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Article

A voltammetric sensor with a multiwall carbon nanotube paste electrode and naphthol green as a mediator for the determination of *N*-actylcysteine in the presence of tryptophan

Mohsen Keyvanfar^{a,*}, Maryam Tahmasbi^b, Hassan Karimi-Maleh^{c,#}, Khadijeh Alizad^a^a Department of chemistry, Majlesi Branch, Islamic Azad University, Isfahan, Iran^b Department of chemistry, Shahreza Branch, Islamic Azad University, Shahreza, Iran^c Department of Chemistry, Graduate University of Advanced Technology, Kerman, Iran

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ABSTRACT

A multiwall carbon nanotube modified electrode prepared by incorporating multiwall carbon nanotubes in the electrode of a sensor and naphthol green as a homogeneous mediator was used as a voltammetric sensor for the determination of *N*-actylcysteine (*N*-AC) in the presence of tryptophan (Trp). The voltammograms of differential pulse voltammetry of *N*-AC in a mixture with Trp were separated from each other by a potential difference of 200 mV, which allowed the determination of both *N*-AC and Trp simultaneously. Under the optimum conditions, the electrocatalytic currents increased linearly with *N*-AC concentration in the range of 0.25–400 $\mu\text{mol/L}$ (two linear segments with different slopes). The detection limit for *N*-AC was 0.08 $\mu\text{mol/L}$. The kinetic parameters of the system were determined using electrochemical methods. The method was applied for the determination of *N*-AC in drug and urine samples.

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1. Introduction

Nano-materials, especially carbon nanotubes, are now used extensively in the fabrication of new nanostructured electrochemical sensors [1–5]. Carbon nanotube modified electrodes have many advantages over other modified carbon electrodes such as their small size, high electrical and thermal conductivity, high chemical stability, high mechanical strength, and high specific surface area, which make them very promising candidates in a wide range of applications [6–10].

N-Acetylcysteine (*N*-AC) is a therapeutic drug that is frequently used as a mucolytic agent [11,12] and as an agent for the treatment of acetaminophen hepatotoxicity [13]. Recently, its antioxidant/radical-scavenging activity [14,15] has been the

subject of considerable attention for extending its therapeutic applications. *N*-AC is a small molecule containing a thiol group. It has antioxidant properties and is freely filterable with ready access to intracellular compartments [16]. The many pharmacological applications of *N*-AC are due mainly to the chemical properties of its cysteinyl thiol group and the ability of reduced thiol groups to scavenge oxygen free radicals [17]. Due to these properties, *N*-AC is widely used in clinical practice as an antioxidant. The determination of *N*-AC concentration has been performed by methods such as chromatography [18–20], spectrophotometry [21–24], fluorimetry [25], flow injection [26], and electrochemical methods [27–29].

Tryptophan (Trp) is an essential amino acid in the human body. It is an essential constituent of proteins and is indispen-

* Corresponding author. Tel: +98-913-1009952; Fax: +98-311-6732054; E-mail: keyvan45638@yahoo.com

Corresponding author. Tel: +98-911-2540112; Fax: +98-341-2121018; E-mail: h.karimi.maleh@gmail.com

sable for establishing and maintaining a nitrogen balance [30]. Trp is occasionally added to dietary food products and pharmaceutical formulations to supplement a diet that is deficient in vegetables. This compound is also a precursor for serotonin, melatonin, and niacin. It has been implicated as a possible cause of schizophrenia in people who cannot metabolize it properly. When improperly metabolized, Trp creates a waste product in the brain that is toxic, and this causes hallucinations and delusions [31]. Thus, the rapid and sensitive determination of Trp concentration in biological samples and food products is of great interest in life science research [32]. Numerous methods have been reported for the determination of Trp concentration in pharmaceutical and biological samples. These methods include high performance liquid chromatography [33–36], capillary electrophoresis [37–39], fluorometric methods [40], chemiluminescence [41], spectrometric analysis [42], and electrochemical methods [43,44]. In comparison to the other methods, electrochemical methods for pharmaceutical, environmental, and biological compounds analysis have attracted more attention in the past two decades because of their sensitivity, accuracy, lower cost, high dynamic range, and simplicity [45–54].

