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Nonenzymatic electrochemical detection of glucose using well-distributed nickel nanoparticles on straight multi-walled carbon nanotubes

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ABSTRACT

A nonenzymatic electrochemical sensor device was fabricated for glucose detection based on nickel nanoparticles (NiNPs)/straight multi-walled carbon nanotubes (SMWNTs) nanohybrids, which were synthesized through in situ precipitation procedure. SMWNTs can be easily dispersed in solution after mild sonication pretreatment, which facilitates the precursor of NiNPs binding to their surface and results in the homogeneous distribution of NiNPs on the surface of SMWNTs. The morphology and component of the nanohybrids were characterized by scanning electron microscopy (SEM) and X-ray powder diffraction (XRD), respectively. Cyclic voltammetry (CV) and amperometry were used to evaluate the catalytic activity of the NiNPs/SMWNTs nanohybrids modified electrode towards glucose. It was found that the nanohybrids modified electrode showed remarkably enhanced electrocatalytic activity towards the oxidation of glucose in alkaline solution compared to that of the bare glass carbon electrode (GCE), the NiNPs and the SMWNTs modified electrode, attributing to the synergistic effect of SMWNTs and Ni^{2+}/Ni^{3+} redox couple. Under the optimal detection conditions, the as-prepared sensors exhibited linear behavior in the concentration range from 1 μM to 1 mM for the quantification of glucose with a limit of detection of 500 nM (3σ). Moreover, the NiNPs/SMWNTs modified electrode was also relatively insensitive to commonly interfering species such as ascorbic acid (AA), uric acid (UA), dopamine (DA), galactose (GA), and xylose (XY). The robust selectivities, sensitivities, and stabilities determined experimentally indicated the great potential of NiNPs/SMWNTs nanohybrids for construction of a variety of electrochemical sensors.

1. Introduction

Glucose sensing is of significantly importance in diagnosis and treatment of diabetes mellitus as well as monitoring and control of food preparation processes (Jin et al., 1997; Mizutani et al., 1998). Until now, few spectrophotometric strategies have been developed for measuring the glucose levels, which is attributed to the lack of chromophoric or fluorophoric ligands for glucose. Electrochemistry holds great potential as the next-generation detection strategy for glucose because of its high sensitivity, reliability and selectivity, simple instrumentation, low cost and excellent compatibility with miniaturization. Glucose oxidases (GOx) were widely used for the fabrication of the electrochemical sensor devices for glucose determination (Zayats et al., 2002; Liu et al., 2010; Wang, 2008; Zeng et al., 2011; Liu et al., 2007). Although these enzyme-based sensors show high selectivity and excellent sensitivity, inevitable drawbacks such as chemical and thermal deformation originating from the intrinsic nature of the enzyme as well as the severe interferences from other oxidable species in blood samples may limit their applications (Kohma et al., 2007). The nonenzymatic glucose sensors based on direct electrocatalytic oxidation of glucose at an electrode surface would exhibit conveniences and advantage to avoid the enzyme electrode drawbacks.

Recently, a major concern in a practical nonenzymatic glucose sensor has been focused on the efforts to develop highly electrocatalytic activity of the electrode materials, which is the key factor that affects both the sensitivity and selectivity of glucose detection. Various nanostructured metals (Pt, Au, Pd, Ni, Cu) (Park et al., 2003; Jena and Raj, 2006; Bai et al., 2010; Lu et al., 2009), alloys (Pt–Pb, Pt–Ir, Pt–Au) (Wang et al., 2008; Hindle et al., 2008; Ryu et al., 2010) and metal oxides (CuO, Co_3O_4, NiO) (Zhang et al., 2008; Ding et al., 2010; Safavi et al., 2009) have been explored as the electrode substrates for directly electro-catalyzing glucose. Among these, Ni-based nanomaterials exhibit remarkably catalyzed capability for glucose as result of the catalytic effect originating from the redox couple of $Ni(OH)_2/NiOOH$ on the electrode surface in alkaline medium. Most of Ni-based glucose sensors were fabricated by modifying traditional electrodes with Ni-based nanomaterials such as dispersing NiNPs in disordered graphite-like carbon (You et al., 2003), doping carbon paste electrode with nano-NiO powder

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(Mu et al., 2011), and mixing powdered nanoscale nickel hydroxide with graphite powder and ionic liquid (Safavi et al., 2009). However, one severe problem with these electrodes is the instability of the catalytic film for extended period of time under applied potential. To solve this problem, Ni was loaded on the surface of various nanomaterials such as carbon nanofiber (Liu et al., 2009), Ti/TiO_2 nanotube array (Wang et al., 2010). However, these support materials were not favorable for facilitating electron transfer during electrochemical process. Therefore, it is still highly desirable for Ni-based glucose sensor to develop novel electrode materials with good stability, excellent conductivity and high electrocatalytic activity.

