Rapid, sensitive, and reusable detection of glucose by highly monodisperse nickel nanoparticles decorated functionalized multi-walled carbon nanotubes

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**ABSTRACT**

Addressed herein, functionalized multi-walled carbon nanotube (MWCNT) supported highly monodisperse nickel nanoparticles modified on glassy carbon electrode (Ni@f-MWCNT/GCE) were synthesized through microwave assisted method and examined for non-enzymatic glucose sensing in ionic liquids by cyclic voltammetry and chronoamperometry. The results of Ni@f-MWCNT/GCE electrode were compared with NiNPs/GCE electrode and the results revealed that f-MWCNTs increased the electrocatalytic properties of Ni nanoparticles regarding glucose oxidation. They also demonstrated a good linear span of 0.05–12.0 mM and a detection boundary of 0.021 µM. Specifically, in the amperometric signal of the electrodes after 200th cycles, no major change was observed. This non-enzymatic glucose sensor presents one of the record electrocatalytic activity, stability and response towards glucose under the optimized situations. As a result, prepared novel Ni@f-MWCNT/GCE was utilized to detect glucose in real serum species.

**1. Introduction**

Diabetes is a chronic disease caused by increased of blood glucose levels and takes place at the beginning of a major health problem in the worldwide (Fu et al., 2015; Choi et al., 2015). Since 1960, advancement of recognizing small molecules via electrochemical systems has extensively considered very important. Sugar oxidation by electrocatalysis carries importance in various areas, such as therapeutic applications, wastewater treatment, biological fuel cell development, and analytical applications of food enterprises. Glucose oxidation has been accepted as a basic step for the oxidation of substantial organic materials and examined through many scientists (Park et al., 2006; Kang et al., 2007; Li et al., 2009; Wang et al., 2009; Si et al., 2013a, 2013b). In spite of the fact that the glucose oxidation is thermodynamically advantageous, its prolonged reaction kinetics using typical electrodes slows down its usage in analytical analysis (Guo et al., 2013a, 2013b, 2013c). In addition, the extensive over-potential of this reaction needs a high applied potential, bringing about diminished selectiveness and, furthermore, oxidation reaction products usually destroy the surface of the electrodes (Guo et al., 2013a, 2013b, 2013c). Attraction is still existent in the improvement of materials that can be used in the electrocatalytic glucose reduction to lessen the normally large over potentials experienced in its direct reduction at nearly all surfaces of electrodes. For electrochemical glucose detection, enzymatic glucose sensors have made several disadvantages such as high cost, instability, immobilization problems between the electrode and the enzyme. In contrast to enzymatic sensors, non-enzymatic glucose sensors have benefits like being economic, high sensitivity, long-term stability especially for the glucose oxidation (Park et al., 2006; Kang et al., 2007; Li et al., 2009) Electroactivity degree toward carbohydrates, particularly glucose, has been good when various transition metal and metal oxide electrodes (Au, Co, Cu, In, Ni, NiO(OH), Pt, RuO2, Ru,WO3, etc.) (Wang et al., 2009; Si et al., 2013a, 2013b; Guo et al., 2013a, 2013b, 2013c; Wang et al., 2013; Huo et al., 2014a, 2014b; Li et al., 2012; Ye et al., 2004) and different metal combinations or composite electrodes (Au–Cu, Au–Ni, Ni–Cr, Pt–Pd, etc.) (Wang et al., 2009; Si et al., 2013a, 2013b; Gavalias et al., 2004; Merkoci et al., 2005; Wang and Lin, 2008) are utilized. Additionally, a few unique compounds have been reported as electrocatalysts to adjust the surfaces of electrodes to oxidize glucose (Chang et al., 2013; Zhao et al., 2013; Kim et al., 2013;...
Since carbon nanotubes (CNTs) (Mu et al., 2011a, 2011b) have unique properties, for example, critical mechanical quality, large surface area, fabulous electrical conductivity, and great chemical stability, they have attracted researchers for various uses. Other than different utilizations of the CNTs, they are additionally of enthusiasm for making biosensors and electrochemical sensors (Nai et al., 2013; Rasee and Fakhari, 2013). Lately, some metal nanoparticles and CNT composites were presented to demonstrate superior sensitivity on small molecules, for example, hydrogen peroxide (Zhao et al., 2007a, 2007b), glucose (Yu et al., 2012) and methanol (Çelik et al., 2016a, 2016b, 2016c). A few examinations managing use of carbon nanotubes (Lu et al., 2009a, 2009b; Gao et al., 2011) as promising catalyst supports have as of now been completed. This study concentrates on utilization of multi-walled carbon nanotubes (MWCNTs) as catalyst support for the adjustment of a glassy carbon–Ni nanoparticles electrode to enhance its electroactivity towards glucose (Lu et al., 2013a, 2013b; Zhang et al., 2013; Liu et al., 2009; Lu et al., 2013a, 2013b; Zhu et al., 2011; Ding et al., 2010; Chen et al., 2013a, 2013b; Si et al., 2013a, 2013b). These metal nanoparticles (NPs), give wide applications, for example, solid adsorption, substance dependency efficient electro catalytic reaction of sensors and biosensors. Moreover, in various studies, carbon-based materials are utilized as support material. Among of these, carbon nanotubes (CNTs) have large surface area, amazing conductivity and repairman toughness. These properties of CNTs give all the more quickly electron-exchange between metal nanoparticles and anode surface. To build the viability and solvency of multi-walled carbon nanotubes, practical gatherings side-dividers are connected by utilizing a great deal of procedures. One of them is the treatment with solid acids. Thusly, metal nanoparticles with altered carbon nanotubes are favoured for particularly sensor applications (Wang et al., 2012a, 2012b; Zhang et al., 2011, 2012a, 2012b; Mathew and Sandhyarani, 2013; Chen et al., 2013a, 2013b). In this study, highly monodisperse Ni nanoparticles supported on functionalized multi-walled carbon nanotubes on glassy carbon (Ni@f-MWCNT/OCE) electrode was used drop-casting method toward the oxidation of glucose for non-enzymatic sensor. Prepared monodisperse Ni@f-MWCNT nanocatalysts were investigated for the stability, selectivity, sensitivity, linear range limit of detection (LOD) for non-enzymatic glucose sensor.