N-AC is an active molecule related to natural amino acids that is in contrast to the protein-forming amino acids (such as tryptophan). Therefore, the determination of its concentration and that of Trp is important. On other hand, *N*-AC and Trp have almost the same oxidation overpotential at the surface of unmodified electrodes, and a mixture sample cannot be analyzed using this kind of electrodes. Measuring both *N*-AC and Trp concentrations together will be a big step in the right direction towards achieving an integrated therapeutic benefit. In the present work, we describe the preparation and use of a multi-wall carbon nanotube paste electrode (MWCNTPE) with naphthol green as a homogeneous mediator as a new sensor for the electrocatalysis and determination of *N*-AC concentration in an aqueous buffer solution. We then evaluated the analytical performance of this modified electrode in the quantification of *N*-AC concentration in the presence of Trp.

2. Experimental

2.1. Reagents

All chemicals used were analytical reagent grade purchased from Merck (Darmstadt, Germany) unless otherwise stated. Doubly distilled water was used throughout. *N*-AC was obtained from Merck and Trp from Fluka, and they were used as received.

A 1.0×10^{-3} mol/L *N*-AC solution was prepared daily by dissolving 0.016 g *N*-AC (>99%) in water. The solution was diluted to 100 mL with water in a 100 mL volumetric flask. The solution was kept in a refrigerator at 4 °C in the dark. More dilute solutions were prepared by serial dilution with water.

A 1.0×10^{-3} mol/L Trp solution was prepared daily by dissolving 0.024 g Trp in a buffer solution of pH 7.0 in a 100 mL volumetric flask, which was ultrasonicated for several minutes. More dilute solutions were prepared by serial dilutions with

water. Phosphate buffer (sodium dihydrogen phosphate and disodium monohydrogen phosphate plus sodium hydroxide, 0.1 mol/L) solutions with different pH values were used.

2.2. Preparation of the electrode

Spectrally pure graphite powder (particle size < 50 μm) from Merck and multiwall carbon nanotubes (> 90%, MWCNTs, $d \times l = (100\text{--}70 \text{ nm}) \times (5\text{--}9 \text{ μm})$) from Fluka were used as the substrate for the preparation of the carbon paste electrode. High viscosity paraffin ($d = 0.88 \text{ kg/L}$) from Merck was used as the paste liquid for the preparation of the paste electrodes.

Graphite powder (0.900 g) was dissolved in diethyl ether and hand mixed with 0.100 g carbon nanotubes in a mortar and pestle. The solvent was evaporated by stirring. A syringe was used to add paraffin to the mixture, which was mixed well for 40 min until a uniformly wetted paste was obtained. The paste was then packed into a glass tube. Electrical contact was made by pushing a copper wire down the glass tube into the back of the mixture. 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.

2.3. Voltammetric measurements

All the voltammetric measurements were performed using an Autolab PGSTAT 302N potentiostat/galvanostat (Utrecht, The Netherlands) connected to a three-electrode cell, Metrohm (Herisau, Switzerland) Model 663 VA stand linked to a computer with the Autolab software. A platinum wire was used as the auxiliary electrode. MWCNTPE and Ag/AgCl/KCl_{sat} were used as the working and reference electrodes, respectively. The electrode prepared with carbon nanotubes was characterized by scanning electron microscopy (SEM, Seron Tech. AIS 2100). A digital pH/mV meter (Metrohm model 710) was applied for pH measurements.

2.4. Determination of *N*-AC samples

Seven *N*-AC tablets (labeled 600 mg) were ground. The tablet solution was prepared by dissolving 600 mg of the powder in 100 mL water by ultrasonication. Then, 0.1 mL of the solution was diluted with the buffer solution (pH 7.0) in a 10 mL volumetric flask. The *N*-AC content was analyzed by the proposed method using the standard addition method.

