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Article

Rapid nonenzymatic monitoring of glucose and fructose using a CuO/multiwalled carbon nanotube nanocomposite-modified glassy carbon electrode

Hajar SHEKARCHIZADEH^a, Mahdi KADIVAR^a, Ali A. ENSAFI^{b,*}^a Department of Food Science and Technology, College of Agriculture, Isfahan University of Technology, Isfahan 84156–83111, Iran^b Department of Chemistry, Isfahan University of Technology, Isfahan 84156–83111, Iran

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ABSTRACT

A nonenzymatic electrochemical sensor for glucose and fructose was fabricated that contained a glassy carbon electrode modified with a copper oxide (CuO)/multiwalled carbon nanotube (MWCNT) nanocomposite. The electrochemical properties of the CuO/MWCNT-modified glassy carbon electrode were investigated. Two distinguishable anodic peaks were observed around 0.30 and 0.44 V corresponding to the oxidation of glucose and fructose, respectively, at the surface of the modified electrode. The detection limits for glucose and fructose were both 0.04 mmol/L. The sensor was used to simultaneously determine the concentrations of glucose and fructose in hydrolyzed sucrose samples, and to measure glucose in blood serum samples, demonstrating its potential as a nonenzymatic carbohydrate sensor.

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1. Introduction

Reliable, rapid determination of the concentration of glucose is of considerable importance in many areas such as biotechnology, clinical diagnostics, and food industries. As a result, the development of electrochemical glucose sensors has attracted extensive attention [1–5]. Glucose oxidase (GOx) has been widely used to prepare biosensors for glucose detection because of its high selectivity for glucose. However, the activity of GOx is easily affected by factors such as temperature, humidity, pH, and toxic chemicals. Therefore, numerous efforts have focused on nonenzymatic electrooxidation of glucose [6–8].

Oxide electrodes are likely to be suitable for carbohydrate oxidation because molecules should readily adsorb on the oxide layer through the formation of hydrogen bonds via –OH

groups, which facilitate electron transfer [9–11]. A range of electrodes including platinum, gold, silver, nickel, cobalt, and copper have been explored for direct electrooxidation of carbohydrates. However, most possess drawbacks such as low sensitivity or poor selectivity caused by poisoning/fouling of the electrode surface [12–19].

In recent years, nanomaterials with specific physical and chemical properties have been widely used in electrochemical sensors [20–23]. Carbon nanotubes (CNTs) have become an attractive candidate in electroanalysis because of their high electrical conductivity, chemical stability, large surface area, high surface/volume ratio, high mechanical strength, and chemically modifiable surface [24–27]. Copper oxide (CuO) is a p-type semiconductor with a narrow band gap of 1.2 eV and is also of particular interest because of its promise in heteroge-

* Corresponding author. Tel: +98-311-3912351; Fax: +98-311-3912350; E-mail: Ensafi@cc.iut.ac.ir

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neous catalysts for the oxidation of carbohydrates, methanol, carbon monoxide, and nitric oxide. There have been several efforts to detect carbohydrates using nanostructured CuO. In addition, other researchers have fabricated nanosensors containing CNTs and metals/metal oxides using various techniques [28–32].

In this paper, a glassy carbon electrode (GCE) is modified with CuO nanoparticles and multiwalled carbon nanotubes (MWCNTs) to improve its electroactivity and selectivity for nonenzymatic detection of some carbohydrates; in particular, sensing of glucose and fructose. The modified GCE is sensitive to glucose and fructose at different applied potentials. Therefore, it could be used for the simultaneous determination of the concentrations of these carbohydrates in the same solution. Differential pulse voltammetry (DPV) results show simultaneous measurement of glucose and fructose with two distinguishable anodic peaks at potentials of around 0.30 and 0.44 V vs a Ag/AgCl (KCl_{sat}) electrode, corresponding to the oxidation of glucose and fructose, respectively. The ability of the sensor to detect other carbohydrates with similar structure, such as sucrose and raffinose, is also investigated.

