



Third-generation electrochemical biosensor based on nitric oxide reductase immobilized in a multiwalled carbon nanotubes/1-*n*-butyl-3-methylimidazolium tetrafluoroborate nanocomposite for nitric oxide detection

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ABSTRACT

Nitric oxide (NO) has a crucial role in signaling and cellular physiology in humans. Herein, a novel third-generation biosensor based on the *Marinobacter hydrocarbonoclasticus* metalloenzyme (nitric oxide reductase (NOR)), responsible for the NO reduction in the denitrifying processes, was developed through the direct adsorption of a new nanocomposite (multiwalled carbon nanotubes (MWCNTs)/1-*n*-butyl-3-methylimidazolium tetrafluoroborate (BMIMBF₄)/NOR) onto a pyrolytic graphite electrode (PGE) surface. The NOR direct electron transfer behavior (formal potential of -0.255 ± 0.003 V vs. Ag/AgCl) and electrocatalysis towards NO reduction (-0.68 ± 0.03 V vs. Ag/AgCl) of the PGE/[MWCNTs/BMIMBF₄/NOR] biosensor were investigated in phosphate buffer at pH 6.0. Large enzyme loading (2.04×10^{-10} mol/cm²), acceptable electron transfer rate between NOR and the PGE surface ($k_s = 0.35$ s⁻¹), and high affinity for NO ($K_m = 2.17$ μmol L⁻¹) were observed with this biosensor composition. A linear response to NO concentration (0.23–4.76 μmol L⁻¹) was perceived with high sensitivity (0.429 μA/μmol L⁻¹), a detection limit of 0.07 μmol L⁻¹, appropriate repeatability (9.1% relative standard deviations (RSD)), reproducibility (6.0–11% RSD) and 80–102% recoveries. The biosensor was stable during 1 month retaining 79–116% of its initial response. These data confirmed that NOR incorporated in the MWCNTs/BMIMBF₄ nanocomposite can efficiently maintain its bioactivity paving a new and effective way for NO biosensing.

1. Introduction

Nitric oxide radical (NO, herein abbreviated as NO), produced in humans from L-arginine by the action of NO synthases, is one of three fundamental gasotransmitters (together with hydrogen sulfide and carbon monoxide) [1,2]. NO sensing is needed in a variety of applications, including medical and pharmaceutical industry [3], asthma monitoring [4], human breath [5], rat kidney monitoring [6], among others. Excessive amounts of NO can damage cells and cause many pathological conditions including neurodegenerative diseases, endothelial dysfunction and cancer [7]. Therefore, the development of efficient, fast and selective methods capable of NO detection in the cellular milieu has been in the last years a hot research topic [8].

In bacteria, NO is an intermediate in denitrification, a "respiratory"

pathway, where nitrate is reduced to dinitrogen [9]. In this pathway, NO is reduced into nitrous oxide (N₂O), in a reaction catalyzed by the specific nitric oxide reductase (NOR) enzyme [10,11]. The specificity and efficiency of this enzyme towards NO make them a very interesting target to develop a new biosensor for the NO detection. Until now, NOR has not been used in electrochemical biosensors but, concerning its electrochemical characteristics reported by few authors [12–15], its application in third-generation biosensors development could be considered. Third generation biosensors are based on the direct electron transfer (DET) of proteins, where the absence of mediator is the main advantage providing high selectivity [16]. Because they operate in a closer potential window to the redox potential of the protein, these biosensors are less prone to interfering reactions [16]. However, the stabilization of the enzyme within the biosensor can be a major problem