Urine samples were stored in a refrigerator immediately after collection. Ten milliliters of the sample was centrifuged for 20 min at 2500 r/min. The supernatant was filtered out using a 0.45 μm filter and then 8.0 mL of the resulting solution mixed with 2.0 mL of the buffer (pH 7.0). The solution was transferred into the voltammetric cell for analysis without further pretreatment. The standard addition method was used for the determination of *N*-AC in these samples.

3. Results and discussion

3.1. SEM characterization

Fig. 1. SEM images of CPE (a) and MWCNTPE (b).

Figure 1 shows SEM images of the MWCNTPE and carbon paste electrode (CPE). At the surface of CPE, layers of irregular flakes of graphite powder were present and isolated from one another. After MWCNTs were added to the carbon paste, the MWCNTs were distributed on the surface of the electrode with a special three-dimensional structure, indicating that the MWCNTs were successfully incorporated on the MWCNTPE.

3.2. Electrochemistry of naphthol green

As naphthol green is soluble in an aqueous solution, it can be easily used as a homogeneous mediator for the determination of electroactive compounds. Initially, the electrochemical behavior of naphthol green at the surface of MWCNTPE was investigated. The cyclic voltammograms of the modified electrode in 0.1 mol/L phosphate buffers (pH 7.0) are shown in Fig. 2(a). The cyclic voltammogram exhibits an anodic peak at the forward scan of the potential related to the oxidation of the naphthol green_(Red) to the naphthol green_(Ox) form. In the reverse scan of the potential, a cathodic peak appeared, which was related to the reduction of the naphthol green_(Ox) form to the naphthol green_(Red). A pair of quasi-reversible peaks were observed at $E_{pa} = 0.597$ V and $E_{pc} = 0.421$ V versus Ag/AgCl. The half-wave potential ($E_{1/2}$) was 0.510 V versus Ag/AgCl, and ΔE_p ($E_{pa} - E_{pc}$) was 0.176 V. The electrode process was quasi-reversible with ΔE_p larger than the expected value ($59/n$ mV) for a reversible system. The plot of the anodic peak current was linearly dependent on $\nu^{1/2}$ for all scan rates (Fig. 2(b)). This behavior indicated that the redox process was diffusion controlled. Also, the result showed that the redox process of naphthol green was independent on the pH of the aqueous solution. So, Fe^{2+}/Fe^{3+} electrooxidation occurred as a potential phenomenon at the surface of the electrode.

3.3. Catalytic effect

In order to optimize the electrocatalytic response of the sensor to *N*-AC oxidation, we investigated the effect of pH on the electrocatalytic oxidation of *N*-AC in 0.1 mol/L buffer solutions with various pH values ($5.0 < \text{pH} < 9.0$) at the modified electrode using cyclic voltammetry. It is well known that the electrochemical behavior of *N*-AC is dependent on the pH value of the aqueous solution, while the electrochemical property of

the naphthol green redox couple is nearly independent of the solution pH. As the result showed, the maximum electrocatalytic current was obtained at pH 7.0. Therefore, pH 7.0 was chosen as the optimum pH for the determination of *N*-AC at the modified electrode.

Figure 3 depicts the cyclic voltammogram responses for the electrochemical oxidation of 100 $\mu\text{mol/L}$ *N*-AC at MWCNTPE in the presence of the mediator (curve c), at CPE in the presence of the mediator (curve b), and at MWCNTPE and CPE without the mediator (curves d and e). While the anodic peak potential for *N*-AC oxidation at the MWCNTPE and CPE in the presence of mediator was 595 mV, the corresponding potentials at the MWCNTPE and CPE without the mediator were 600 and 650

Fig. 2. (a) Cyclic voltammograms of 500 $\mu\text{mol/L}$ naphthol green at scan rates of (1) 5, (2) 10, (3) 15, (4) 20, (5) 30, (6) 60, (7) 150, (8) 200, (9) 400, and (10) 600 mV/s in 0.1 mol/L PBS (pH 7.0). (b) Plot of I_{pa} versus $\nu^{1/2}$ for the oxidation of naphthol green at the surface of MWCNTPE.

