (first row of Table 2). Also several solutions with different concentration

of EP were prepared form EP ampoule and then different amount of AC and FA were added in to these solutions. The recoveries for each substance were obtained between 98.6% and 102.7% for 5 replicate measurements (Table 2).

Table 1. Comparison of some electrochemical procedures used for determination of EP

Electrode	Modifier	pH	Detection limit (μM)	Dynamic range (μM)	Reference
CPE	ZrO$_2$	7.0	0.095	0.2-2200	[44]
Pt	Lyophilized biomass of White rot fungi (Phanerochaete chrysosporium ME446)	4.5	1.04	0.03-100	[45]
Paraffin/MWCNT composite	CoPc[a]	6.0	0.015	1.33-5.50	[46]
Gold	DPDSAM[b]	8.0	0.51	0.7-500	[47]
GCE[c]	PXSP[d]	4.0	0.1	2-390	[48]
CPE	BBNBH[e]	8.0	0.2	1.0-600.0	[27]
CPE	DH[f]	7.0	1.0	5.0-600.0	[49]
CPE	DBHB	7.0	2.8	10.0-6000.0	This work

[a] cobalt phthalocyanine; [b] 2-(2,3-dihydroxy phenyl)-1,3-dithiane self-assembled monolayer; [c] glassy carbon electrode; [d] poly (p-xylenolsulfonephthalein); [e] 2,2′-[1,2-Butanediylbis(nitriloethylidyne)]-bishydroquinone; [f] 2,2′-[1,2-ethanediylbis (nitrilomethylidyne)]-bishydroquinone.

Table 2. Determination of EP, AC and FA in solutions prepared from EP ampoule

Number of solutions	Concentration of substance (μM)			Recovery (%)		
	EP	AC	FA	EP	AC	FA
1	200.0	-	-	100.8	-	-
2	250.0	200.0	100.0	99.1	102.7	99.0
3	200.0	160.0	80.0	99.53	99.02	101.6
4	150.0	120.0	60.0	102.4	98.6	101.4
5	100.0	80.0	40.0	101.3	100.7	98.9
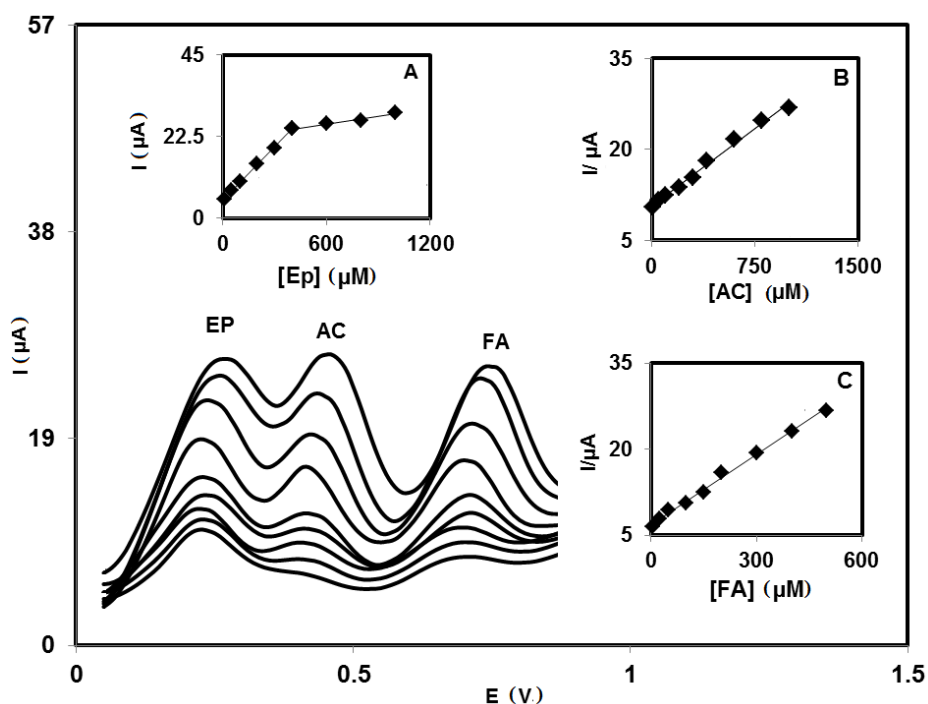
Fig. 5. DP voltammograms of DCNPE in 0.1 M phosphate buffer solution pH 7.0 containing different concentrations of EP+AC+FA in µM, from inner to outer: 10+5+15, 50+25+75, 100+50+150, 200+100+300, 300+150+450, 400+200+600, 600+300+900, 800+400+1200, 1000+500+1500, respectively; Insets A-C are calibration plots of EP, AC and FA, respectively