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[17,18]. Multiwalled carbon nanotubes (MWCNTs) have been widely used as solid platforms to immobilize enzymes in electrochemical biosensors due to their unique physical and chemical properties, namely easy functionalization, high electric conductivity and large surface area, enhancing the electrocatalysis [19–22]. Additionally, room temperature ionic liquids (ILs) may act as electrolytes and solvents in biosensor design [23] being good dispersants for MWCNTs [24]. ILs are a broad class of salts that are liquid below 100 °C [25] and have been recognized as green solvents (as alternative to volatile organic solvents) due to their negligible vapor pressure, good thermal stability and biocompatibility [26]. These sustainable characteristics offer benefits, namely simplicity of containment, recovery and recycling facility [27]. In electrochemistry, ILs also exhibit a wide potential window and appropriate intrinsic conductivity and viscosity [23,28]. Recently, they have been successfully explored in the preparation of IL-carbon nanomaterial hybrids since synergistic effects have been noticed, offering unique advantages for electrodeposition, electrosynthesis and electrocatalysis [29]. Furthermore, these composite materials can also be used as immobilization matrix to entrap proteins and enzymes [29,30].

BMIMBF₄ is composed by a small anion tetrafluoroborate and a large organic cation 1-*n*-butyl-3-methylimidazolium. The high potential applicability of this IL for electrochemical biosensors development can be assessed by the reported studies regarding enzymatic and heme-protein third generation biosensors (Table 1S and 2S, Supplementary Material). The main applied enzymes (presented by decreasing order of number of studies) were glucose oxidase, horseradish peroxidase, but others, such as choline oxidase, laccase, catalase, superoxide dismutase and chloroperoxidase have been also tested but in a more limited way; the involved substrates were methomyl, superoxide anion, glucose, cholesterol, choline, trichloroacetic acid and hydrogen peroxide (Table 1S, Supplementary Material). Furthermore, and because NOR is a hemic enzyme, the heme-protein biosensors that have been described using BMIMBF₄ were also reviewed (Table 2S, Supplementary Material). Hemoglobin, myoglobin and cytochrome *c* were exploited for H₂O₂, trichloroacetic acid and nitrite biosensing [31–33]. As far as we know, BMIMBF₄ or NOR enzyme were not yet explored for the development of biosensors for NO.

Thus, the main aim of this study was to develop a novel third-generation enzymatic biosensor for NO determination taking advantage of the inherent features of *Marinobacter hydrocarbonoclasticus* NOR, MWCNTs and BMIMBF₄. With this goal in mind, the selected metalloenzyme (which is not commercially available) was purified, characterized, and subsequently incorporated in an optimized MWCNTs/BMIMBF₄ nanocomposite, which was used to modify a pyrolytic graphite electrode (PGE). The DET behavior and electrocatalysis towards NO reduction of the PGE/[MWCNTs/BMIMBF₄/NOR] biosensor were investigated. The optimized approach provided high biosensor sensitivity and stability.

2. Materials and methods

2.1. Reagents

MWCNTs-COOH (thin, extent of labeling: > 8% carboxylic acid functionalized, avg. diam. × L 9.5 nm × 1.5 μm), BMIMBF₄ (≥ 97.0%), 2-phenylethanol (PE; ≥ 99.0%), potassium hexa-cyanoferrate (II) trihydrate (C₆FeK₄N₆·3H₂O; ≥ 99%), *N,N*-dimethylformamide (DMF; 99%), potassium hexa-cyanoferrate (III) (C₆FeK₃N₆; ≥ 99%) were purchased from Sigma-Aldrich (Steinheim, Germany). Ethanol (EtOH; 99.5%), sulfuric acid (H₂SO₄; 96%) and *n*-dodecyl-β-D-maltoside (DM) were obtained from Panreac (Barcelona, Spain). Potassium dihydrogen phosphate (KH₂PO₄, p.a.) and di-potassium hydrogen phosphate (K₂HPO₄, p.a.) were used to prepare phosphate buffer (100 mmol L⁻¹, pH 6.0); they were bought from Riedel-de-Haën (Germany) as well as potassium hydroxide (p.a.). NO solutions of different concentrations were prepared by dilution from a buffer standard stock solution of

100 μmol L⁻¹, prepared by bubbling a 5% NO/95% He gas mixture (Air Liquid, Portugal) into buffer 100 mmol L⁻¹ phosphate buffer pH 6.0 [34]. All solutions and stock were prepared immediately before being used. Ultrapure water obtained from a Millipore water purification system (18 MΩ, Milli-Q, Millipore, Molsheim, France) was used in all assays.