2. Experimental section

2.1. Synthesis of monodisperse Ni@f-MWCNT NPs

To form a stable suspension, 0.25 mmol of Ni(Ac)₂ was dispersed in 30 mL ethylene glycol solution under brisk stirring. The pH was adjusted using NaOH—EG solution. Next, the beaker was kept in the centre of microwave oven at 1200 W for 60 s. Under this condition, EG adjusted using NaOH—EG solution was filtered, and then washed several times with deionized water and acetone. To stabilize the metal nanoparticles against agglomeration, the microwave synthesis was carried out in the presence of OA (oleylamine) where OA is used as a capping agent. The prepared NPs were mixed with f-MWCNTs (1:1, v:v) by an ultrasonic tip sonicator. Lastly, the Ni@f-MWCNT NPs were dried under vacuum at room temperature (Xiu-tian-feng et al., 2014; Lin et al., 2013).

3. Results and discussion

3.1. Material characterization

The characterization of f-MWCNT has been shown in Fig. S1 in detail. Moreover, by the help of SEM, Ni@f-MWCNT NPs’ morphologies were determined. The Fig. S1(d) and (e) demonstrates a representative SEM image of monodisperse Ni@f-MWCNT NPs that has the mass of the Ni nanoparticles, having an approximate diameter of 9 nm. This image indicates that the pure MWCNT having lengths up to several micrometers and diameters up to few nanometers has no impurity on their surfaces.

It can be seen that the monodisperse Ni nanoparticles decorated MWCNTs are randomly distributed with uneven nanoparticles decorated on the surface of the MWCNT tubes, and it seems like the plant root nodules. The multi-walled-nanotubes were connected with Ni and Ni NPs attached on multi-walled-nanotubes. The existence of nickel and carbon was proved by EDS results (Fig. S1,e) (Xiu-tian-feng et al., 2014; Lin et al., 2013; Huo et al., 2014a, 2014b; Karatepe et al., 2016).

