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ORIGINAL PAPER

Electrochemical applications and computational studies on ephedrine drug

Voltammetric determination using a new pseudo-carbon paste electrode modified with poly(acrylic) acid

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Abstract A novel, simple, sensitive and highly selective pseudo-carbon paste electrode modified with poly(acrylic) acid (PCPE-PAA) was described to be useful for the electrochemical determination of ephedrine substance. The PCPE-PAA electrode was characterized using scanning electron microscope (SEM) and cyclic voltammetry. Cyclic voltammogram for ephedrine shows only one anodic oxidation peak at 1.15 V (vs. SCE) using Britton–Robinson buffer (pH 9). Theoretical calculations were performed using PM3 method to be helpful in studying the electrochemical behavior of ephedrine. The highest occupied orbitals (HOMO) of ephedrine and the lowest unoccupied orbitals (LUMOs) of its oxidation product (methcathinone) are mainly localized in the side chain of benzene ring. The values of HOMOs, LUMOs and atomic charges clearly indicate that the oxidation process occurs on the hydroxyl group of ephedrine forming ketone group, supporting the proposed electrochemical mechanism. Square wave voltammetry was used for the direct electrochemical determination of ephedrine. Ephedrine gives a linear range from 6×10^{-5} to 1×10^{-3} M with a correlation coefficient of 0.998 and a relative standard deviation of 2.165×10^{-7}. A lower detection limit of 3.5×10^{-7} M was obtained. The effect of some interferences such as ascorbic acid, uric acid, urea, glucose and glycine on the peak height of ephedrine was examined. The suggested method has been applied successfully for the direct electrochemical determination of ephedrine in urine and different pharmaceutical formulations.

Keywords Ephedrine · Square wave voltammetry · Poly (acrylic) acid · Carbon paste electrode · Urine

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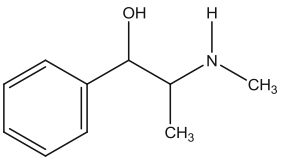
Introduction

Ephedrine, (1*R*, 2*S*)-2-(methylamino)-1-phenylpropan-1-ol, is a naturally occurring sympathomimetic drug derived from the botanical plant Ephedra. Its principal mechanism of action relies on its indirect action on the adrenergic receptor system. Ephedrine was used as a drug in therapeutic doses at levels of 15–20 mg in the treatment of asthma, allergic states, catalepsy and myasthenia gravis; to raise the arterial pressure; as nasal decongestive; as an antidote for poisoning by central nervous system depressants and in spinal anaesthesia [1].

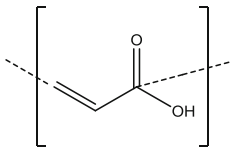
Ephedrine was included in the doping list published by the International Olympic Committee (IOC); the committee has adopted a urinary threshold concentration of 10.0 gL^{-1} above which is regarded positive [2]. Therefore, monitoring ephedrine levels is a very important task in both urine samples and pharmaceutical formulations. Different analytical methods have been introduced in the literature for the determination of ephedrine. These methods include spectroscopy [3–5], HPLC [6–11], GC [6], capillary electrophoresis (CE) [12–17] and electrochemical methods [18–26]. Spectroscopic methods, HPLC, GC and CE are complicated, expensive and time consuming, while the electrochemical methods have different advantages such as high sensitivity and selectivity with high speed, less cost, relative simplicity and low detection limit. Different types of working electrodes were used for

the electrochemical determination of ephedrine such as DME [26], Glassy carbon electrode [23] and carbon fiber electrode [19]. Modified electrodes were also used for the electrochemical determination of ephedrine such as polypyrrole-modified electrode [18]. Alternatively, chemically modified carbon paste electrodes based on different electroactive materials are manufactured to provide them with a functional and selective activity to the studied compounds. C_{18} bonded silica gel [25] and cobalt phthalocyanine [24] carbon paste electrodes were used for the electrochemical determination of ephedrine. Modification of carbon paste electrode modified with different electroactive materials has different advantages such as improving the selectivity and sensitivity as well as wide potential range, lower background current and inexpensiveness [27, 28]. The electrochemical determination of ephedrine is based on the electrochemical oxidation to methcathinone at the working electrode.

The main objectives of the present work are to prepare pseudo-carbon paste electrode modified with poly (acrylic) acid (PCPE-PAA) and to study the electrochemical behavior of ephedrine. The experimental results from cyclic voltammetry were compared with the theoretical calculations obtained by PM3 method. At the end, PCPE-PAA was used as an electrochemical sensor for the direct electrochemical determination of ephedrine. Measurements were conducted under various operating conditions using cyclic voltammetry and square wave voltammetric techniques.



Ephedrine



Poly(acrylic) acid (PAA)

Experimental

Chemicals and reagents

All chemicals used were of analytical grade and used without further purifications. Ephedrine HCl, uric acid, ascorbic acid, urea, glucose, glycine, graphite powder, paraffin wax and poly(acrylic) acid (PAA) (average MW 450000 $g\,mol^{-1}$) were obtained from Sigma-Aldrich company. H_3BO_3, H_3PO_4, CH_3COOH and NaOH were obtained from Merck company. Britton–Robinson buffer was prepared by mixing 0.04 M H_3BO_3, 0.04 M H_3PO_4 and 0.04 M CH_3COOH. Stock solution of 0.01 M ephedrine was freshly prepared daily in Britton–Robinson buffer. The desired pH was adjusted by the addition of 0.2 M NaOH. Double distilled water was used for the preparation of solutions.