2. Experimental

2.1. Chemicals

All chemicals used were of analytical reagent grade. MWCNTs (>90%; $d = 70\text{--}110\text{ nm}$, $l = 5\text{--}9\text{ }\mu\text{m}$) were purchased from Sigma-Aldrich. To remove any metal oxide within the MWCNTs, they were heated under reflux in a mixture of 3.0 mol/L HNO_3 and 2.0 mol/L H_2SO_4 (3:1, V/V) for 22 h. The MWCNTs were cooled, washed several times with distilled water to neutrality, and then dried at room temperature.

Glucose, fructose, sucrose, raffinose, galactose, uric acid, dopamine, ascorbic acid, copper(II) acetate monohydrate ($\text{Cu}(\text{CH}_3\text{COO})_2\cdot\text{H}_2\text{O}$), ammonium hydroxide (NH_4OH , 25%, m/m), and sodium hydroxide were purchased from Merck and used without further purification. A fresh solution of the chosen carbohydrate in NaOH (0.50 mol/L) was prepared daily for sensing experiments.

2.2. Preparation of the CuO/MWCNT nanocomposite

The CuO/MWCNT composite was prepared by the method developed by Wang et al. [33]. $\text{Cu}(\text{CH}_3\text{COO})_2\cdot\text{H}_2\text{O}$ was used as the source of copper. $\text{Cu}(\text{CH}_3\text{COO})_2\cdot\text{H}_2\text{O}$ (16 mg) was dissolved in deionized water (5.0 ml). NH_4OH solution ($w = 25.0\%$, 0.10 ml) was slowly added to the stirred solution to form a precursor solution. MWCNTs (10 mg) were added to the solution, which was then aged for 17 h. The MWCNTs were centrifugally separated from the solution and then dried at $70\text{ }^\circ\text{C}$ under vacuum. The final product was obtained by calcination at $300\text{ }^\circ\text{C}$ in the presence of N_2 for 2 h.

2.3. Preparation of the modified electrode CuO/MWCNT/GCE

The GCE was polished with $0.05\text{ }\mu\text{m}$ alumina powder, rinsed

thoroughly with distilled water, ultrasonicated in ethanol for 5 min, and then allowed to dry at room temperature before each experiment. CuO/MWCNT powder was dispersed in ethanol and ultrasonicated for 5 min. The mixture (10 μl) was added dropwise onto the surface of the GCE, and then the ethanol was allowed to evaporate. The resulting modified electrode (CuO/MWCNT/GCE) was used as the working electrode.

2.4. Characterization of the materials

Cyclic voltammetry (CV), electrochemical impedance spectroscopy (EIS), and DPV were performed using an analytical system, in which a potentiostat/galvanostat (Autolab PGSTAT 12) was connected to a three-electrode cell (Metrohm Model 663 VA). The system was run on a PC using GPES and FRA 4.9 software packages (Eco Chemie, The Netherlands). A conventional three-electrode cell assembly consisting of a platinum wire as an auxiliary electrode and a Ag/AgCl (KCl_{sat}) electrode as a reference electrode was used. The working electrode was the modified GCE. For impedance measurements, a frequency range of 100 kHz to 0.01 Hz and AC voltage amplitude of 5 mV were used. The modified electrode was characterized by scanning electron microscopy (SEM, XLC, Philips).

X-ray powder diffraction (XRD) measurements were performed on an X'pert X-ray diffractometer (Philips) with graphite-monochromatized $\text{Cu K}\alpha$ radiation ($\lambda = 0.15418\text{ nm}$) and a nickel filter.

3. Results and discussion

3.1. Characterization of the CuO/MWCNT nanocomposite

Direct observation of the morphology of the prepared CuO/MWCNT nanocomposite was achieved by SEM. Figure 1(a) shows that CuO nanoparticles with size of 10–50 nm are homogeneously coated on the surface of the MWCNTs.