2.2. NOR purification and characterization

NOR was purified from membrane extracts of *Marinobacter hydrocarbonoclasticus* grown anaerobically as described by Prudêncio et al. [35]; the NOR preparation used in these studies was evaluated by sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) (Bio-Rad, Mini-PROTEAN® Tetra Handcast Systems, Portugal) based on the protocol of Laemmli [36] and UV-vis spectrum (UV 1800-Shimadzu, 250–800 nm, Germany). An ISO-NO Mark II amperometric sensor (2 mm, World Precision Instruments, Inc., UK: one unit corresponds to 1 μmol of NO/min) was used to achieve the specific activity of 760 U/mg (14 mg/mL) (determined as described previously by Timóteo et al. [34]).

2.3. Biosensor fabrication

Preparation of the modified electrode included the pretreatment of a pyrolytic graphite electrode (PGE; A = 7.07 mm²; ALS Co., Ltd; Tokyo, Japan) and subsequent immobilization of the prepared nanocomposite on it. The PGE was successively polished with alumina powder (1.0 and 0.3 μm, Gravimeta Lda, Portugal), ultrasonicated with ethanol and washed with ultra-pure water for 10 min. PGE surface activation was performed by cyclic voltammetry (CV) in H₂SO₄ 0.5 mol L⁻¹ at 100 mV/s in the range of 0 V to 1.6 V vs. Ag/AgCl/Cl⁻ sat. For the preparation of MWCNTs/BMIMBF₄/NOR nanocomposite, the optimum amount of 6 μL of 1.0 mg/mL MWCNTs (dispersed in DMF) was mixed with 4 μL of BMIMBF₄ and 4 μL of NOR (760 U/mg; 14 mg/mL). The as prepared nanocomposite was immobilized on the PGE surface by the solvent casting technique and the solvent was evaporated with a very gentle nitrogen flow.

2.4. Electrochemical measurements

A three-electrode cell consisting in the modified PGE (PGE/MWCNTs; PGE/[MWCNTs/BMIMBF₄], PGE/[MWCNTs/BMIMBF₄/NOR] or PGE/NOR) as the working electrode, and a platinum wire and silver/silver chloride saturated with KCl 3 mol L⁻¹ as the secondary and reference electrodes, respectively. Electrochemical experiments were performed with an Autolab PGSTAT 204 potentiostat-galvanostat controlled by GPES 4.9.7 and Nova 1.10 software (Metrohm Autolab). The assays were conducted in one conventional compartment cell using as electrolyte 100 mmol L⁻¹ of phosphate buffer with 0.02% DM and 0.01% PE at pH 6.0 for NOR redox behavior and NO bioelectrocatalysis or the same buffer with 5.0 mmol L⁻¹ [Fe(CN)₆]^{3-/4-} for characterization of the biosensor construction. The redox behavior of NOR was evaluated by CV applying a step potential of 3 mV and a potential range of 0.4 to -1.0 V, with a previous deoxygenation of the electrolyte using high purity nitrogen gas (99.999%) during 20 min. NO bioelectrocatalysis was performed in the same potential window and with the same deoxygenation step using square wave voltammetry (SWV) (because of its fast electroanalytical response and high sensitivity) at a frequency of 10 Hz, amplitude of 20 mV and step potential of 3 mV. For each NO tested concentration, a new solution was prepared by adding an aliquot of the freshly prepared 100 μmol L⁻¹ NO stock standard solution [34] to the deoxygenated electrolyte solution with the help of a microsyringe. NO has a very short half-life in biological milieu (typically within the seconds range [37]), therefore, in this work, electroanalytical data were based on the maximum peak current, which was attained in the first scan.