Preparation of unmodified PCPE and its modification by poly(acrylic)

Unmodified PCPE was prepared by mixing 65% graphite powder and 35% paraffin wax. Paraffin wax was heated till melting and then mixed very well with graphite powder to produce a homogeneous paste. The resulted paste was then packed into the end of an insulin syringe (i.d. 2 mm). External electrical contact was established by forcing a copper wire down the syringe. The PCPE-PAA was prepared by mixing 60% graphite powder, 10% poly(acrylic) acid and 30% paraffin wax. The surface of the electrode was polished with a piece of weighting paper and then rinsed with distilled water thoroughly.

Electrochemical measurements

Cyclic voltammetry (CV) and square wave voltammetry were preformed using an Autolab potentiostat PGSTAT 302 N (Eco Chemie, Utrecht, The Netherlands) driven by the General Purpose Electrochemical Systems data processing software (GPES, software version 4.9, Eco Chemie). Electrochemical cell with three electrodes was used; unmodified PCPE or PCPE-PAA was acting as a working electrode, SCE as a reference electrode and platinum wire as a counter electrode. The pH values were measured using a Metrohom pH-meter with a combined glass electrode. Scanning electron microscopy (SEM; JEOL JSM-6390) was used to characterize the morphology of bare PCPE and PCPE-PAA.

Preparation of samples

Ephedrine in drug formulation samples

Ten tablets of ephedrine drug were weighted accurately and finely powdered in a mortar. Then, 0.2 g of the powder was weighted accurately and transferred to a 100-mL calibrated flask, which then was completed to the volume with the supporting electrolyte. Finally, the resulted solution was filtered to get the clear sample solution. For injection sample, the injection solution was directly diluted 1:10 by the supporting electrolyte.

Urine samples

For the determination of ephedrine in urine sample, 1.0 mL of human urine was mixed with 9.0 mL of Britton–Robinson buffer pH 9 without any treatments; the optimum conditions

were applied, and the voltammograms were recorded in the presence of different ephedrine concentrations.

Computational methods

Molecular modeling and quantum semi- empirical calculations were carried out using MP3 method. The geometry optimization was obtained by the application of the Polak–Ribiere algorithm with convergence limit of 0.01 kcal mol^{-1} and RMS gradient of 0.01 kcal mol^{-1}.

Results and discussion

Characterization of carbon paste electrode

Scanning electron microscopy (SEM) was used to characterize the morphology of pseudo-carbon paste electrode (PCPE) and carbon paste electrode modified with poly (acrylic) acid (PCPE-PAA). Figure 1 presents the SEM morphologies for the two types of electrodes. The SEM images of the bare PCPE (Fig. 1a) showed a microstructure with a discontinuous grain growth with a large unclear crystal structure. In addition, the surface structure of the bare PCPE shows that a very thin film of paraffin wax covers the graphite particles. Figure 1b shows the surface of PCPE-PAA which is relatively homogeneous and smoother than PCPE. This morphology is very much different from that of original surface, and the presence of PAA makes the electrode surface much smoother than PCPE surface. This smoothness in the electrode surface increases the conductivity on the surface of PCPE-PAA electrode.