Carbon nanotubes (CNTs) have attracted growing interest in nonenzymatic sensors due to their combination of beneficial properties such as their relatively large surface area, excellent electric conductivity, good mechanical properties and outstanding ability to promote electron-transfer reactions. Recent studies of CNT-based enzyme-free sensors have focused on utilizing CNTs as the templates for supporting metal or metal oxides nanoparticles catalysts (such as Pt, Pd, Cu, MnO_2) (Meng et al., 2009; Su et al., 2010; Yang et al., 2010; Chen et al., 2008), which cannot only improve the dispersion of catalysts but also enhance the load amounts of catalysts. Therefore, it is expected that the advantageous features of CNTs coupling with Ni-based nanomaterials in electrocatalytic oxidation of glucose can make Ni/CNTs nanohybrids very promising in the development of nonenzymatic glucose sensors with high sensitivity, selectivity, and stability. Although there are few reports about CNTs coupling with Ni-based nanomaterials for electrocatalytic oxidation of glucose (Shamsipur et al., 2010; Zheng et al., 2009), these strategies involve harshly acid-oxidized pretreatment of CNTs, which causes structural damage to the CNTs and lead to the loss of their electrical conductivity and mechanical properties. The loss of mechanical properties is not assisting catalysts stably distributed on the wall of CNTs, and usually results in the poor sensitivity and stability for glucose determination. Furthermore, these sensors exhibit poor reproducibility and great limitation in their applications in real samples. Therefore, it is indispensable to develop an efficient functionalized method without or with little damage to the CNTs for supporting catalysts in batch.

Herein, we utilized mildly pretreated straight multi-walled CNTs (SMWNTs) as the templates for supporting NiNPs catalysts, and developed a nonenzymatic glucose sensor based on NiNPs/SMWNTs nanohybrids, which were synthesized through in situ precipitation procedure. Comparing with the tangled CNTs widely applied in nonenzymatic sensors, SMWNTs can be more easily dispersed in solution after mild sonication pretreatment, which keep them intrinsic electrical conductivity and mechanical properties. These properties can facilitate the NiNP precursor binding to their surface, which make NiNPs stably and homogeneously distributed on the surface of SMWNTs. The well-distributed NiNPs can be easily and fully accessing to glucose, and amplifying the electrochemical signal for glucose determination. An efficient electrical network through NiNPs directly anchoring on the surface of SMWNTs can promote the electron transfer rate and improve the sensitivity. More importantly, the NiNPs/SMWNTs can be prepared on a large scale by precipitation procedure, which not only makes this sensor exhibit excellent reproducibility but also broadens their application in the real sample analysis. Moreover, the modification of glass carbon electrodes (GCE) with the NiNPs/SMWNTs nanohybrids not only increases their active area but also promotes the electron transfer for the glucose oxidation reaction via the SMWNTs. The proposed sensor demonstrated that NiNPs/SMWNTs could allow highly sensitive, fast, stable, and reproducible amperometric sensing of glucose.

2. Experiment

2.1. Reagents and materials

Straight multi-walled carbon nanotubes (SMWNTs) were prepared according to the previous report (Yang et al., 2008). D-(+)-Glucose, ascorbic acid (AA), uric acid (UA), dopamine (DA), galactose (GA), and xylose (XY) were obtained from Alfa Aesar. All of other reagents were of analytical grade and used without further purification. All aqueous solutions were prepared using ultrapure water, which was obtained through a Millipore Milli-Q water purification system (Billerica, MA) with an electric resistance >18.3 MΩ. The glucose stock solution was allowed to mutarotate for at least 24 h before use.

2.2. Apparatus and measurement

Scanning electron microscopy (SEM) images were conducted using (FEI Nova NanoSEM 200). X-ray diffraction (XRD) analysis was recorded on a (Smart APEX CCD, Bruker, Germany). The cyclic voltammetry (CV) and amperometry were executed on a CH Instruments model 760C electrochemical analyzer (Shanghai, China). All of electrochemical measurements were performed in 0.1 M NaOH supporting electrolyte at room temperature using a three-electrode system consisting of a KCl saturated calomel electrode (SCE) as the reference electrode, a platinum wire as the counter electrode, and the modified glass carbon electrodes (GCE) as the working electrode.

2.3. Synthesis of NiNPs/SMWNTs nanohybrids

Prior to the preparation of NiNPs/SMWNT nanohybrids, SMWNTs were pretreated by sonication in a mixture of sulfuric acid and nitric acid (3:1) for 30 min, and then washed with distilled water by centrifugation until the pH of the resulting SMWNTs solution become neutral.