Fig. 3. Cyclic voltammograms of 500 $\mu\text{mol/L}$ naphthol green at the surface of MWCNTPE in 0.1 mol/L PBS (pH 7.0) at a scan rate of 20 mV/s in the absence (a) and in the presence of 100 $\mu\text{mol/L}$ *N*-AC (c). (b) as (c) for the carbon paste electrode. (d) as (c) and (e) as (b) for the unmodified electrode without naphthol green.

mV, respectively. These results indicated that the peak potential for *N*-AC oxidation at the MWCNTPE and CPE in the presence of the mediator were shifted by 55 and 105 mV towards negative values compared to MWCNTPE and CPE (without the mediator). However, MWCNTPE with the mediator showed a much higher anodic peak current for the oxidation of *N*-AC as compared to CPE with the mediator, indicating that the combination of CNTs and the mediator (naphthol green) significantly improved the performance of the electrode for *N*-AC oxidation. In fact, MWCNTPE with the mediator in the solution in the absence of *N*-AC exhibited a well-behaved redox reaction (Fig. 3, curve a) in 0.1 mol/L PBS (pH 7.0). However, there was a drastic increase in the anodic peak current in the presence of 100 $\mu\text{mol/L}$ *N*-AC (curve b or c), which was due to the strong electrocatalytic action of the mediator on this compound (Scheme 1) [55–58].

The effect of scan rate on the electrocatalytic oxidation of 200 $\mu\text{mol/L}$ *N*-AC at the MWCNTPE was investigated by cyclic voltammetry (Fig. 4(a)) in the presence of naphthol green. The

Scheme 1. Electrocatalytic mechanism for the determination of *N*-AC at the surface of MWCNTPE.

oxidation peak potential shifted towards a more positive potential with increasing scan rates, confirming the kinetic regime of the electrochemical reaction. Also, a plot of peak height (I_p) against square root of scan rate ($v^{1/2}$) in the range of 2–35 mV/s was constructed, which was found to be linear. It suggested that at a sufficient overpotential, the process was diffusion controlled rather than reaction controlled (Fig. 4(b)).

To obtain information about the rate determining step, the Tafel plot was drawn. This was derived from points in the Tafel region of the cyclic voltammogram (not shown). The slope of the Tafel plot was equal to $n(1-\alpha)F/2.3RT$, which was 7.8824 V/decade. Therefore, we obtained the value of $\alpha = 0.53$.

The rate constant for the chemical reaction between *N*-AC and the mediator at the surface of MWCNTPE, k_h , was evaluated by chronoamperometry using the method of Galus [59]:

$$I_c/I_L = \pi^{1/2} \gamma^{1/2} = \pi^{1/2} (k_h C_b t)^{1/2} \quad (1)$$

where I_c is the catalytic current of *N*-AC at MWCNTPE in the presence of mediator, I_L is the limited current in the absence of *N*-AC, and t is the time (s). This equation can be used to calculate the rate constant of the catalytic process k_h . Based on the slope of the I_c/I_L versus $t^{1/2}$ plot, k_h was obtained for the *N*-AC concentration. From the slopes, the average value of k_h was $4.674 \times 10^3 \text{ M}^{-1} \text{ s}^{-1}$. This large value of k_h explained the sharp feature of the catalytic peak observed for the catalytic oxidation of *N*-AC at the surface of MWCNTPE in the presence of the me-

Fig. 4. (a) Cyclic voltammograms of 200 $\mu\text{mol/L}$ *N*-AC in the presence 500 $\mu\text{mol/L}$ naphthol green at scan rates of (1) 2, (2) 5, (3) 10, (4) 15, (5) 20, (6) 25, (7) 30, and (8) 35 mV/s in 0.1 mol/L PBS (pH 7.0). (b) Plot of I_{pa} versus $v^{1/2}$ for the oxidation of 200 $\mu\text{mol/L}$ *N*-AC in the presence 500 $\mu\text{mol/L}$ naphthol green at the surface of MWCNTPE.

diator.