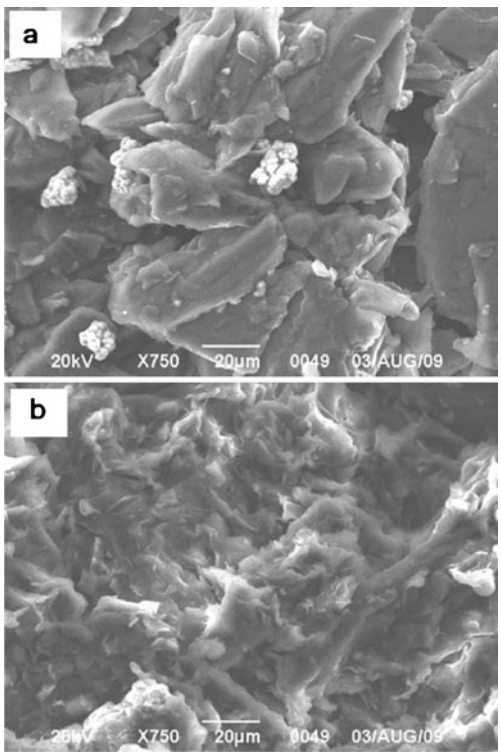


Fig. 1 SEM micrographs of **a** bare PCPE and **b** PCPE-PAA

Cyclic voltammetry of ephedrine

Cyclic voltammetry was used to study the electrochemical behavior of ephedrine at PCPE and PCPE-PAA, using a potential range from −0.6 to +1.3 V (vs. SCE) with a potential scan rate of 50 mV s^{-1}. Figure 2 shows the cyclic voltammograms of ephedrine using PCPE and PCPE-PAA in Britton–Robinson buffer. Figure 2a shows the cyclic voltammogram for PCPE in the absence of ephedrine, where no signals appeared. Figure 2b, c shows the resulted voltammograms for 2×10^{-3} M ephedrine using PCPE and PCPE-PAA, respectively. In case of PCPE, ephedrine shows only one broad irreversible oxidation wave with a peak potential of 0.97 V (vs. SCE), while in case of PCPE-PAA, a well-defied oxidation peak was observed at 1.15 V (vs. SCE); no cathodic peak appeared using both types of electrodes. Using PCPE-PAA, the oxidation peak current is much higher than that obtained in the case of carbon paste electrode. The enhancement of the peak current of ephedrine may be due to the electrocatalytic activity of PAA towards the oxidation of ephedrine. This might be due to the combination of two reasons. The first one may be the incorporation of PAA with a large surface area into the carbon paste, which increased the surface area of carbon paste electrode. The second reason may be the higher electrostatic interaction between ephedrine as a positively charged molecule [29] and the poly-anionic polymer PAA. This behavior is similar to that observed for the electrocatalytic oxidation of

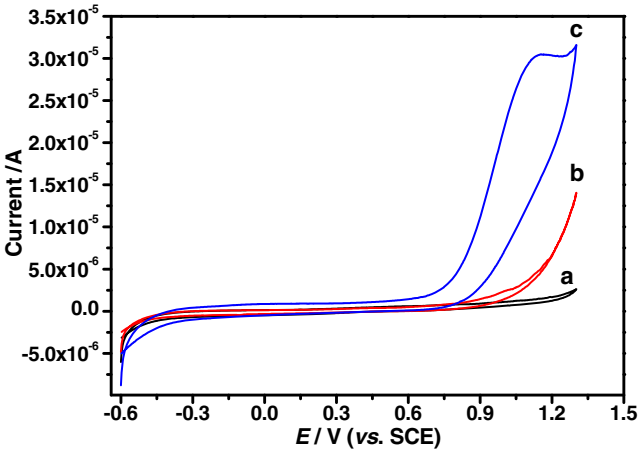


Fig. 2 Cyclic voltammetric response for a PCPE in absence of ephedrine in Britton–Robinson buffer, b 2 mM ephedrine PCPE and c PCPE-PAA with a scan rate of 50 mV s^{-1}

polyaniline at PAA film electrodes modified by platinum microelectrodes [30]. The mechanism of electrochemical oxidation of ephedrine can be represented by Scheme 1, in which ephedrine is oxidized to methcathinone.

Effect of supporting electrolyte and pH

Different types of supporting electrolytes were investigated to check the electrochemical behavior of ephedrine using PCPE-PAA by applying square wave voltammetric techniques, such as sodium phosphate buffer, sodium acetate buffer, borate buffer and Britton–Robinson buffer. The highest peak current and the best peak shape for ephedrine were observed using Britton–Robinson buffer. Therefore, Britton–Robinson buffer was selected for further studies.

The influence of pH on the oxidation peak current and peak potential of ephedrine using PCPE-PAA in Britton–Robinson buffer was investigated in different pH values ranging from 2.0 to 11.7, and the obtained result is represented in Fig. 3. The oxidation peak of ephedrine is dependent on the pH of Britton–Robinson buffer. The peak current of ephedrine increased with the increasing of pH value until it reached a maximum value at pH 9. At higher pH values, the peak current of ephedrine decreased. Therefore, Britton–Robinson buffer at pH 9 was chosen for the electrochemical determination of ephedrine.

Effect of potential scan rate

The effect of potential scan rate on the electrochemistry of 1.0 mM ephedrine was studied using PCPE-PAA in Britton–Robinson buffer at pH 9 using a potential scan rate from 10 to 300 mV s^{-1}. The oxidation peak currents increased with the increase in the scan rate values (Fig. 4a). The oxidation peak currents were proportional to the square root of the scan rate ($\nu^{1/2}$) (Fig. 4b), which indicates that the electron transfer reaction is diffusion controlled. The linear regression equation is I_p (A)=2.26×10^{-6}+3.17×10^{-6} V with a 0.996 correlation coefficient.

A linear relation between the peak potential (E_p) and log ν was obtained (Fig. 4c) using a potential scan rate from 10 to 100 mV s^{-1}. Such behavior reveals the irreversible nature of the electrochemical process for ephedrine [31]. The irreversible behavior for ephedrine can also be observed from

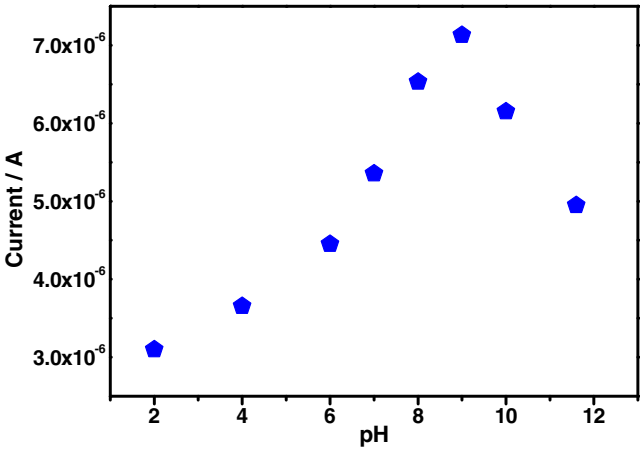


Fig. 3 Effect of pH on the peak height of 1.0 mM ephedrine in Britton–Robinson buffer, using 50 mV s^{-1} scan rate

the appearance of one oxidation peak in the anodic scan, and no reduction peaks were observed in the cathodic scan.