NiNPs/SMWNTs nanohybrids were obtained from the reduction of NiO/SMWNTs complex, which were synthesized through in situ precipitation procedure. Briefly, 20 mg $Ni(NO_3)_2$ was added into 20 mL of the treated SMWNTs solution and ultrasonic agitated for 1 h at room temperature. Subsequently, 60 mL of 2.2 mM NaOH solution was added dropwise to the above mixture under constant stirring at 80 °C, the $Ni(OH)_2$/SMWNTs complex was formed and the reaction was carried out under magnetic stirring for 2 h at room temperature. Finally, the $Ni(OH)_2$/SMWNTs complex was separated and rinsed with distilled water several times, followed by heat treatment at 650 °C for 2 h in the H_2/N_2 mixture atmosphere ($H_2/N_2 = 3/1$) to reduce Ni^{2+} and get NiNPs/SMWNTs nanohybrids.

2.4. Fabrication of the NiNPs/SMWNTs-modified electrode

Prior to coating, GCE with a diameter of ~3 mm were polished on a microcloth (Buehler) with 0.3 and 0.05 μm alumina slurry for 5 min, followed by sonication in ultrapure water and ethanol for 5 min in each. Then, the polished electrodes were dried under mild nitrogen stream. 2 mg NiNPs/SMWNTs was dispersed in 10 mL ultrapure water with the aid of ultrasonic agitation to give 0.2 mg mL^{-1} black solution. 10 μL of the black solution was dropped onto the GCE surface, and the electrode was dried slowly to obtain the NiNPs/SMWNTs modified electrode. A NiNPs-modified GCE and SMWNTs-modified GCE were prepared in the same way.

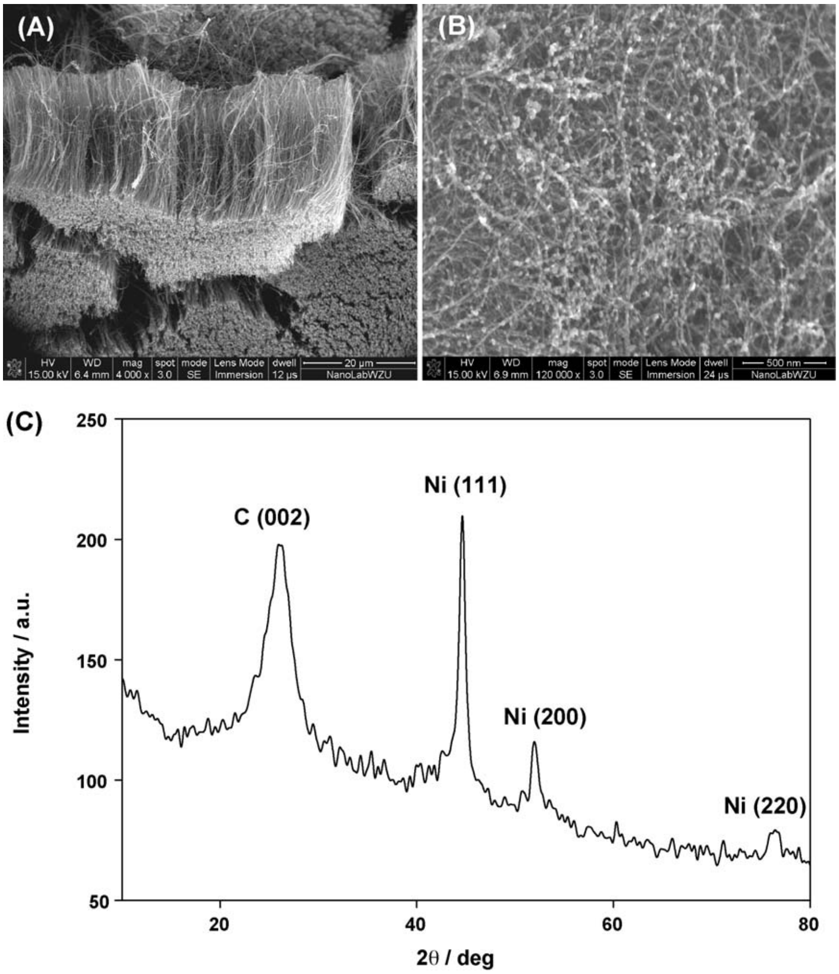

Fig. 1. Typical SEM images of SMWNTs (A), and NiNPs/SMWNTs nanohybrids (B) and XRD pattern of the NiNPs/SMWNTs nanohybrids (C).