3.4. Electrochemical impedance spectroscopic studies

Nyquist diagrams of the imaginary impedance (Z_{im}) versus the real impedance (Z_{re}) of the EIS obtained at the modified electrode were recorded at 0.55 V dc-offset in the absence and in the presence of 500 $\mu\text{mol/L}$ Trp and *N*-AC at pH 7.0 (Fig. 5). This figure showed that in the absence of *N*-AC, the Nyquist diagram comprised a depressed semicircle at high frequencies, which was related to the combination of charge transfer resistance of naphthol green electrooxidation and the double-layer capacitance. This was followed by a straight line with a slope of nearly 45° . This was due to the occurrence of mass transport by diffusion. In the presence of *N*-AC, the diameter of the semicircle decreased, confirming the electrocatalytic ability of the electrocatalyst for the oxidation of *N*-AC. This was due to the instantaneous chemical reaction of *N*-AC with the high valence naphthol green species. The catalytic reaction of the oxidation of *N*-AC that occurred by the participation of naphthol green species caused an increase in the surface concentration of the low valence species on the electrocatalyst, and the charge transfer resistance decreased, depending on the concentration of *N*-AC in the solution. On the other hand, Trp cannot be electrocatalyzed on this modified electrode to provide the necessary conditions for the selective determination of *N*-AC concentration in real samples. Therefore, in the presence of these compounds, the value of the charge transfer coefficient cannot change in the buffer solution. We can conclude that we can determine *N*-AC concentration in a mixture sample with Trp.

3.5. Calibration and limit of detection

Differential pulse voltammetry (DPV) was used to determine *N*-AC and Trp concentrations. The DP voltammograms clearly showed two linear dynamic ranges where the plots of the peak current versus *N*-AC concentration were linear. For 0.25–2.5 $\mu\text{mol/L}$ *N*-AC the regression equation was $I_p(\mu\text{A}) =$

Fig. 5. Nyquist diagrams of 500 $\mu\text{mol/L}$ naphthol green on the MWCNTPE in the absence (a) and presence (b) of 500 $\mu\text{mol/L}$ Trp and (c) 500 $\mu\text{mol/L}$ *N*-AC (pH 7.0). Bias is 0.55 V with $E_{ac} = 5$ mV and frequency range of 10 kHz to 0.1 Hz.

Table 1

Comparison of the efficiency of some methods in determination of *N*-AC concentration.

Electrode	Method	LOD ^d ($\mu\text{mol/L}$)	LDR ^e ($\mu\text{mol/L}$)	Sensitivity $\mu\text{A}(\mu\text{mol/L})^{-1}$	Ref.
CP ^a	Cyclic voltammetry	—	600–6000	Not report	[60]
GC ^b	DPV	0.8	4–130	0.018	[61]
CP	DPV	0.08	0.1–100	0.00646	[62]
CP	DPV	10	30–2000	0.06191	[27]
PB/Pd-Al ME ^c	Amperometry	0.54	2.0–40	Not report	[63]
CP	DPV	0.2	0.5–200	0.1032	[28]
CP	DPV	0.6	1.0–400	0.0063	[64]
CP	DPV	0.08	0.24–400	1.0630	This work

^a Carbon paste electrode. ^b Glassy carbon electrode. ^c Palladized aluminum modified electrode. ^d Limit of determination. ^e Linear dynamic range.