To get some information on the rate-determining step, the following equation was used [32]:

$$E_p = b/2 \log \nu + a \quad \text{where, } b = \frac{2.3RT}{(1-\alpha)n_a} \log \nu$$

where α is the transfer coefficient, n_a is the number of electrons transferred, ν is the potential scan rate, F is the Faraday's constant (96487 $Cmol^{-1}$), R is the rate gas constant (8.314 JK^{-1} mol^{-1}), T is the absolute temperature and b is the Tafel slope. Plotting the relation between the peak potential (E_p) and log ν for 1.0 mM ephedrine displayed a straight line (Fig. 4c). The linear regression equation was calculated as E_p (V)=0.068 log ν + 1.097 (r=0.999). The slope of the previous equation was found to be 0.068 V, so b=0.136 V. This slope indicates that a one-electron transfer process is the rate-determining step. Assuming that the number of transferred electrons in the rate-determining step equals one, a transfer coefficient (α = 0.56) is obtained. If we assumed two electrons in the rate-determining step, α should be 0.78, which is not a common value, because for most electrode processes α ranges from 0.7 to 0.3 [33].

Effect of square wave voltammetric parameters

The effect of different square wave voltammetric parameters was examined on the peak height of ephedrine as shown in Fig. 5. Figure 5a shows the influence of square wave

Scheme 1 The mechanism of electrochemical oxidation of ephedrine, in which ephedrine is oxidized to methcathinone

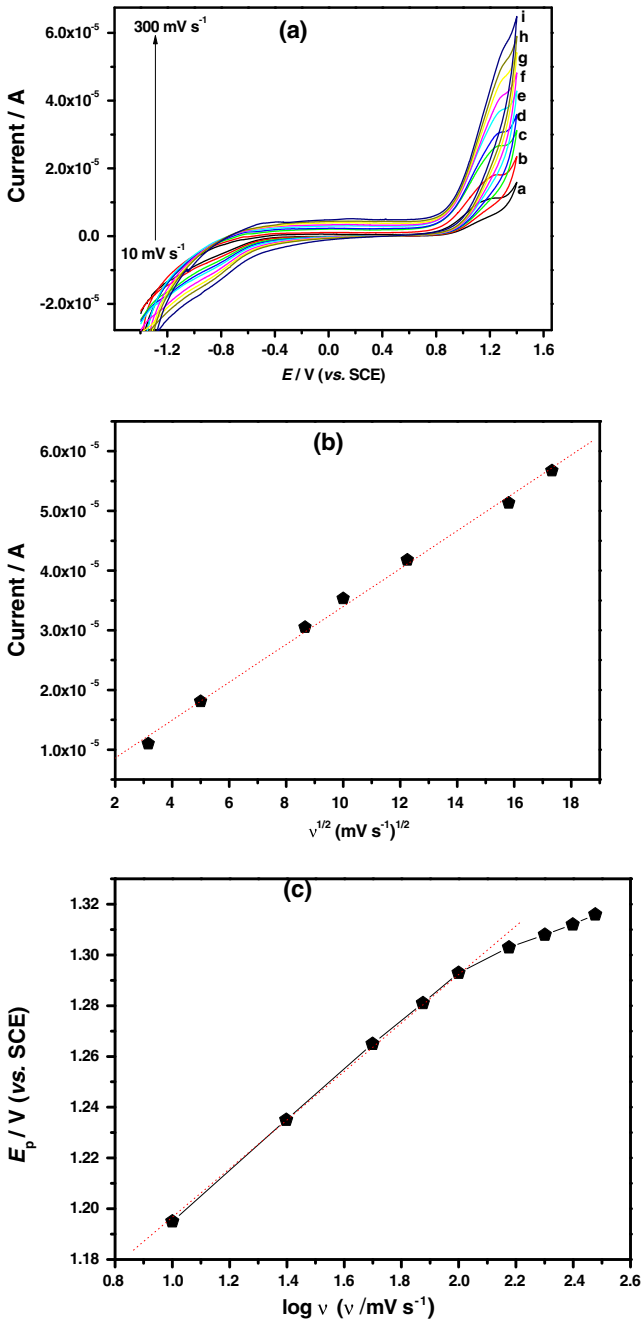


Fig. 4 **a** Cyclic voltammograms of 1.0 mM ephedrine at PCPE-PAA in Britton–Robinson buffer at various scan rates from 10 to 300 mV s^{-1}. **b** Plot of anodic peak current I_p of ephedrine vs. $\nu^{1/2}$. **c** Plot of peak current E_p vs. log ν