3. Results and discussion

3.1. Characterization of NiNPs/SMWNTs nanohybrids

Fig. 1(A) gives a SEM image of the SMWNT sample. It can be observed that all of the CNTs are almost straight and aligned along a uniform direction, which makes them more easily dispersed in solution after mild sonication pretreatment comparing with the tangled CNTs due to the weaker van der waals attraction force in SMWNTs bundles (Kim et al., 2011). The morphology of the prepared NiNPs/SMWNTs nanohybrids were observed using SEM, as depicted in Fig. 1(B). One can see that the surface of the SMWNTs is homogeneously decorated with high-loading NiNPs. The well-distributed NiNPs on the wall of SMWNTs are expected to favor NiNPs/SMWNTs nanohybrids accessing to glucose and amplify the electrochemical signal for glucose determination. The constitution of the NiNPs/SMWNTs nanohybrids was further characterized by XRD analysis, as shown in Fig. 1(C). The peak at 25.96° comes from the plane of (0 0 2) of graphite of SMWNTs. Three characteristic diffraction peaks positioned at 44.5°, 51.8°, and 76.5° can be attributed to the (1 1 1), (2 0 0) and (2 2 0) crystalline planes of the fcc (face centered-cubic) Ni, respectively. These results are consistent with the reported literature (Liu et al., 2009). No reflection for $Ni(OH)_2$ or NiO is observed, indicating that $Ni(OH)_2$ was totally reduced to Ni after high temperature treatment in the H_2 atmosphere.

3.2. Properties of NiNPs/SMWNTs modified electrode

Prior to the implementation of the as-prepared NiNPs/SMWNTs nanohybrids based nonenzymatic sensor, the electrochemical behavior of NiNPs/SMWNTs modified electrode was investigated using cyclic voltammogram (CV). Fig. 2(A) represents the CV responses on the bare GCE (a), NiNPs (b), SMWNTs (c), and NiNPs/SMWNTs (d) modified electrode in 0.1 M NaOH at a scan rate of 50 mV s^{-1}. As can be seen from the curve (a) and (c), no reaction peak current is observed, indicating that GCE and SMWNTs modified electrodes cannot undergo the redox reaction in the potential range of interest. However, in both NiNPs and NiNPs/SMWNTs modified electrode ((b) and (d)), a pair of well-defined redox peaks corresponding to Ni^{2+}/Ni^{3+} redox couple are observed. The cathodic and anodic peak currents in NiNPs/SMWNTs modified electrode are stronger than those for the NiNPs modified electrode, which is attributed to a larger surface area of the NiNPs/SMWNTs modified electrode. These experimental results are consistent with the reported literatures (Lu et al., 2009; Mu et al., 2011). The electrochemical reactions of the Ni^{2+}/Ni^{3+} peaks may be as follows:

$$Ni + 2OH^- - 2e \rightarrow Ni(OH)_2$$

$$Ni(OH)_2 + OH^- - e \rightarrow NiO(OH) + H_2O$$

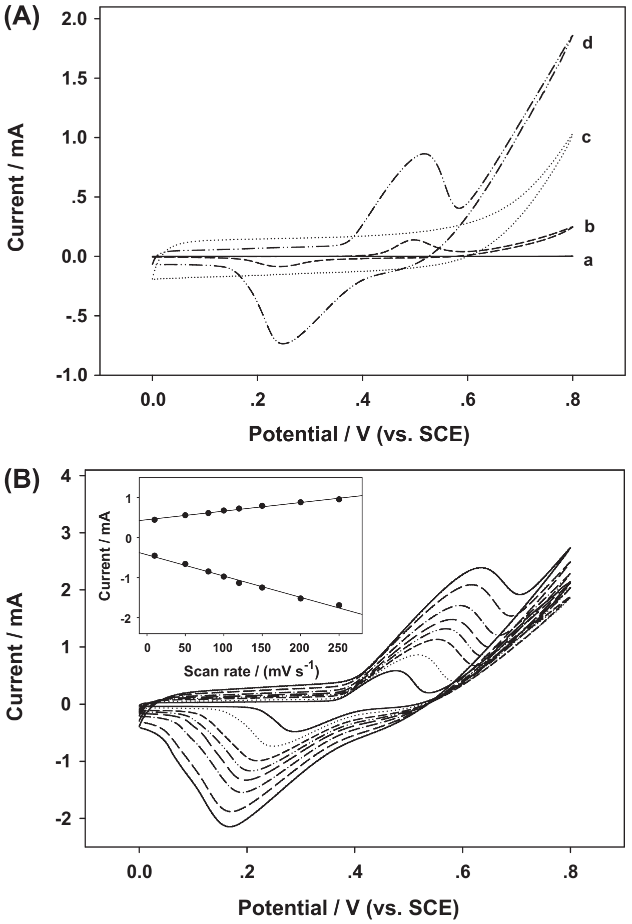

Fig. 2. Cyclic voltammograms obtained in 0.1 M NaOH solution at bare (a), NiNPs (b), SMWNTs (c) and NiNPs/SMWNTs nanohybrids (d).

Fig. 2(B) depicts the cyclic voltammograms of the NiNPs/SMWNTs modified electrode in 0.1 M NaOH solution at different scan rates. It can be seen that the peak-to-peak separation becomes widened with increasing scan rate. The peak potential shifts to increasingly high potentials with increasing scan rate. In the range of 20–250 mV s^{-1}, both the anodic and the cathodic peak current increase linearly with the scan rates (correlation coefficients of 0.991 and 0.990 for anodic and cathodic peaks, respectively), indicating that the electrochemical kinetics reaction is surface-controlled (Fig. 2(B) inset). We examined the stability for NiNPs/SMWNTs modified electrode by recording its 15 consecutive CV curves in 0.1 M NaOH at a scan rate of 50 mV s^{-1}. There is no obvious peak current change during 15 consecutive curves (Fig. S1 in Supplementary Materials), implying that the NiNPs/SMWNTs are very stably modified onto the surface of GCE.