The Fig. 1(a) displays a representative TEM image of monodisperse Ni@f-MWCNT NPs. In this TEM image, it can be seen that all particles exist homogeneously on the CNT surface and no agglomerations or aggregations were observed. The average particle size was measured as 6.96 ± 1.05 nm. The Fig. 1(c) is the HRTEM image of Ni NPs and displays the atomic lattice fringes. Here, Ni (111) spacing of 0.20 nm of Ni NPs is exactly same with nominal Ni (111) spacing which reasserts the nanoparticle formation. The Fig. 1(b) and (d) present the EELS elemental color-mapping and the EELS line profile scanned on the arrow of Ni@f-MWCNT NPs. The Fig. 2(a) demonstrates the Raman spectra that exhibits that the core level of Ni 2p₃/₂ was at 853.2 eV. This finding suggests that the most of the Ni atoms were in the metallic oxidation state (Çelik et al., 2016a, 2016b, 2016c). The particular Ni(II) peak from 861.5 eV as shown in Fig. 2(a) and (b) may indicate the oxidation occurred in the surface and/or chemisorption of environmental oxygen while the NPs were prepared. Moreover, using the relative peak area of the Ni 2p₃/₂ spectrum, Ni(0) to Ni(II) ratio of the catalysts was found to be 3.27. Fig. 2(c) represents the Raman spectrum of f-MWCNTs that shows an augmented D/G ratio compared to the ratio that pristine MWCNTs have (ID/IG=1.25 for f-MWCNTs and ID/IG=1.09 for pristine MWCNTs). Fig. 2(d) and (e) show the atomic force microscopy (AFM) (Çelik et al., 2016a, 2016b, 2016c) results that explain the height and lateral diameter distribution. Although the AFM lateral diameter of the catalyst is much

![Fig. 1. (a) Representative TEM image and nanoparticle size histogram, (b) EELS elemental color-mapping, (c) Representative HRTEM image, and (d) EELS line profile scanned on the arrow of Ni@f-MWCNT NPs.](image-url)
larger than the size of those obtained by the SEM and TEM which is very likely due to the tip contamination and/or the tip convolution. The obtained AFM particle height values of monodisperse Ni@f-MWCNT NPs are in good agreement with the results obtained by the TEM.

3.2. Electrochemical properties

3.2.1. Cyclic voltammetry measurements

By cyclic voltammetry, the glucose oxidation at the bare GC electrodes and modified GC electrodes was studied. Fig. 3(a) shows the cyclic voltammetric responses that were obtained in 0.10 M NaOH at the Ni/GCE and Ni@f-MWCNT/GCE electrodes. In the basic medium, to detect glucose, CV data were obtained by glassy carbon electrode and by glassy carbon electrode exposured to modification. The data were achieved by Ni@GCE, Ni@f-MWCNT/GCE (a,c-without glucose) and by Ni@GCE, Ni@f-MWCNT/GCE (b,d-with 0.1 mM glucose). The anodic and cathodic peaks stand for Ni(II)/Ni(III) couple were detected at about 0.56 and 0.33 V vs. Ag/AgCl, at a scan rate of 50 mV s⁻¹, respectively. Notwithstanding the cathodic and anodic peak potentials are very close for both Ni/GCE and Ni@f-MWCNT/GCE modified electrodes, the cathodic and anodic peak currents in the Ni@f-MWCNT/GCE modified electrode are significantly enhanced. This relative enhancement in the peak current is due to a greater surface area of the Ni@f-MWCNT/GCE modified electrode. These results indicated that both Ni/GCE and Ni@f-MWCNT/GCE can catalyse the electro-oxidation of glucose to gluconolactone (Zhu et al., 2011). The glucose detection mechanism involved is proposed as follows: a layer of Ni(OH)₂ is generated on the surface of Ni@f-MWCNT/GCE during the oxidation of glucose. The measured currents are enhanced due to the increased surface area and the catalytic activity of Ni@f-MWCNT/GCE.

Fig. 2. (a) XPS spectra of Ni 2p for Ni@f-MWCNT, (b) XPS spectra of Ni 2p 3D view, (c) Raman spectrum of f-MWCNT, (d) AFM 3D view, and (e) AFM phase view of Ni@f-MWCNT.