4. CONCLUSIONS

In the present study, a carbon paste electrode modified with DBHB and CNTs was used for the electrocatalysis of EP, which cause decreasing the potential and enhancing the current of oxidation of EP. DPV investigation showed simultaneous determination of EP, AC and FA, with complete resolution of their anodic peaks is possible by the modified electrode. Good selectivity and reproducibility of the voltammetric responses, together with the ease of preparation and surface regeneration, makes the proposed modified electrode very useful for accurate determination of EP in real samples.

REFERENCES

[1]   M. Mazloum-Ardakani, M. A. Sheikh-Mohseni, B. B. F. Mirjalili, and L. Zamani, J. Electroanal. Chem. 686 (2012) 12.

[2]   M. Mazloum-Ardakani, M. A. Sheikh-Mohseni, and A. Benvidi, Anal. Bioanal. Electrochem. 2 (2010) 155.

[3]   F. Gholamian, M. A. Sheikh-Mohseni, and H. Naeimi, Mater. Sci. Eng. C 32 (2012) 2344.

[4]   M. H. Maashhadizadeh, R. Refahati, and E. Amereh, Anal. Bioanal. Electrochem. 5 (2013) 270.

[5]   M. Mazloum-Ardakani, M. A. Sheikh-Mohseni, M. Abdollahi-Alibeik, and A. Benvidi, Analyst 137 (2012) 1950.

[6]   H. W. Chu, R. Thangamuthu, and S. M. Chen, Electroanalysis 19 (2007) 1944.

[7]   W. A. Banks, Brain Res. 899 (2001) 209.

[8]   J. Wang, R. P. Deo, P. Poulin, and M. Mangey, J. Am. Chem. Soc. 125 (2003) 14706.

[9]   S. Engelborghs, E. Vloeberghs, and N. L. Bastard, Neurochem. Int. 52 (2008) 1052.

[10]   Z. Lin, X. Wu, X. Lin, and Z. Xie, J. Chromatogr. A 1170 (2007) 118.

[11]   S. Wei, G. Song, and J. M. Li, J. Chromatogr. A 1098 (2005) 166.

[12]   P. Solich, C. K. Polydorou, M. A. Koupparis, and C. E. Efstathiou, J. Pharm. Biomed. Anal. 22 (2000) 781.

[13]   M. Mazloum-Ardakani, A. Talebi, H. Naeimi, and M. A. Sheikh-Mohseni, Anal. Methods 3 (2011) 2328.

[14]   Y. X. Sun, S. F. Wang, and X. H. Zhang, Sens. Actuators B 113 (2006) 156.

[15]   H. Jeong, H. Kim, and S. Jeon, Microchem. J. 78 (2004) 181.

[16]   Online available: http://www.drugs.com/acetaminophen.html.

[17]   F. F. Daly, J. S. Fountain, L. Murray, A. Graudins, and N. A. Buckley, Med. J. Aust. 188 (2008) 296.

[18]   A. M. Larson, J. Polson, and R. J. Fontana, Hepatology 42 (2005) 1364.

[19]   A. Bertolini, A. Ferrari, A. Ottani, S. Guerzoni, R. Tacchi, and S. Leone, CNS Drug Rev. 12 (2006) 250.

[20]   M. Mazloum-Ardakani, H. Beitollahi, M. A. Sheikh-Mohseni, H. Naeimi, and N. Taghavinia, Appl. Catal. A Gen. 378 (2010) 195.

[21]   H. Beitollahi, M. Mazloum-Ardakani, B. Ganjipour, and H. Naeimi, Biosens. Bioelectron. 24 (2008) 362.

[22]   R. S. Andulescu, S. Mirel, and R. Oprean, J. Pharm. Biomed. Anal. 23 (2000) 77.

[23]   N. Wangfuengkanagul, and O. Chailapakul, J. Pharm. Biomed. Anal. 28 (2002) 841.