Electrochemical impedance spectroscopy (EIS) assays were performed in the buffer solution with 5.0 mmolL^{-1} $[\text{Fe}(\text{CN})_6]^{3-/4-}$ (pH 6.0) applying a frequency range from 10^{-1} to 10^5 Hz with an amplitude perturbation of 5 mV and 0.2 V as conditioning potential.

2.5. Morphological characterization

The morphological biosensor characterization was realized by a High resolution Environmental Scanning Electron Microscope with X-Ray Microanalysis and Electron Backscattered Diffraction analysis: Quanta 400 FEG ESEM / EDAX Genesis X4M (Schottky).

2.6. Statistical analysis

Statistical analysis was performed using SPSS software (IBM SPSS Statistics 20). The non-parametric Wilcoxon Mann-Whitney U test was used due to non-normal distribution of the data. Statistical significance was defined at $p \leq 0.05$.

3. Results and discussion

3.1. Biosensor construction

3.1.1. Electrochemical characterization

CV and EIS were used to characterize the impact of each modification on the electrochemical behavior and interface properties of the biosensor and thus to optimize its construction. Assays were performed with 5.0 mmolL^{-1} $[\text{Fe}(\text{CN})_6]^{3-/4-}$ as redox probe in phosphate buffer (pH 6.0).

Firstly, the optimum MWCNTs:BMIMBF₄ ratio in the nanocomposite was established by testing six different proportions (0:10, 2:8, 4:6, 6:4, 8:2 and 10:0 (v/v)) and maintaining constant the total drop cast volume (10 μL) (Fig. 1(A)). Synergetic effects were attained since higher sensitivity was reached when both composite constituents were present, when compared with the electrode modification with only one of the individual component (MWCNTs or BMIMBF₄) (Fig. 1(A) and (B)). The decrease of the MWCNTs volume from 10 till 6 μL and simultaneous increase of BMIMBF₄ in the nanocomposite from 0 till 4 μL originated the best significant ($p < 0.05$) enhancement of the signal (72.5% higher current for PGE/[MWCNTs/BMIMBF₄] than PGE) (Fig. 1(B)), thus the 6:4 (v/v) MWCNTs:BMIMBF₄ ratio was considered the optimum one. Moreover, it can be observed that MWCNTs contributed more significantly than BMIMBF₄ to the marked positive impact on the PGE current intensity and on the process reversibility. These data are in accordance with the MWCNTs properties, i.e. high electric conductivity, electrocatalytic activity and electroactive surface area [22,38]. BMIMBF₄ has high viscosity (99.9 cP at 20 °C [39]; which may increase the resistance), but may support charge transport by behaving as a fortifying source of ion carriers (conductivity of 0.35 S/m at 25 °C [39,40]). This electrochemical behavior is in agreement with those observed by Zhang et al. [41] and Shangguan et al. [42].

Fig. 2 displays the representative cyclic voltammograms (Fig. 2(A)) and the impedance spectra represented as Nyquist plots (Fig. 2(B)) of the PGE, PGE/NOR, PGE/[MWCNTs/BMIMBF₄], PGE/[MWCNTs/NOR] and PGE/[MWCNTs/BMIMBF₄/NOR]. The impedance spectra were fitted to the Randles equivalent electric circuit with a constant phase element with charge transfer resistance indicated by the diameter of the semicircle [43], while the linear part locating at lower frequency gave information on the diffusion process [42]. The observed changes in the cyclic voltammograms (Fig. 2(A)), caused by enzyme incorporation, are in general agreement with those exhibited by the EIS profiles (Fig. 2(B)) of the different modified electrodes suggesting the successful immobilization of MWCNTs/BMIMBF₄/NOR or simply NOR at the PGE surface. The charge transfer resistance (R_{ct}) increased from 81.7 to 147 Ω (1.8 times higher) and to 255 Ω (three fold change) after NOR adsorption onto the PGE surface and PGE/MWCNTs, respectively,