3.3. *Electrocatalytic oxidation of glucose*

In order to address the analytical applicability of the NiNPs/SMWNTs nanohybrids, we investigated the electrocatalytic activity of the as-prepared NiNPs/SMWNTs modified electrodes towards glucose by CVs. Fig. 3(A) presents the CV responses on a NiNPs/SMWNTs modified electrode in 0.1 M NaOH with and without 2 mM glucose. In the absence of glucose, one couple of well-behaved Ni^{2+}/Ni^{3+} redox peaks can be observed. Upon the addition of glucose, an increase of the anodic peak current and a little decrease of the cathodic peak current are obtained, indicating that the NiNPs/SMWNTs nanohybrids exhibit excellent electrocatalytic activity towards the oxidation of glucose. The anodic peak potential shifts to high potential, which may be attributing to the diffusion limitation of glucose at the electrode surface. These results are consistent with the literatures (Lu et al., 2009; Liu et al., 2009). As indicated in literatures, the catalytic effect of the Ni^{3+}/Ni^{2+} redox couple for oxidation of glucose to glucolactone was according to the following reactions:

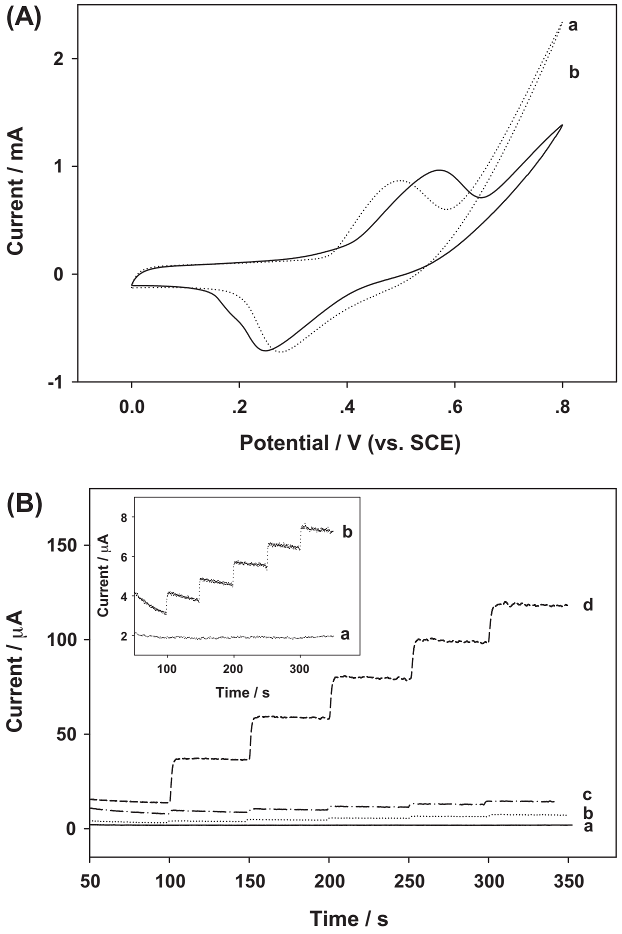

Fig. 3. Cyclic voltammograms of the NiNPs/SMWNTs modified electrode in 0.1 M NaOH solution with (curve b) and without (curve a) 2 mM glucose at a scan rate of 50 mV s^{-1} (A) and amperometric responses of bare (a), NiNPs (b), SMWNTs (c), and NiNPs/SMWNTs (d) modified GC electrodes to successive addition of 100 µM glucose in 0.1 M NaOH at +0.4 V (B).

$$Ni(OH)_2 + OH^- \rightarrow NiO(OH) + H_2O + e^-$$

$$NiO(OH) + \text{Glucose} \rightarrow Ni(OH)_2 + \text{Glucolactone}$$

For comparison, a similar sensor with SMWNTs or NiNPs alone as the electrode modifying material was prepared and tested, and the amperometric responses for successive addition of 100 µM glucose in 0.1 M NaOH at an applied potentials +0.4 V were obtained as shown in Fig. 3(B). It can be seen that the NiNPs (b), and SMWNTs (c) modified electrode only display slight increases in current response to successive addition of glucose. There is no obvious increase in current response for the bare GCE (a). In contrast, the NiNPs/SMWNTs (d) modified electrode exhibits dramatic increases in current response to successive addition of glucose. Such excellent catalytic activity of NiNPs/SMWNTs nanohybrids may be attributed to the synergistic effect of NiNPs and SMWNTs, which includes high catalytic active sites for the glucose oxidation provided by the well-distributed NiNPs on the surface of SMWNTs and high electron transfer rate provided by an efficient electrical network through NiNPs direct anchoring on the surface of SMWNTs. The effect of scan rate on peak current for oxidation of 1 mM glucose was investigated. The anodic and cathodic peak current increase with increased scan rates (Fig. S2 in Supplementary Materials), and the peak currents are proportional to the scan rate (inset), demonstrating a surface-controlled electron transfer process.