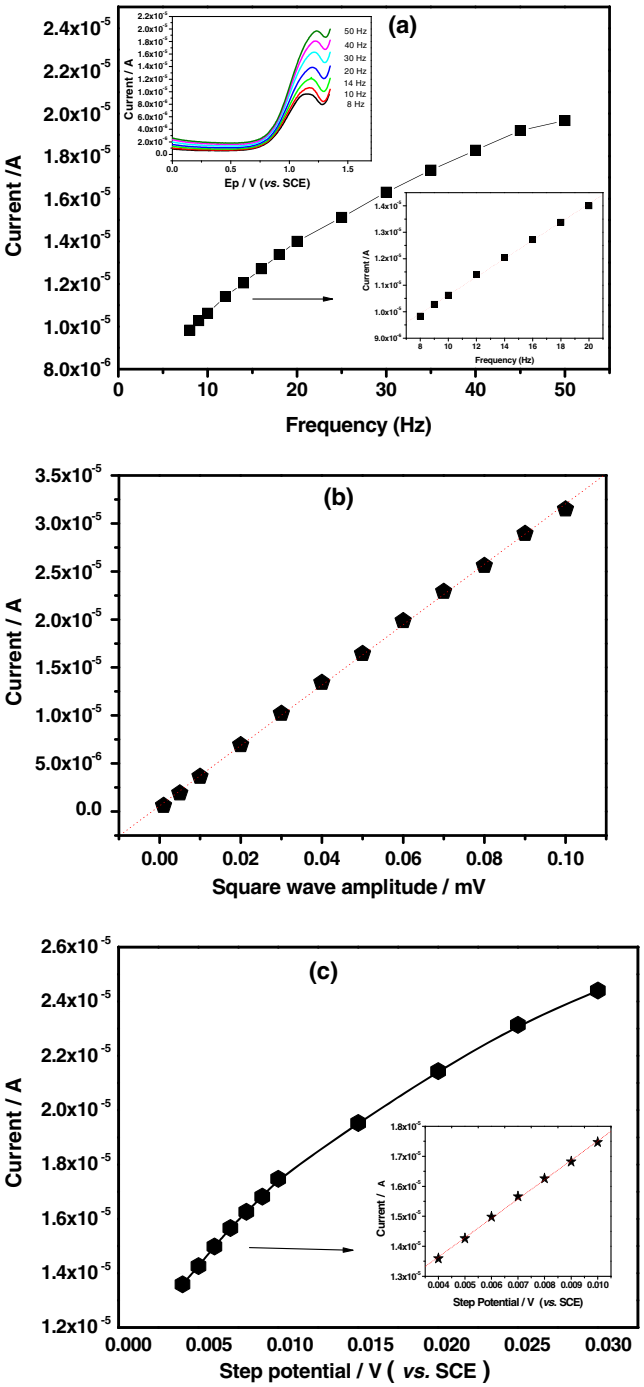


Fig. 5 **a** Square wave voltammetric peak current at different square wave frequencies from 8 to 50 Hz for 1.0 mM ephedrine with initial potential −1.4.1 V, final potential 1.3 V, square wave step potential 0.005 V and square wave amplitude 0.004 V. **b** Square wave voltammetric peak current at different square wave amplitudes from 1.0 to 100 mV for 1.0 mM ephedrine with initial potential −1.4.1 V, final potential 1.3 V, step potential 0.002 V, 20 Hz square wave frequency and 120 s accumulation time. **c** Square wave voltammetric peak current at different square wave step potentials from 4 to 30 mV for 1.0 mM ephedrine with initial potential −1.4 V, final potential 1.3 V, square wave amplitude 100 mV and 20 Hz square wave frequency

frequency on the peak current of 1.0 mM ephedrine using different values from 8 to 50 Hz. By increasing the square wave frequency, the peak current increased. A linear part was observed from 8 to 20 Hz square wave frequency. Thus, for further study the 20 Hz square wave frequency was selected for further investigations. The effect of square wave pulse amplitude on the peak current of 1.0 mM ephedrine using 20 Hz square wave frequency is shown in Fig. 5b. The

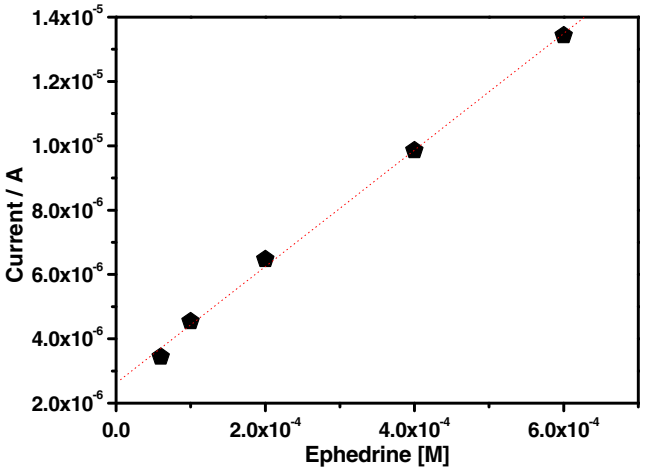


Fig. 6 Calibration plots for different ephedrine concentrations from 6×10^{-5} to 1×10^{-3} M with the regression data obtained at the following optimum conditions: −1.4 V accumulation potential, final potential 1.3 V, square wave amplitude 100 mV, 20 Hz square wave frequency and 10 mV square wave step potential