[24]   M. Mazloum-Ardakani, M. A. Sheikh-Mohseni, M. Abdollahi-Alibeik, A. Benvidi, Sensor Actuat. B 171 (2012) 380.

[25] F. Ghorbani-Bidkorbeh, S. Shahrokhian, A. Mohammadi, and R. Dinarvand, Electrochim. Acta 55 (2010) 2752.

[26] Z. A. Alothman, N. Bukhari, S. M. Wabaidur, and S. Haider, Sens. Actuators B 146 (2010) 314.

[27] M. Mazloum-Ardakani, H. Beitollahi, M. A. Sheikh Mohseni, A. Benvidi, H. Naeimi, M. Nejati-Barzoki, and N. Taghavinia, Colloids Surf. B 76 (2010) 82.

[28] R. L. Blakley, The Biochemistry of Folic Acid and Related Pteridines, American Elsevier, New York (1969).

[29] M. Mazloum-Ardakani, M. A. Sheikh-Mohseni, H. Beitollahi, A. Benvidi, and H. Naeimi, Turk. J. Chem. 35 (2011) 573.

[30] M. Mazloum-Ardakani, M. A. Sheikh-Mohseni, and M. Abdollahi-Alibeik, J. Mol. Liq. 178 (2012) 63.

[31] Y. P. Sun, K. Fu, Y. Lin, and W. Huang, Acc. Chem. Res. 35 (2002) 1096.

[32] P. M. Ajayan, Chem. Rev. 99 (1999) 1787.

[33] J. P. Salvetat, J. M. Bonard, N. H. Thomson, A. J. Kulik, L. Forro, W. Benoit, and L. Zuppiroli, Appl. Phys. A 69 (1999) 255.

[34] M. Mazloum-Ardakani, M. A. Sheikh-Mohseni, In: M. Naraghi (Ed.), Carbon Nanotubes-Growth and Applications, InTech, Croatia, (2011).

[35] A. Salimi, R.G. Compton, and R. Hallaj, Anal. Biochem. 333 (2004) 49.

[36] M. Mazloum-Ardakani, M. A. Sheikh-Mohseni, and B. B. F. Mirjalili, Electroanalysis 25 (2013) 2021.

[37] C. Wang, Y. Mao, D. Wang, G. Yang, Q. Qu, and X. Hu, Bioelectrochem. 72 (2008) 107.

[38] M. Mazloum-Ardakani, A. Naser-Sadrabadi, M. A. Sheikh-Mohseni, H. Naeimi, A. Benvidi, and A. Khoshroo, J. Electroanal. Chem. 705 (2013) 75.

[39] H. Chen, and S. Dong, Biosens. Bioelectron. 22 (2007) 1811.

[40] A. J. Bard, and L. R. Faulkner, Electrochemical Methods fundamentals and applications, 2nd edition, Wiley, New York (2001).

[41] E. Laviron, J. Electroanal. Chem. 101 (1979) 19.

[42] M. Sharp, M. Petersson, and K. Edstrom, J. Electroanal. Chem. 95 (1979) 123.

[43] Z. Galus, Fundamentals of Electrochemical Analysis, Ellis Horwood, New York (1976).

[44] M. Mazloum-Ardakani, H. Beitollahi, M. K. Amini, F. Mirkhalaf, and M. Abdollahi-Alibeik, Anal. Methods 3 (2011) 673.

[45] E. Akyilmaza, M. Turemisa, and I. Yasa, Biosens. Bioelectron. 26 (2011) 2590.

[46] F. C. Moraes, D. L. C. Golinelli, L. H. Mascaro, and S. A. S. Machado, Sens. Actuators B 148 (2010) 492.

[47] M. Mazloum-Ardakani, H. Beitollahi, M. K. Amini, B. B. F. Mirjalili, and F. Mirkhalaf, J. Electronal. Chem. 651 (2011) 243.

[48] A. A. Ensafi, M. Taei, and T. Khaymian, Colloids. Surface B. 79 (2010) 480.

[49] M. Mazloum-Ardakani, N. Rajabzadeh, A. Dehghani-Firouzabadi, M. A. Sheikh-Mohseni, A. Benvidi, H. Naeimi, M. Akbari, and A. Karshenas, Anal. Method. 4 (2012) 2127.