3.4. *Optimization of experimental variables*

The impact of applied potentials was systemically investigated on the amperometric response of the NiNPs/SMWNTs electrode to glucose. Constant potential chronoamperometry was performed at the potential range from +0.1 to +0.5 V with a settle interval of 0.05 or 0.1 V of the NiNPs/SMWNTs electrode for successive addition of 100 μM glucose (Fig. S3 in Supplementary Materials). The steady-state current increases gradually from 0 to +0.4 V, and reach the maximum at +0.4 V, then keeps the equilibrium at +0.5 V. Considering that the maximum current response and the fact that high potential may oxidize endogenous interfering species, hence, +0.4 V was chosen as the optimum applied potential.

In nonenzymatic sensors, an alkaline medium can be favorable for enhancing the electrocatalytic activity of the catalysts towards glucose. Hence, we investigated the effect of the NaOH concentration on the response current of the glucose electrooxidation using amperometric technique (not shown). It was found that with the increase of NaOH concentration from 0 to 0.5 M, the current gradually increases because glucose is more easily oxidized and the electrocatalytic activity of NiNPs is greatly enhanced at high pH. However, too much OH^- can block the further electroadsorption of glucose anion (per glucose molecule lost one proton at about −0.12 V) and result in a decrease in response signal current. Furthermore, we also have systematically investigated the effect of different medium such as phosphate buffer (PB), bicarbonate buffer, and borate buffer on the amperometric response for glucose. Under the optimal experiment conditions (concentration, pH, applied potential), it can be observed that the amperometric responses are lower than that in NaOH solution (not shown), possibly due to less glucose anion obtained or less catalytic activity of NiNPs originating from be poisoned by PB. Thus, 0.1 M NaOH solution was chosen as the optimized medium for the subsequent experiment.

We further investigated the effect of the weight ratio of $Ni(NO_3)_2$ to SMWNTs on the electrocatalytic activity towards glucose in 0.1 M NaOH at a potential of +0.4 V. The $Ni(NO_3)_2$/SMWNTs (1:2) exhibits the maximum amperometric response for glucose sensing (Fig. S4 in Supplementary Materials). When the amount of $Ni(NO_3)_2$ is too large, the obtained NiNPs are ease to agglomerate, thus causing glucose inaccessible to single NiNPs surface and lowering the sensitivity. In contrast, the $Ni(NO_3)_2$/SMWNTs (1:4) gives lower sensitivity, possibly due to decreased loading of NiNPs.

The influence of the temperature of the heat treatment of the NiNPs/SMWNTs nanohybrids on the electrocatalytic activity towards glucose was investigated. Considering the fact that the size of NiNP is closely related with the temperature of the heat treatment of the NiNPs/SMWNTs, we further characterized the average sizes and the specific surface areas of the NiNPs on the surface of SMWNTs at different temperatures of the heat treatment. From Table S1 in Supplementary Materials, it can be observed that with the increase of the temperature of the heat treatment, the sizes of NiNPs gradually increase, while the corresponding specific surface areas gradually decrease. The electrocatalytic activity towards glucose achieves the maximum when the average size of NiNPs is 15 nm at 650 °C. When the temperature of the heat treatment is too high, larger sizes of NiNPs can be obtained which result in smaller specific surface area, thus lowering the sensitivity. However, when the temperature of the heat treatment is too low, the sensor also exhibits lower sensitivity in spite of the larger specific surface area, which may be attributed to lower catalytic activity sites of NiNPs originating from lower crystal properties.