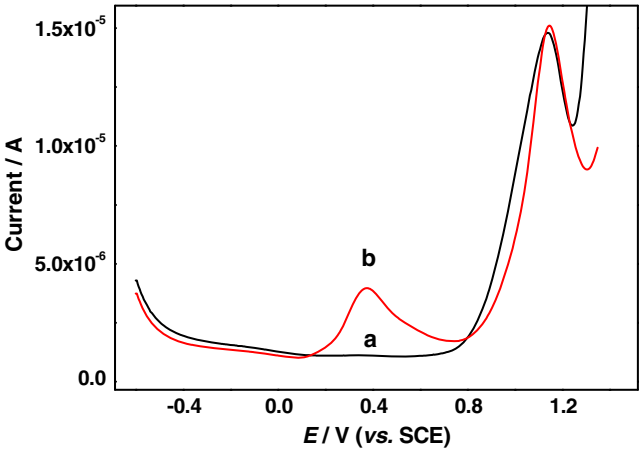


Fig. 7 Effect of uric acid on the peak current of ephedrine: **a** 1×10^{-3} M ephedrine and **b** 1×10^{-3} M ephedrine 6×10^{-4} M and uric acid; other conditions as in Fig. 6

pulse amplitude ranged from 1.0 to 100 mV. The peak current increased linearly from 1.0 to 100 mV with 0.999 correlation coefficient and 9.919×10^{-7} standard deviation. Therefore, 100 mV will be the optimum square wave pulse amplitude height and will be used in the next work.

The last square wave parameter examined was the step potential. The effect of step potential (4–30 mV) on the peak height of 1.0 mM ephedrine is depicted using 20 Hz square wave frequency and 100 mV square wave pulse amplitude and the other experimental parameters as shown in Fig. 5b. As the step potential increases, the peak height increases linearly up to 10 mV; after that the increase in the peak height is not pronounced (Fig. 5c). Therefore, step potential with 10 mV was selected for further studies.

Calibration curve and detection limit

To examine the readability of the prepared electrode under investigation, the following optimum conditions were used for the square wave determination of ephedrine: 0.1 M Britton–Robinson buffer pH 9, 20 Hz square wave frequency, 100 mV square wave pulse amplitude and 10 mV step potential. Ephedrine showed a linear range from 6×10^{-5} to 1×10^{-3} M (Fig. 6) with a correlation coefficient of 0.998 and a relative standard deviation (RSD) of 2.165×10^{-7}. The lower detection limit for ephedrine was calculated based on three signal to noise ratios, and it was found to be 3.5×10^{-7} M. The obtained value for lower detection limit in this method was compared with the values from the different methods sited in the literature, and the data is given in Table 1.

Table 1 Detection limits (LOD) of ephedrine using the proposed method and the methods from literature

Technique	LOD	Reference
Square wave voltammetry	3.5×10^{-7} M	The present work
Cyclic voltammetry	0.5 mM	20
Flow injection-pulse amperometric detection	0.8 μM	26
Differential pulse voltammetry	2 μg/mL	25
Linear sweep voltammetry	270 μg/mL	28
Differential pulse voltammetry	7 μg/mL	28

Reproducibility

To examine the readability of the prepared electrode under investigation, the produced peak current of 1×10^{-4} M ephedrine using the optimum conditions mentioned previously was examined by successive ten measurements. The RSD was calculated, and it was found to be 1.26%; this value indicates that this method gives a good reproducibility for the obtained results.

Table 2 Determination of ephedrine in synthetic samples (water and urine) by the proposed method (n=5)

Concentration added (M)	Water samples Recovery (%)	Urine samples Recovery (%)
2×10^{-4}	106	98.5
4×10^{-4}	104.3	107.5
6×10^{-4}	97.83	102.2
8×10^{-4}	96	98.1
1×10^{-3}	92.7	95.1
2×10^{-2}	92.1	93.3
4×10^{-2}	-91.6	91.3
6×10^{-2}	90.7	89.6

Table 3 Determination of ephedrine in pharmaceutical formulations: tablet 50 mg and injection solution 30 mg/mL (n=5)

Sample	Labeled (mg)	Obtained (mg)	Recovery (%)
Tablet	50	47.3±0.2	94.6
Injection solution	30	30.03±0.1	101.1

Interferences

The effect of uric acid, ascorbic acid, urea, glucose and glycine as the most interfering substances in the electrochemical determination of ephedrine was examined. Uric acid shows an oxidation peak at 0.37 V (vs. SCE), and this peak is completely separated from the oxidation peak of ephedrine as shown in Fig. 7. Addition of different uric acid concentrations ranging from 2×10^{-4} to 1×10^{-3} M, to 1×10^{-3} M ephedrine has a very small effect on the peak signal of ephedrine. Addition of 2×10^{-4}, 4×10^{-4}, 6×10^{-4}, 8×10^{-4} and 1×10^{-3} M uric acid reduced the peak current of 1×10^{-3} M ephedrine by 3.6, 4.1, 1.2, 4.45 and 1.5%, respectively. The effect of ascorbic acid on the peak current of ephedrine was also examined. Ascorbic acid shows one anodic oxidation peak at 0.285 V (vs. SCE) under the same conditions mentioned before. The influence of ascorbic acid was examined over a concentration range from 1×10^{-5} to 1×10^{-3} M in the presence of 1×10^{-3} M ephedrine, where no marked effect on the peak current was observed. Addition of different concentrations (1×10^{-5} to 1×10^{-3} M) from urea, glucose or glycine did not show any effect on the peak current of 1×10^{-3} M ephedrine.