To confirm the structure and phase composition of the CuO/MWCNT nanocomposite, XRD analysis was also carried out (Fig. 1(b)). The diffraction peaks confirm that the prepared nanocomposite contains both MWCNTs and CuO. Diffraction peaks at 2θ of 33.52° , 35.47° , 38.52° , 48.87° , 57.57° , 61.77° , 66.57° , and 68.17° can be assigned to the (110), ($\bar{1}11$), (111), ($\bar{1}02$), (202), ($\bar{1}13$), ($\bar{1}31$), and (220) planes of crystalline CuO, respectively (JCPDS 80-1916). Peaks with 2θ of 26.32° , 43.32° , 43.92° , and 53.42° are consistent with diffraction from the (002), (100), (101), and (004) planes, respectively, of the MWCNTs. No peaks belonging to impurities were observed, indicating that the prepared nanocomposite was of high purity. The size of the CuO particles was calculated from the ($\bar{1}11$) diffraction peak using the Debye-Scherrer equation $L = k\lambda/\beta\cos\theta$, where L is the average size of the particles, λ is the X-ray wavelength (0.154 nm), k is equal to 0.89, β is the peak broadening, and θ is the angle of the peak maximum. The calculated average size of the CuO particles in the composite was 10.4 nm. Thus, the CuO particles larger than 10 nm in size observed in the SEM image are considered to be nanoclusters of CuO crystallites.

Fig. 1. The SEM image (a) and XRD pattern (b) of the CuO/MWCNT nanocomposite.

3.2. Electrochemical characteristics of the modified electrode

The active area of the CuO/MWCNT/GCE was estimated using a solution of $K_3(Fe(CN)_6)$ (0.50 mmol/L) with KCl (1.0 mol/L). Figure 2(a) shows a typical cyclic voltammogram of the modified electrode at a scan rate of 50 mV/s at the surface of the CuO/MWCNTs/GC electrode. A pair of anodic and cathodic peaks related to the redox reactions of $Fe(CN)_6^{3-}$ were observed between +0.20 and +0.30 V. In addition, the anodic peak current was not the same as the cathodic peak current. These observations indicate that the redox reaction is quasi-reversible at the surface of the modified electrode. Another pair of anodic and cathodic peaks were found between +0.70 and +0.80 V that were related to redox reactions of CuO.

The active surface area of the modified electrode was estimated from the slope of a plot of I_p versus $\nu^{1/2}$ based on the Randles-Sevcik equation $I_p = 0.4463 n^{3/2} F^{3/2} A C (\nu D / RT)^{1/2}$, where I_p is the anodic peak current (A), n is the electron transfer number ($= 1$), A is the surface area of the electrode (cm^2), F is the Faraday constant (C/mol), R is the gas constant (8.314 J/(K·mol)), D is the diffusion coefficient ($0.76 \times 10^{-5} cm^2/s$), T is the temperature (K), C is the concentration of electroactive species ($K_3Fe(CN)_6$, mol/L), and ν is the scan rate (V/s). The calculated surface areas of the bare GCE and CuO/MWCNT/GCE were 0.034 and 0.56 cm^2 , respectively, at 25 °C based on the

redox peaks of $(Fe(CN)_6)^{3-}$. These results obviously show that the CuO/MWCNT nanocomposite increases the active surface area of the electrode.

EIS was also used to study the characteristics of the modified electrode. In EIS, the diameter of the semicircle in a Nyquist plot corresponds to the electron transfer limited process and is equivalent to the electron transfer resistance (R_{ct}). Figure 2(b) shows the EIS measured on a bare GCE and CuO/MWCNT/GCE in an electrolyte containing KCl and $(Fe(CN)_6)^{4-/3-}$ (both 0.1 mol/L). In the equivalent circuit shown in the inset of Fig. 2(b), R_s , C_1 , R_{ct} , and Z_w represent the resistance of the electrolyte solution, capacitance, charge-transfer resistance, and Warburg impedance, respectively. R_{ct} of the bare GCE was 2000 Ω . After the GCE was modified with the CuO/MWCNT nanocomposite, R_{ct} decreased markedly to 140 Ω . This result shows that the CuO/MWCNT nanocomposite was successfully immobilized on the surface of the GCE, and it acts as a powerful electron mediator.

3.3. Electrocatalysis of glucose at the CuO/MWCNT/GCE

The electrocatalytic activity of the bare GCE and CuO/MWCNT/GCE towards the oxidation of glucose in alkaline solution was investigated by CV. Figure 3 displays CVs of the bare GCE and CuO/MWCNT/GCE in NaOH solution (0.5 mol/L) in the absence and presence of glucose (15.0 mmol/L). An obvi-

Fig. 2. (a) Cyclic voltammogram of CuO/MWCNT/GCE in $K_3(Fe(CN)_6)$ (0.50 mmol/L) containing KCl (1.0 mol/L); (b) EIS of bare GCE and CuO/MWCNT/GCE. Inset is the equivalent circuit. The frequency range is from 0.01 Hz to 100 kHz.