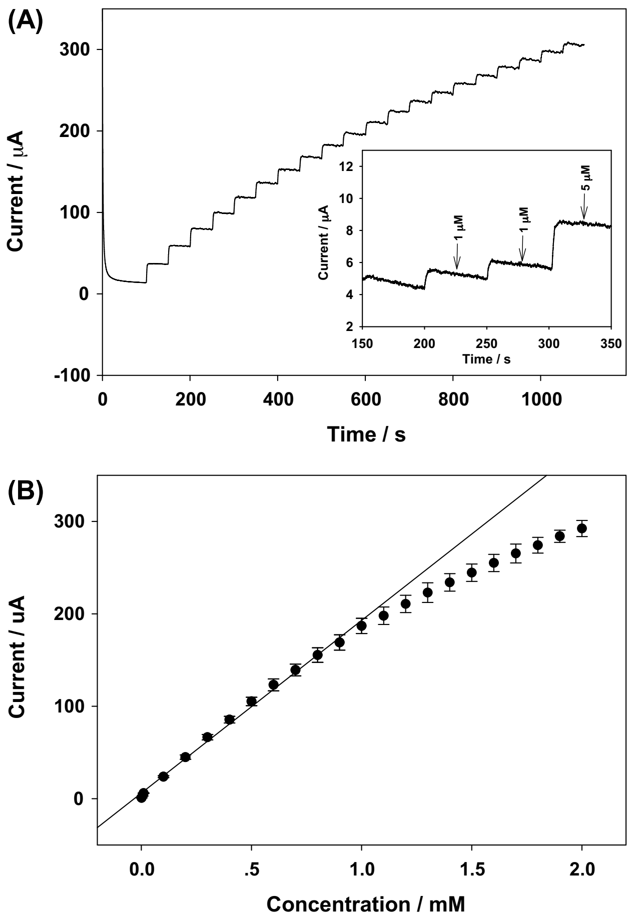

Fig. 4. Amperometric responses of the NiNPs/SMWNTs modified electrodes to successive addition of 100 μM glucose in 0.1 M NaOH at +0.4 V (amperometric response of NiNPs/SMWNTs modified electrodes with the addition of 1 μM, 5 μM, 10 μM) (inset) (A) and its corresponding calibration plot (B).

3.5. *Amperometric sensing of glucose*

For amperometric sensing application, NiNPs/SMWNTs modified electrodes are generally evaluated by measuring current response for glucose under the optimal condition. Fig. 4(A) presents the amperometric response at the NiNPs/SMWNTs electrode for successive addition of 100 μM glucose in 0.1 M NaOH solution at an applied potentials +0.4 V. A steep increase in current responses was obtained after each addition of glucose solution, and a steady-state current was achieved within 3 s, indicating that the NiNPs/SMWNTs catalysts exhibit very sensitive and rapid response characteristics. This might be due to the fact that SMWNTs are highly electroconductive, which provides a low resistance pathway and promotes the electron transfer and reduces the response time. Fig. 4(B) depicts the calibration curve for the electrochemical responses of the NiNPs/SMWNTs electrode to glucose at +0.4 V in the concentration range from 1 μM to 2 mM. The response to glucose exhibits a good linear range from 1 μM to 1 mM with a correlation coefficient of 0.995 and a slope of 186.95 $\mu A\,mM^{-1}$. A sensitivity of 1438 $\mu A\,mM^{-1}\,cm^{-2}$ is obtained by dividing the slope of the linear regression equation by the electroactive surface area (Fig. S5 in Sup-

Table 1
Comparison of the present NiNPs/SMWNTs electrode with other nonenzymatic glucose sensors.

Type of electrode	Response time (s)	Potential (V)	Sensitivity (μA mM^{-1} cm^{-2})	Linear range	LOD (μM)	Reference
NiNP/SMWNTs	3	+0.4	1438	1 μM–1 mM	0.5	Present work
Platinum nanoflower on SWCNTs membrane	–	+0.4	7.266	2 μM–1 mM	2	Su et al. (2010)
Ti/TiO$_2$ nanotube array/Ni composite electrode	–	+0.55	200	0.1 mM–1.7 mM	4	Wang et al. (2010)
Ni nanoparticles loaded carbon nanofiber paste electrode	5	+0.6	–	2 μM–2.5 mM	1	Liu et al. (2009)
MnO$_2$/MWNTs	10	+0.3	33.19	10 μM–28 mM	10	Chen et al. (2008)
Co$_3$O$_4$ nanofibers	7	+0.59	36.25	1 μM–2 mM	0.97	Ding et al. (2010)
Cu nanocubes/well-aligned MWNT arrays	1	+0.55	1096	1 μM–7.5 mM	1	Yang et al. (2010)

plementary Materials). The limit of detection was estimated to be 500 nM at a signal-to-noise ratio of 3.

The performance of the as-prepared NiNPs/SMWNTs catalyst is compared with some of existing nonenzymatic sensor, as shown in Table 1. It can be concluded that the as-prepared NiNPs/SMWNTs catalyst is among the top list of sensors with a higher sensitivity, a faster response speed, and a lower detection limit. These superiorities are believed to be attributed to the high catalytic activity of NiNPs and the electrical network formed through NiNPs directly distributing on the surface of mildly pretreated SMWNTs, which not only can keep their intrinsic excellent electrical conductivity but also facilitate Ni precursor binding to their surface due to their ease of dispersibility. Moreover, the well-distributed NiNPs on the SMWNTs surface can favor single NiNPs easily accessing to glucose, and the electrochemical response for glucose oxidation can be greatly enhanced.