$1.0630C_{N-AC} + 4.4293$ ($R^2 = 0.9937$, $n = 10$), and for 2.5–400 $\mu\text{mol/L}$ *N*-AC the regression equation was $I_p(\mu\text{A}) = 0.0076C_{N-AC} + 7.1430$ ($R^2 = 0.9930$, $n = 8$). On other hand, the DP voltammograms clearly showed two linear dynamic ranges where the plots of the peak current versus Trp concentration were linear. For 2.0–100 $\mu\text{mol/L}$ Trp the regression equation was $I_p(\mu\text{A}) = 0.0576C_{Trp} + 0.8838$ ($R^2 = 0.9986$, $n = 7$) and for 100–600 $\mu\text{mol/L}$ Trp the regression equation was $I_p(\mu\text{A}) = 0.0257C_{Trp} + 3.6395$ ($R^2 = 0.9974$, $n = 7$). The detection limit was determined as 0.08 $\mu\text{mol/L}$ *N*-AC and 1.0 $\mu\text{mol/L}$ Trp using the definition of $Y_{LOD} = Y_B + 3\sigma$. The detection limit, linear dynamic range, and sensitivity for *N*-AC obtained with the sensor were comparable to or better than those obtained with several other modified electrodes (Table 1).

3.6. Simultaneous determination of *N*-AC and Trp

A key objective of this study was to develop a modified electrode with the capability of separated electrochemical responses of *N*-AC and Trp. Therefore, DPV was used for the simultaneous determination of *N*-AC and Trp. Figures 6(1) and (2)

Fig. 6. Differential pulse voltammograms of (1) 30.0 $\mu\text{mol/L}$ *N*-AC and (2) 40.0 $\mu\text{mol/L}$ Trp at the surface of MWCNTPE, and (3) 30.0 $\mu\text{mol/L}$ *N*-AC + 40.0 $\mu\text{mol/L}$ Trp at the surface of the MWCNTPE with the mediator. Conditions: in 0.1 mol/L PBS (pH 7.0).

Fig. 7. (a) DPVs of MWCNTPE in the presence of 500 $\mu\text{mol/L}$ naphthol green in 0.1 mol/L PBS (pH 7.0) containing different concentrations of *N*-AC-Trp in $\mu\text{mol/L}$. (1) 0.0+3.0; (2) 0.4+90; (3) 0.95+190; (4) 1.2+290; (5) 1.45+390. (b) I_p versus *N*-AC concentration obtained from the DPVs.

show DP voltammograms of *N*-AC and Trp at the surface of unmodified CPE. As can be seen, at the unmodified CPE, the peak potential of *N*-AC and Trp overlapped. On the other hand, at the modified electrode these compounds gave three well separated peak potential peaks (Fig. 6(3)). Therefore, the modifier has a critical role, and it was necessary for determination of *N*-AC and Trp simultaneously. Using MWCNTPE with the mediator as the working electrode, the analytical experiments were carried out by varying the concentration of *N*-AC and Trp in 0.1 mol/L PBS (pH 7.0). The DP voltammetric results showed two well distinguished anodic peaks at the potentials of 520 and 720 mV, corresponding to the oxidation of *N*-AC and Trp, respectively, indicating that the simultaneous determination of *N*-AC and Trp concentrations is possible with MWCNTPE with the presence of the mediator (Fig. 7).

The sensitivity of the modified electrode for *N*-AC in the absence ($1.0630 \mu\text{A}(\mu\text{mol/L})^{-1}$) and presence ($0.9235 \mu\text{A}(\mu\text{mol/L})^{-1}$) of Trp were about the same, which further indicated that the oxidation of *N*-AC and Trp at the MWCNTPE by the mediator was independent and therefore, the simultaneous measurements of the three analytes without mutual interference are feasible.

3.7. Stability and reproducibility

The repeatability and stability of MWCNTPE with the medi-

Table 2

Interference study for the determination of 10.0 $\mu\text{mol/L}$ *N*-AC under the optimized conditions.

Species	Tolerante limit ($W_{\text{substance}}/W_{\text{N-AC}}$)
L-Threonin, L-Aspartic acid, L-orinthine, NO_3^- , SO_4^{2-} , Zn^{2+} , Al^{3+} , Se^{2+} glucose, sucrose, lactose, fructose, glycine, methionine, alanine, and phenyl alanine	1000
Urea, glutamic acid, isolucin, and succinic acid	800
Cysteine and ascorbic acid *	3
Starch	Saturation

* Ascorbic acid interference can be minimize using ascorbic oxidaze.

ator were investigated by DP voltammetric measurements of 5.0 $\mu\text{mol/L}$ *N*-AC. The relative standard deviation (RSD) for nine successive assays was 1.9%. When four different electrodes were used, the RSD for five measurements was 2.5%. When the electrode was stored in the laboratory, the modified electrode retained 97% of its initial response after a week and 94% after 35 days. These results indicated that MWCNTPE has good stability and reproducibility and can be used for *N*-AC analysis.