Fig. 3. CVs of GCE (a) and CuO/MWCNT/GCE (b) in the absence (1) and presence (2) of glucose (15.0 mmol/L) in NaOH (0.50 mol/L) at a scan rate of 50 mV/s.

ous increase in the peak current was observed when the CuO/MWCNT/GCE was used as a working electrode (Fig. 3(b), curve (2)). This indicates that the CuO/MWCNT nanocomposite greatly improves the performance of the GCE, which is attributed to the larger surface area and increased number of active sites at the surface of the modified electrode. Upon addition of glucose, a single forward oxidation peak corresponding to the irreversible oxidation of glucose was observed for both electrodes. Curves (2) in Fig. 3(a) and (b) show that the modified electrode exhibited a decrease in anodic peak potential and substantial increase in peak current compared with those obtained for the bare electrode. The unmodified GCE shows an oxidation starting at about +0.30 V and a peak potential of +0.43 V, whereas the CuO/MWCNT/GCE displays an oxidation of glucose starting at approximately +0.20 V and an oxidation peak centered at +0.39 V. This shift in overpotential can be attributed to a kinetic effect caused by an increase in the electroactive surface area and a change in the rate of electron transfer from glucose to the CuO/MWCNT/GCE versus that between glucose and the bare electrode. All of these results show that immobilization of the CuO/MWCNT nanocomposite onto the surface of the GCE greatly improves the oxidation of glucose.

CVs of glucose solution measured at different scan rates are illustrated in Fig. 4(a). The anodic peak current of glucose oxidation is proportional to the square root of scan rate. Good linearity was obtained, as indicated in the inset of Fig. 4(a). A linear regression equation of $I/\mu\text{A} = (186.00 \pm 0.092)/\mu\text{A} + (65.480 \pm 0.001)\nu/\mu\text{A mV}^{-1}\text{ s}$ with a correlation coefficient (R) of 0.995 was determined. This result indicates that the electrochemical kinetics of glucose oxidation is controlled by the diffusion of glucose to the surface of the electrode. It should also be noted that the peak potential for the oxidation of glucose exhibits a positive shift with increasing scan rate.

It is well known that an alkaline medium is required to enhance the synergistic effect of CuO for the oxidation of carbohydrates. In this study, the effect of NaOH concentration on glucose (15.0 mmol/L) oxidation at CuO/MWCNT/GCE was also investigated. The concentrations of NaOH investigated were 0.10, 0.25, 0.50, 0.75, and 1.00 mol/L. As shown in Fig. 4(b), with increasing NaOH concentration, the oxidative current increases and the oxidative potential exhibits a negative shift until the NaOH concentration reaches 0.50 mol/L. Then, as the NaOH concentration increases further, the oxidative current decreases. A high concentration of NaOH would destabilize the electrode materials. From these results, 0.50 mol/L was

Fig. 4. (a) CVs of CuO/MWCNT/GCE in NaOH (0.5 mol/L) containing glucose (15.0 mmol/L) at scan rates of 25 mV/s (1), 50 mV/s (2), 75 mV/s (3), 100 mV/s (4), 250 mV/s (5), and 500 mV/s (6). Inset is oxidation peak current vs scan rate. (b) Effect of NaOH concentration on the peak current for glucose (15.0 mmol/L) at CuO/MWCNT/GCE.

Fig. 5. (a) Calibration curve for glucose determination using CuO/MWCNT/GCE; (b) DPVs of glucose with different concentrations of 0.5 (1), 1.0 (2), 2.5 (3), 5.0 (4), 10.0 (5), 20.0 (6), 30.0 (7), 40.0 (8), and 50.0 (9) mmol/L.

selected as the optimal concentration of NaOH to obtain the highest glucose oxidation current at low potential.