3.6. *Studies of interferences*

One of the major challenges in nonenzymatic glucose detection is to eliminate the electrochemical response generated by some easily oxidizable endogenous interfering compounds such as ascorbic acid (AA), uric acid (UA), dopamine (DA), galactose (GA), and xylose (XY). In the physiological sample, glucose concentration (3–8 mM) is generally much higher than those of interfering species of UA (0.1 mM), AA (0.1 mM), DA (0.1 mM), GA (0.1 mM), and XY (0.1 mM). Nevertheless, these interfering species can produce the oxidation current comparable to that of glucose, attributing to their higher electron transfer rates. It is expected that NiNPs/SMWNTs modified electrodes with a high active surface area can favor a kinetically controlled sluggish reaction (the oxidation of glucose) to a greater extent than a diffusion controlled reactions (the oxidation of interfering species). To verify this, we investigated the amperometric responses of the NiNPs/SMWNTs modified electrode at an applied potential of +0.4 V in 0.1 M NaOH solution with continuous additions of 1 mM glucose, 0.1 mM UA, 0.1 mM AA, 0.1 mM DA, 0.1 mM GA, and 0.1 mM XY. From the current response in Fig. 5, a remarkable glucose signal was obtained comparing to the other five interfering species. Compared to glucose, the interfering species yielded current response ranging from 7.1% (UA), 3.9% (AA), 4.9% (DA), 4.8% (GA) to 5.0% (XY). These results indicated that the NiNPs/SMWNTs could be used for the selective and sensitive detection of glucose with negligible interference from UA, AA, DA, GA, and XY.

3.7. *Reproducibility and stability*

The reproducibility of the NiNPs/SMWNTs modified electrode has been determined. Eight successive amperometric measurements of 100 μM glucose on the electrode yielded a reproducible current with a relative standard deviation (RSD) of 4.0%. The batch-to-batch reproducibility was estimated from the current responses of five electrodes separately prepared under the same condition towards 100 μM glucose, and a RSD of 5.9% was obtained. These results indicated that the NiNPs/SMWNTs modified electrode exhibited the acceptable reproducibility for glucose.

The stability of the NiNPs/SMWNTs modified electrode was evaluated by measuring the current response to 100 μM glucose at every 5 days intervals. When the electrode was not in use, it was stored in air at ambient conditions. It was found that the sensor retained about 90% of its initial response after 60 days, suggesting that the NiNPs/SMWNTs electrode is relatively stable.

3.8. *Real sample analysis*

In order to verify the reliability of the NiNPs/SMWNTs nanohybrids for routine analysis, the sensor was applied to determine glucose in human blood serum samples of healthy people. Here, 60 μL of serum sample was added to 6 mL 0.1 M NaOH solution, and the current response was recorded at +0.4 V. The recovery of glucose was testified using standard addition method with three times addition of pure glucose to the solutions containing the serum samples. The results (Table S2 Supplementary Materials) show that the sensor gives recoveries in the range of 90.7–106.2%, indicating that the as-prepared NiNPs/SMWNTs nanohybrids hold great potential in real sample analysis.

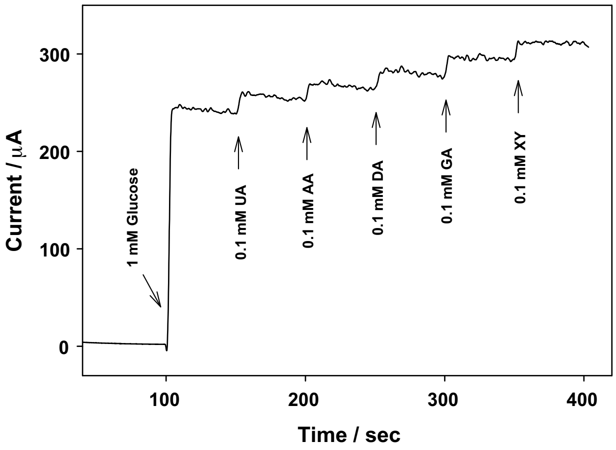

Fig. 5. Amperometric response of the NiNPs/SMWNTs modified electrodes with successive addition of 1.0 mM glucose, 0.1 mM UA, 0.1 mM AA, 0.1 mM DA, 0.1 mM GA, and 0.1 mM XY in 0.1 M NaOH solution at +0.4 V.

4. Conclusions

In summary, a nonenzymatic amperometric sensor based on the NiNPs/SMWNTs nanohybrids for glucose oxidation has been fabricated and investigated. The NiNPs/SMWNTs nanohybrids modified electrodes exhibit a very large electrochemical active surface area and high electrocatalytic activity for the glucose electrooxidation in basic conditions. The amperometric response revealed that the as-prepared sensor based on NiNPs/SMWNTs nanohybrids has high sensitivity, low detection limit, excellent selectivity, and good reproducibility. Thus, the NiNPs/SMWNTs nanohybrids hold the great potential for the development of nonenzymatic glucose sensor.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.bios.2011.08.022.

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