3.8. Interference study

In order to evaluate the selectivity of the method of *N*-AC determination, the effects of various foreign species on the determination of 10.0 $\mu\text{mol/L}$ *N*-AC were investigated. The tolerance limit was taken as the maximum concentration of the foreign substance causing $\pm 5\%$ relative error in the determination. The results are shown in Table 2. Most of these compounds did not interact with the mediator. So these compounds did not interfere with the determination of *N*-AC concentration. Ascorbic acid or cysteine can interact with the mediator in an electrocatalytic mechanism and interfere in *N*-AC determination. Those results confirmed good selectivity of the proposed sensor for *N*-AC determination.

3.9. Determination of *N*-AC in real samples

In order to demonstrate the ability of the modified electrode to determine *N*-AC in real samples, these compounds were determined in tablet and urine samples at pH = 7.0. The results are presented in Table 3. To check the accuracy of the proposed method for the analysis of *N*-AC and also to compare the results, a published method [28] was used to check the results. The results clearly demonstrated and confirmed that the sensor gave high selectivity, accuracy, and good reproducibility in the voltammetric determination of *N*-AC.

4. Conclusions

A carbon paste electrode chemically modified with multi-wall carbon nanotubes and with naphthol green as mediator was prepared. This voltammetric sensor was simple to prepare and its surface renewal was easy. The electrochemical behavior of naphthol green was studied by cyclic voltammetry and chronoamperometry in the absence and presence of *N*-AC. The

Table 3Determination of *N*-AC in real samples at pH = 7.0.

Sample	Added (μmol/L)	Expected (μmol/L)	Founded (μmol/L)	Recovery (%)	Founded by the published method [28] (μmol/L)
Tablet ^a	2.00	2.00	2.05 ± 0.10	102.50	2.10 ± 0.12
	8.00	10.00	9.81 ± 0.59	98.10	10.45 ± 0.61
	30.00	40.00	40.84 ± 1.0	102.00	41.02 ± 1.11
Urine	—	—	<LOD	—	<LOD
	20.00	20.00	19.41 ± 0.83	97.05	19.64 ± 0.91
	30.00	50.00	51.01 ± 1.12	102.02	51.24 ± 1.35
Urine ^b	—	—	4.45 ± 0.61	—	5.03 ± 0.78
	5.55	10.00	10.37 ± 0.79	103.70	10.85 ± 0.86

^a 600 mg tablet, Zambon, Iran.^b Sampling was made after 3.0 h from a healthy man who used *N*-AC.

results showed that *N*-AC oxidation was catalyzed at a pH value of 7.0, where the peak potential of *N*-AC was shifted by 105 mV to a less positive value at the surface of the modified electrode. Using differential pulse voltammetry, we independently measured *N*-AC and Trp in mixtures and found that their peaks were separated by a potential difference of 200 mV. The modified electrode was used for the determination of *N*-AC in real samples and it gave satisfactory results.

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Graphical Abstract

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A voltammetric sensor with a multiwall carbon nanotubes paste electrode and naphthol green as a mediator for the determination of *N*-acetyl cysteine in the presence of tryptophan

Mohsen Keyvanfard*, Maryam Tahmasbi, Hassan Karimi-Maleh*, Khadijeh Alizad

Majlesi Branch, Islamic Azad University, Iran

Shahreza Branch, Islamic Azad University, Iran

Graduate University of Advanced Technology, Iran

A modified multiwall carbon nanotube paste electrode with naphthol green as a mediator was used as a voltammetric sensor for the selective determination of *N*-acetyl cysteine and tryptophan.

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