Table 4 The atomic charges for the optimized ephedrine by PM3 method

Atom	Charge
O_{11}	−0.235
C_{10}	+0.065
N_8	−0.004
C_1	−0.100
C_2	−0.129
C_3	−0.098
C_4	−0.101
C_5	−0.100
C_6	−0.102
C_7	−0.300
C_9	−0.104
C_{12}	−0.067

Analytical applications

In order to test the validity of the prepared PCPE-PAA, the proposed method was applied for the electrochemical determination of ephedrine in different samples such as human urine and pharmaceutical formulations. Using the optimum conditions and calibration curve (analytical equation: y= $2.62\times10^{-6}+0.018x$), the obtained results are represented in Table 2. As shown in this table, the concentrations are added to synthetic samples (water and urine). The recovery ranges between 90.7 and 106% for water, and 89.6 and 107.5% for urine samples. The proposed method was also applied for the determination of ephedrine in two different pharmaceutical formulations (tablet and injection solution). Table 3

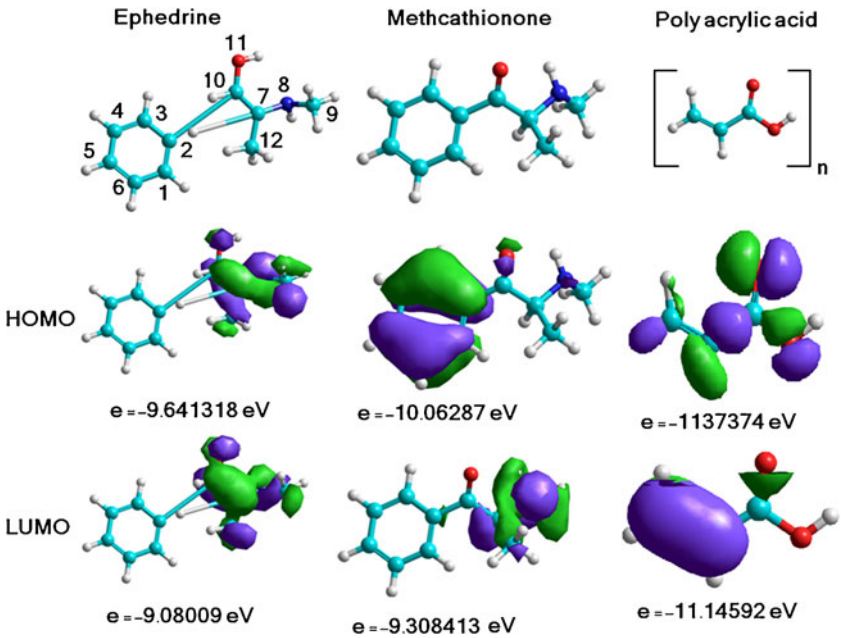


Fig. 8 Ball and stick model for the optimized geometry and the electronic density in the HOMOs and LUMOs obtained from semi-empirical PM3 for ephedrine, methcathinone and poly(acrylic) acid

collects the results obtained in the present study for ephedrine pharmaceutical formulations.

Computational studies

In order to characterize redox orbitals for ephedrine and to confirm the results obtained from the cyclic voltammetric experiments, quantum chemical calculations were performed. The optimized structure for ephedrine was obtained through molecular mechanics calculation by applying semi-empirical PM3 method. Figure 8 shows the ball and stick model for the optimized geometries of ephedrine, methcathinone and PAA. The total energy for ephedrine (−43166.5 kcal mol^{-1}) was found to be much higher in their electronegativity than the total energy calculated for PAA (−23161.8 kcal mol^{-1}). This higher electronegative gap between ephedrine and PAA increases the possibility of transformation of electrons from ephedrine to PAA, and this increases in the catalytic oxidation of ephedrine related to the presence of PAA. The energy values for the highest energy occupied orbital (HOMO) and the lowest energy unoccupied orbital (LUMO), and their energy gaps, reflect the chemical activity of the molecules. HOMO represents the ability of the molecule to donate electrons (oxidation), whereas LUMO represents the ability of the molecule to obtain electrons (reduction). The electronic density of HOMOs for ephedrine (Fig. 8) is mainly located in the side chain of benzene ring indicating that the side chain is the active site in ephedrine and responsible for losses of electrons which lead to the oxidation of ephedrine. In the other side, the electronic density for methcathinone, the LUMOs are located in the side chain of benzene ring (Fig. 8), which indicates its ability to accept electrons and easily formed from the oxidation of ephedrine. For PAA, the electronic density of LUMO is located in C=C bond (Fig. 8), which indicates that the C=C bond has the ability to accept electrons and increase the catalytic oxidation of ephedrine.

The energy gap between LUMO of methcathinone (−9.308 eV) and HOMO of ephedrine (−9.641 eV) is +0.333 eV; this lower energy gap makes the oxidation of ephedrine to methcathinone easy. On the other hand, the energy gap between LUMO of ephedrine (−9.08 eV) and HOMO of methcathinone (−10.063 eV) is +0.983 eV; this relatively high-energy gap makes the reduction of methcathinone to ephedrine more difficult.

Therefore, electrocatalytic oxidation of ephedrine increases in the presence of PAA, as shown from cyclic voltammetry. By applying a positive potential on the working electrode in the electrooxidation process of ephedrine, the atoms with higher negative values could be the most adsorbed sites on the PCPE-PAA surfaces. The semi-empirical method with PM3 was applied to calculate the atomic charges of ephedrine in order to predict the centers which are responsible for donating or withdrawing electron sites. Table 4 gives the atomic charges of ephedrine, where the higher negative charge lies on the oxygen atom of the hydroxyl group (−0.235). The carbon atoms of the aromatic ring and the other carbon atoms have negative values less than that of the oxygen atom, except the carbon atom bonded to hydroxyl group, which has a positive charge. The values of HOMOs, LUMOs and atomic charges clearly indicate that the oxidation process occurs easily on the hydroxyl group of ephedrine forming ketone group, which supports the proposed electrochemical mechanism presented in Scheme 1. This leads one to predict that ephedrine can be easily oxidized, which confirms the electrochemical oxidation of ephedrine at the PCPE-PAA as mentioned by the pervious mechanism from cyclic voltammetric techniques.