The CuO/MWCNT/GCE responds to the changes in glucose concentration. DPV measured from 0.00 to 0.80 V with a pulse amplitude of 50 mV, modulation time of 0.05 s, and step potential of 8 mV was used to determine the concentration of glucose because of its higher sensitivity than CV. The corresponding calibration curve is presented in Fig. 5(a). The plot of peak current vs glucose concentration is linear up to 30.0 mmol/L, with a regression equation of $I_p/\mu\text{A} = (2.10 \pm 0.25)/\mu\text{A} + (2.852 \pm 0.001)[\text{glucose}]/(\mu\text{A mmol}^{-1} \text{ L})$ with $R^2 = 0.994$, where I_p is the peak current in μA . The response is saturated at glucose concentration exceeding about 30.0 mmol/L. In addition, the peak potential shifts to a more positive value as the glucose concentration increases (Fig. 5(b)). This is related to the irreversibility of the oxidation of glucose at the surface of the modified electrode.

The detection limit of the modified electrode was 0.04 mmol/L glucose, and its sensitivity was $5.089 \mu\text{A mmol}^{-1} \text{ cm}^{-2}$. The high sensitivity, low detection limit, and fast response of the modified electrode are attributed to its large active surface area and the fact that the CuO/MWCNT nanocomposite can form a network to shuttle electrons between glucose and the working electrode, increasing the catalytic activity of the electrode.

Next, the CuO/MWCNT/GCE was used to sense other carbohydrates. The current responses for other carbohydrates, including fructose, galactose, sucrose, and raffinose (all 15.0 mmol/L in 0.50 mol/L NaOH), were analyzed and compared with that for glucose. Fructose (75.0%), galactose (87.5%), sucrose (58.3%), and raffinose (106.2%) gave similar responses to glucose. Fructose is an important carbohydrate that is structurally related to glucose and usually coexists with it. Therefore, simultaneous determination of glucose and fructose, which has not been reported before, is desirable.

The electrocatalytic activity of the CuO/MWCNT/GCE towards the oxidation of fructose in alkaline solution was investigated by CV (Fig. 6). Upon addition of fructose (curve (2)), a single forward oxidative wave corresponding to the irreversible oxidation of fructose was observed. The calibration curve for fructose (results not shown) indicates that the peak cur-

rents are proportional to the fructose concentration in the range of 0.1–20.0 mmol/L, with a regression equation of $I_p/\mu\text{A} = (1.70 \pm 0.13)/\mu\text{A} + (2.797 \pm 0.0015)[\text{fructose}]/(\mu\text{A mmol}^{-1} \text{ L})$ with $R^2 = 0.993$. The detection limit for fructose was 0.04 mmol/L.

The CuO/MWCNT/GCE was used to determine the concentrations of glucose and fructose at the same time, which was demonstrated by changing the concentrations of glucose and fructose. DPV results showed simultaneous measurement of glucose and fructose with two distinguishable anodic peaks at potentials of around 0.30 and 0.44 V, corresponding to the oxidation of glucose and fructose, respectively (Fig. 7). Plots of peak current vs glucose or fructose concentration were linear up to 20.0 mmol/L with regression equations of $I_p/\mu\text{A} = 3.86/\mu\text{A} + 3.48[\text{glucose}]/(\mu\text{A mmol}^{-1} \text{ L})$ with $R^2 = 0.993$ and $I_p/\mu\text{A} = 4.56/\mu\text{A} + 3.18[\text{fructose}]/(\mu\text{A mmol}^{-1} \text{ L})$ with $R^2 = 0.993$, respectively.

Analytical experiments were carried out by varying glucose concentration (2.5–10.0 mmol/L) in the presence of a fixed amount of fructose (5.0 mmol/L), as presented in Fig. 8. A regression equation of $I_p/\mu\text{A} = 2.98/\mu\text{A} + 15.5[\text{glucose}]/(\mu\text{A mmol}^{-1} \text{ L})$ with $R^2 = 0.998$ was obtained. In addition, the concentration of fructose was varied (2.5–10.0 mmol/L) in the presence of a fixed amount of glucose (5.0 mmol/L). A regres-

Fig. 6. CVs of CuO/MWCNT/GCE in the absence (a) and presence (b) of fructose (10.0 mmol/L) in NaOH (0.50 mol/L) at a scan rate of 50 mV/s.