Fig. 3. (a) Cyclic voltammograms obtained for “a)Ni/GCE” and “c)Ni@f-MWCNT/GCE” (without glucose) and “b)Ni/GCE” and “d)Ni@f-MWCNT/GCE” (with 0.1 mM glucose) at 50 mV/s scan rate in 0.1 M NaOH solution. (b) Cyclic voltammograms of the Ni@f-MWCNT/GCE in the presence of 1 mM glucose at varying scan rates: (a) 20, (b) 40, (c) 60, (d) 80, (e) 100, (f) 120, (g) 140, (h) 160, (i) 180, (j) 200 mV s⁻¹, respectively. (Inset: plot of peak current (IP) vs. scan rate (V)).
LSV process in alkaline medium. The produced Ni(OH)$_2$ is further oxidized to NiOOH on the Ni@f-MWCNT/GCE surface. The oxidation of glucose to glucolactone catalyzed by the Ni(OH)$_2$/NiOOH redox couple according to the following reactions leads to an increase of anodic current:

\[
2\text{Ni(II)} \rightarrow 2\text{Ni(III)} + 2e^-
\]

\[
2\text{Ni(III)} + \text{glucose} \rightarrow 2\text{Ni(II)} + \text{glucolactone}
\]

In Fig. 3(b), the anodic peak currents obtained from the Ni@f-MWCNT/GCE electrode in 0.1 M NaOH buffer at different scan rates during the experiments at different scan speeds are demonstrated.

The electrochemical behaviours of Ni@f-MWCNT/GCE were investigated using 0.5 mM glucose at several scan rate values in 0.1 M sodium hydroxide (Fig. 3(b)). As it is seen, reduction-oxidation peak current of glucose was enhanced with increasing scan speed from 20 mV/s to 200 mV/s. This result suggests that the electro-catalytic glucose oxidation is increased charge-transfer kinetic limitations within the reactions among reduction-oxidation of glucose and Ni@f-MWCNT/GCE. At this point, it is worth mentioning that as 0.1 M of NaOH (a strong supporting electrolyte at high concentration) is employed in all electrochemical investigations, expected chance of potential shift to more positive values because of higher ohmic drop is negligible. Furthermore, the anodic peak current measured at the Ni@f-MWCNT/GCE modified electrode was found to be importantly greater than the current value that the Ni/GCE electrode had. The reason for this finding could be high electrode surface area when carbon nanotubes exist (Fig. S2).

3.2.2. Optimization of sensor and amperometric measurements

The effect of glucose amount on anodic peak current was also examined by the cyclic voltammetry using Ni@f-WCNT/GCE. Fig. 4(a) shows CV data obtained by Ni@f-MWCNT/GCE electrode with different glucose amounts (varying from 0.1mM to 0.6 mM in 0.1 M of sodium hydroxide). In this figure, the relationship between glucose amount and oxidation peak intensity was displayed. It is easy to see that linear results were obtained when the glucose concentration was up to 12 mM. The detection limit was found to be 2.10×10$^{-5}$ mmol/L which was three times of the signal to noise ratio. At higher glucose concentrations, the current varies from the linearity, and the possible reason for this could be passivating the electrode and/or glucose isomers generation as these are known to happen in basic media. In the meantime, saturations of active sites at the electrode surface occurred and therefore the peak current tends to level off at higher glucose concentrations (Fig. 4(a)–(c)).

Fig. 4(b) represents the amperometric responses of the monodisperse Ni@f-MWCNT/GCE electrode in 0.1 M NaOH solution at 0.56 V with increment of glucose in 0.1 mM and 25 µM steps (insets in Fig. 4(b) and Fig. 4(c), respectively). The electrode had an immediate response when glucose was added, and after 3–5 s, the current reached steady-state. In Fig. 4(b), linear equation between the measured current (I) and the glucose was presented. It can be seen that very high correlation coefficients of 0.9983 and 0.9897 were got in the range of 25 µM to 1 mM glucose. One of the lowest detection limits was found to be at the 0.021 µM glucose (S/N=3).

3.2.3. Reproducibility, stability and anti-interference property

The following molecules, namely DA (Dopamine), UA (Uric Acid),...
Table 1
The glucose detection in human blood serum samples (HBS) with the commercial biosensor and our glucose sensor.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Glucose (mM) (proposed sensor)</th>
<th>RSD (Relative Standard Deviation)²</th>
<th>Glucose (mM) (commercial glucose sensor)</th>
<th>Recovery (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.8</td>
<td>4.5%</td>
<td>5.6</td>
<td>98.0</td>
</tr>
<tr>
<td>2</td>
<td>4.5</td>
<td>4.2%</td>
<td>4.3</td>
<td>92.0</td>
</tr>
<tr>
<td>3</td>
<td>7.0</td>
<td>3.7%</td>
<td>6.7</td>
<td>96.4</td>
</tr>
<tr>
<td>4</td>
<td>3.8</td>
<td>3.5%</td>
<td>3.7</td>
<td>98.7</td>
</tr>
<tr>
<td>5</td>
<td>6.7</td>
<td>4.6%</td>
<td>6.5</td>
<td>97.8</td>
</tr>
</tbody>
</table>