Conclusions

1- Carbon paste electrode modified by poly(acrylic) acid (PCPE-PAA) was prepared and characterized using SEM and CV.
2- The electrochemical behavior of ephedrine was investigated PCPE-PAA, where ephedrine showed one oxidation peak at PCPE-PAA due to the oxidation of ephedrine. The PCPE-PAA showed good electrocatalytic activity towards the oxidation of ephedrine.
3- The electrochemical oxidation of ephedrine was confirmed by chemical calculations using PM3 method.
4- The prepared electrode showed also a good sensitivity and selectivity for the direct electrochemical determination of ephedrine using square wave voltammetry.
5- PCPE-PAA was used for the voltammetric determination of ephedrine in human urine and pharmaceutical formulations.

References

1. Goodman & Gilman's (1996) The pharmacological basis of therapeutics. McGraw-Hill, New York
2. http://www.olympic.org/Documents/Fight_against_doping/Rules_and_regulations/WADA_Prohibited_List_2010.pdf. Accessed 14 May 2011
3. Khalil S (1999) J Pharm Biomed Anal 21:697–702
4. Dijiba YK, Zhang A, Niemczyk TM (2005) Int J Pharm 289:39–49
5. Ulu ST (2006) J AOAC Int 89:1263–1267
6. Marchei E, Pellegrini M, Pacifici R, Zuccaro P, Pichini S (2006) J Pharm Biomed Anal 41:1633–1641
7. Li LJ, Li SG, Li HY, Cai Z, Cheng H (2009) Chin Chem Lett 20:84–87
8. Wang W, Li C, Li Y, Hu Z, Chen X (2006) J Chromatogr A 1102:273–279
9. Entürk Z, Erk N, Ozkan SA, Akay C, Lu EC (2002) J Pharm Biomed Anal 29:291–298

10. Aymard G, Labarthe B, Warot D, Berlin I, Diquet B (2000) J Chromatogr B: Biomed Sci Appl 744:25–31
11. Okamura N, Miki H, Harada T, Yamashita S, Masaoka Y, Nakamoto Y, Tsuguma M, Yoshitomi H, Yagi A (1999) J Pharm Biomed Anal 20:363–372
12. Phinney KW, Ihara T, Sander LC (2005) J Chromatogr A 1077:90–97
13. Gomez MR, Sombra L, Olsina RA, Martínez LD, Silva MF (2005) Il Farmaco 60:85–90
14. Mateus-Avois L, Mangin P, Saugy M (2003) J Chromatogr B 791:203–216
15. Amin A, Barclay V, Rundlof T, Jonsson S, Karlsson A, Arvidsson T (2006) Chromatographia 63:143–148
16. Zhou L, Zhou X, Luo Z, Wang W, Yan N, Hu Z (2008) J Chromatogr A 1190:383–389
17. Zhang J, Xie J, Chen X, Hu Z (2003) Analyst 128:369–372
18. Mazzotta E, Picca RA, Malitesta C, Piletsky SA, Piletska EV (2008) Biosens Bioelectron 23:1152–1156
19. Platts M, Smith RB, Mould N, Davis J (2006) Electrochem Commun 8:633–637
20. Nikolelis DP, Raftopoulou G, Siontorou CG (2005) Electroanalysis 17:18701877
21. Nikolelis DP, Petropoulou SE, Theoharis G (2002) Electrochim Acta 47:457–467
22. Nikolelis DP, Petropoulou SE (2002) Biochim Biophys Acta (BBA) – Biomembranes 1558:238–245
23. Chicharro M, Zapardiel A, Bermejo E, Perez JA, Hernández L (1993) Anal Chim Acta 273:361–368
24. Cookeas EG, Efstathiou CE (2000) Analyst 125:1147–1150
25. Chicharro M, Zapardiel A, Bermejo E, Perez JA, Hernandez L (1994) Anal Lett 27:1809–1831
26. Hernandez L, Zapardiel A, Bermejo E, Perez JA, Chicharro M, Carijo MJ (1997) Electroanalysis 9:1214–1218
27. Mersal GAM, Arida HA (2011) Int J Electrochem Sci 6:1116–1126
28. Mersal GAM, Ibrahim MM (2011) Int J Electrochem Sci 6:761–777
29. Bandopadhyay RC (2006) Elucidation of the number of interaction sites between metoclopramide hydrochloride and ephedrine hydrochloride on the veegum surface. ProQuest Information and Learning Company Pag 114–115
30. Cai LT, Chen HY (1998) J Appl Electrochem 28:161–166
31. Zhang Z, Wang E (2000) Electrochemical principles and methods. Science, Beijing
32. Harison JA (1970) Khan ZA Electroanal Chem 28:131–138
33. Bard AJ, Faulkner LR (1980) Electrochemical methods fundamentals and applications. Wiley, New York