Fig. 7. (a) DPVs of different concentrations of glucose and fructose. (1) 1.0, (2) 2.5, (3) 5.0, (4) 10.0, (5) 15.0, and (6) 20.0 mmol/L of glucose or fructose in 0.50 mol/L NaOH at a scan rate of 50 mV/s. (b) Calibration curves for glucose (1) and fructose (2) determination using the CuO/MWCNT/GCE.

Fig. 8. DPVs of glucose and fructose in NaOH (0.5 mol/L). (a) 5.0 mmol/L fructose with different glucose concentrations; (b) 5.0 mmol/L glucose with different fructose concentrations. (1) 2.5 mmol/L; (2) 5.0 mmol/L; (3) 7.5 mmol/L; (4) 10.0 mmol/L.

sion equation of $I_p/\mu\text{A} = 4.80/\mu\text{A} - 3.40[\text{fructose}]/(\mu\text{A mmol}^{-1}\text{L})$ with $R^2 = 0.998$ was determined.

The results indicate that there are no considerable intermolecular interactions during the oxidation of glucose and fructose at the surface of the CuO/MWCNT/GCE. It should also be noted that the responses to glucose and fructose at the modified electrode are relatively independent.

3.4. Reproducibility and stability of CuO/MWCNT/GCE

The reproducibility and stability of the sensor were investigated by CV measurements. Five CuO/MWCNT/GCE were fabricated under the same conditions. Their current responses to glucose (15.0 mmol/L) in NaOH (0.5 mol/L) had a relative standard deviation (RSD) of 2.5%, confirming that the fabrication method was highly reproducible. Seven measurements of glucose (15.0 mmol/L) at the CuO/MWCNT/GCE yielded an RSD of 1.9%, demonstrating that the sensor was stable. The electrode was not deactivated by the oxidation process and could be used several times to detect the concentration of glucose. The stability of the CuO/MWCNT/GCE was also investigated by adding NaCl (0.10 mol/L) to the supporting electrolyte. The linear response for glucose at the CuO/MWCNT/GCE remained almost constant (data not shown), indicating that the

electrode can be used in the presence of chloride ions.

3.5. Real sample analysis

In an attempt to explore the CuO/MWCNT/GCE for practical application, the concentration of glucose in human blood serum was determined. Uric acid, ascorbic acid, and dopamine coexist with glucose in blood and act as interfering species. Therefore, the selectivity of the CuO/MWCNT/GCE was investigated before sample analysis. The normal physiological level of glucose in blood is 3.0–8.0 mmol/L, and the level of interfering species such as uric acid, ascorbic acid, and dopamine is about 0.10 mmol/L. Therefore, interference tests were carried out by adding 0.50 mmol/L of each of uric acid, ascorbic acid, and dopamine to glucose solutions (15.0 mmol/L). A well-defined glucose response was again obtained, and insignificant responses were observed for interfering species. Compared with glucose, the interfering species yielded current responses of uric acid 0.85%, ascorbic acid 0.95%, and dopamine 1.2%, which can be neglected.

The sensor was then used to determine the concentration of glucose in real samples such as blood serum. Random human serum samples were collected from the Health Center of Isfahan University of Technology. Ethanol (2.0 ml) was added to

Table 1

Determination of glucose in human blood serum samples.

Sample	Glucose added (mmol/L)	Found by the sensor (mmol/L)	Recovery (%)	GOD-PAP method (mmol/L)
1	—	4.53(±0.18)	—	4.88
	4.3	9.15(±0.26)	108	—
	6.1	10.48(±0.11)	97	—
2	—	4.31(±0.16)	—	4.22
	4.3	8.28(±0.27)	93	—
	6.1	10.33(±0.09)	98	—
3	—	4.40(±0.21)	—	4.31
	4.3	8.88(±0.32)	104	—
	6.1	10.47(±0.14)	98	—

Table 2

Simultaneous determination of glucose and fructose in hydrolyzed sucrose samples.

Sample	Added (mmol/L)		Found by the sensor (mmol/L)	Recovery (%)	HPLC (mmol/L)
	Glucose	Fructose			
1	—	—	23.00(±0.18)	—	22.51(±0.28)
	0.20	—	23.21(±0.09)	108	—
	0.40	—	23.41(±0.14)	101	—
2	—	—	24.75(±0.11)	—	24.95(±0.18)
	—	0.50	25.19(±0.07)	99	—
	—	1.00	25.72(±0.09)	104	—

Table 3

Comparison of the properties of the developed sensor for the determination of glucose with those of published ones.