AA (Ascorbic Acid), fructose, lactose and NaCl typically coexist with glucose in real samples such as human blood when the glucose is determined. Therefore, we studied the interference by measuring the amperometric responses and the results were given in Fig. 4(d). In this figure, experimental results run at 1 mM concentrations and at 0.5 V were depicted. In our results, when 0.1 mM of AA, DA, UA, NaCl were added, there was no distinct current response except lactose and fructose. When 0.1 mM of lactose and fructose were added, current response has been observed. Besides, when there was 1 mM glucose addition, an important current response was observed. Thus, using monodisperse Ni@f-MWCNT/GCE, interference of biomolecules to glucose response is negligible.

In the present study, long-term stability of monodisperse Ni@f-MWCNT/GCE was also examined. In this part, 10 mM glucose and 0.1 M NaOH solutions were used, and the results were given in Fig. S3. Here, changes in the anodic peak currents of the electrode under dry conditions at room temperature were measured. For both modified electrodes, declines in peak currents occurred in the first three weeks. It is worth noting that the peak current decline of the Ni/GCE is much more declared than the result of Ni@f-MWCNT/GCE modified electrode. In addition, for both cases, the reproducibility of the responses are found to be 70 days. All these findings present that the Ni@f-MWCNT/GCE modified electrode is stable for long-terms and suitable for storage. Besides, monodisperse Ni@f-MWCNT/GCE are compared with other Ni based sensor as shown in Table S1 in terms of LOD, sensitivity and linear range and this table shows that monodisperse Ni@f-MWCNT/GCE has much higher performances compared to the others. (Lu et al., 2009a, 2009b; Mu et al., 2011a, 2011b; Yang et al., 2013; Wang et al., 2012a, 2012b; Kong et al., 2010; Zhang et al., 2012a, 2012b; Shen et al., 2016).

In our study, the applicability of the monodisperse Ni@f-MWCNT/GCE electrode was tested using five different human blood serum samples to determine glucose concentration. In those experiments, 50 µL of each blood serum was mixed with 10 mL of 0.1 M NaOH and then their anodic peak currents were measured by utilizing the Ni@f-MWCNT/GCE modified electrode. The experimental results obtained from these runs are summarized in Table 1 and these data were compared to a standard hospital blood glucose determination method by using a commercial glucose sensor. In Table 1, it can be seen that the obtained glucose results and commercial sensor results are in good agreement. Furthermore, excellent recovery results were obtained (between 96.4% and 98.7%).

4. Conclusions

Highly monodisperse Ni@f-MWCNT/GCE nanocomposites were successfully synthesized using a simple and solvent-free method. The synthesized nanocomposites were like plant root nodules. These novel nanocomposites were used for glucose detection and a non-enzymatic electrochemical sensor was built. This non-enzymatic glucose sensor displays an outstanding sensitivity (70 mA mM⁻¹ cm⁻²) at +0.5 V. Its detection limit was achieved as 0.021 µM. As the synthesis of nanocomposites is easy and they have excellent electrochemical sensing properties, the Ni@f-MWCNT/GCE is a very good non-enzymatic glucose sensor candidate. Our results showed that the reactivity of Ni@f-MWCNT/GCE was significantly improved when f-MWCNTs was used as a support material for glucose oxidation in alkaline medium. The unique structure, the specific interactions between Ni and f-MWCNTs and large surface area to volume ratio of f-MWCNTs may lead to a one of the record electrocatalytic activity. Another advantageous feature of the Ni@f-MWCNT/GCE is its stability, as it showed great stability even it was kept under dry conditions for more than ten weeks. In addition, successful results were gathered when human serum samples were used to determine glucose with the developed modified electrode. As a result, it was observed that the glassy carbon anode altered by Ni nanoparticles and MWCNT (Ni@f-MWCNT/GCE) is profoundly viable electrode for glucose oxidation.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.bios.2017.01.045.

References