Electrode	Detection limit	Linear range	Effect of fructose	Ref.
CuO nanofibers	0.8 $\mu\text{mol/L}$	6–2500 $\mu\text{mol/L}$	interfered	[1]
CuO nanospheres	1 $\mu\text{mol/L}$	up to 2.55 mmol/L	not investigated	[2]
CuO nanowires/Cu nanostructure	50 nmol/L	0.40–4000 $\mu\text{mol/L}$	not investigated	[4]
CuO nanowires	0.4 $\mu\text{mol/L}$	4–2000 $\mu\text{mol/L}$	interfered	[5]
CuO/MWCNTs	0.2 $\mu\text{mol/L}$	up to 1.2 mmol/L	interfered	[6]
CuO nanorods	1.2 $\mu\text{mol/L}$	up to 1 mmol/L	interfered	[10]
Screen-printed CuO	27 $\mu\text{mol/L}$	100–500 $\mu\text{mol/L}$	not detectable	[11]
CuO/MWCNTs	0.8 nmol/L	up to 3 mmol/L	interfered	[25]
CuO/MWCNTs	4 $\mu\text{mol/L}$	up to 30 mmol/L	detectable simultaneously	this work

each serum sample (2.0 ml) and then the mixture was centrifuged at 7000 r/min for 15 min. The supernatant (2.0 ml) was used to determine the concentration of glucose. The results of this experiment are presented in Table 1. The results are in agreement with those determined by the GOD-PAP method [34]. This indicates that the CuO/MWCNT/GCE can be used to detect the concentration of glucose in blood serum samples.

In another experiment, the CuO/MWCNT/GCE was used to simultaneously determine the concentrations of glucose and fructose in hydrolyzed sucrose samples. Sucrose (1.00 g) was dissolved in distilled water, and then hydrochloric acid (5.0 ml) was added. The solution was heated at 72 °C in a water bath for 8 min. In the presence of acid, sucrose hydrolyzes to glucose and fructose. The hydrolyzed solution was cooled to room temperature and then diluted to 100 ml with water in a 100 ml volumetric flask. The concentrations of glucose and fructose in hydrolyzed sucrose samples were determined. The results of this experiment are described in Table 2 and are consistent with those determined by HPLC.

Table 3 compares the figures of merit of reported electroanalytical methods for glucose and fructose determination with that of the developed electrochemical sensor. Although some methods are sensitive for glucose detection, they suffer from fructose interference and could not measure glucose in the

presence of fructose. Our sensor can be used for simultaneous determination of glucose and fructose, overcoming this limitation.

4. Conclusions

The CuO/MWCNT/GCE prepared here possesses many attractive analytical features such as excellent synergistic effect, good reproducibility, high stability, and high selectivity as well as quick response to glucose. The CuO/MWCNT nanocomposite also showed an excellent synergistic effect for the selective electrochemical determination of glucose and fructose simultaneously. Glucose and fructose showed two distinguishable anodic peaks at around 0.30 and 0.44 V, respectively. The electrode was successfully used to measure the concentration of glucose in blood serum samples and to simultaneously determine the concentrations of glucose and fructose in hydrolyzed sucrose samples, revealing its potential as a nonenzymatic carbohydrate sensor. The developed sensor gave results for glucose and fructose detection that were in good agreement with those obtained using standard methods, demonstrating that the developed sensor has great potential for practical use. In addition, the proposed method could be used for simultaneous detection of glucose and fructose.

Graphical Abstract

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Rapid nonenzymatic monitoring of glucose and fructose using a CuO/multiwalled carbon nanotube nanocomposite-modified glassy carbon electrode

Hajar SHEKARCHIZADEH, Mahdi KADIVAR, Ali A. ENSAFI*
Isfahan University of Technology, Iran

A glassy carbon electrode modified with the CuO/MWCNT nanocomposite with excellent synergistic effect, good reproducibility, and strong stability as well as quick response was fabricated as a non-enzymatic electrochemical sensor for the simultaneous determination of glucose and fructose.

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