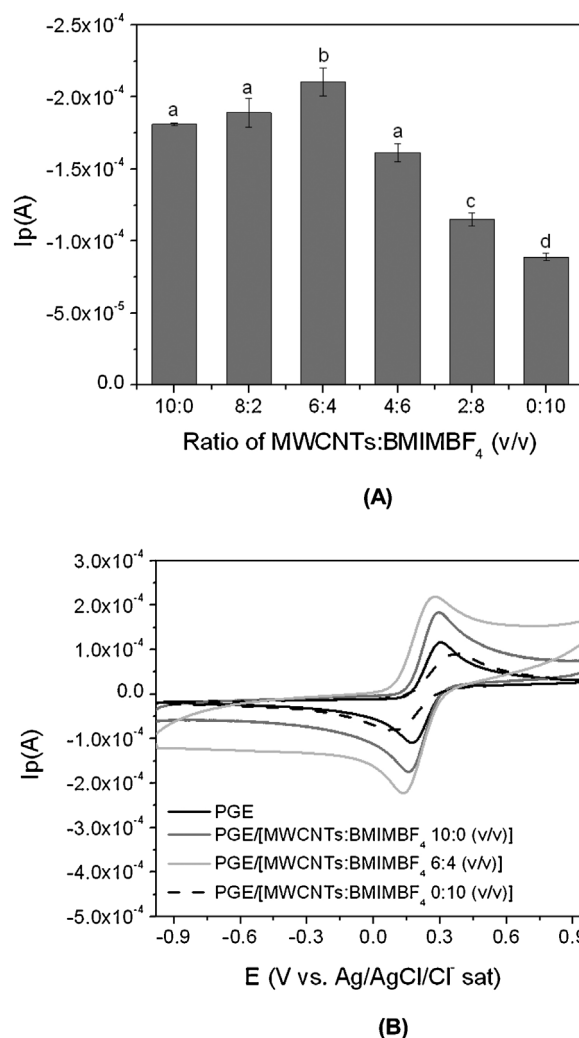
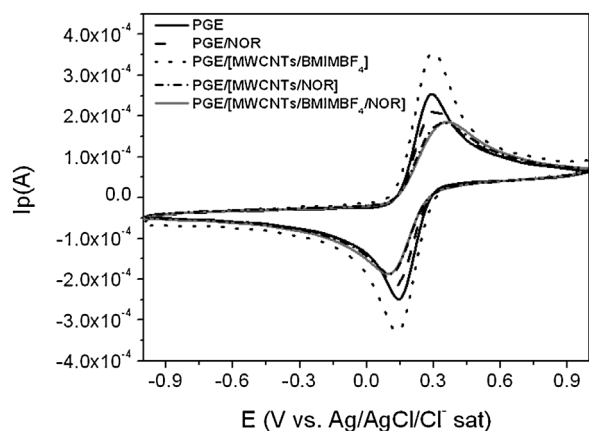


Fig. 1. Optimization of the MWCNTs:BMIMBF₄ ratio: (A) Effect of the MWCNTs:BMIMBF₄ ratio (10:0, 8:2, 6:4, 4:6, 2:8 and 0:10, v/v) on the peak current of the modified pyrolytic graphite electrode (PGE). Different letters indicate that the given medians are significantly different (Wilcoxon Mann-Whitney at $p < 0.05$). (B) Cyclic voltammograms of the bare and modified PGE with the MWCNTs:BMIMBF₄ ratio (v/v) of 10:0 (PGE/MWCNTs), 6:4 (PGE/[MWCNTs/BMIMBF₄]) and 0:10 (v/v) (PGE/BMIMBF₄). Experimental conditions: 5.0 mmolL^{-1} $[\text{Fe}(\text{CN})_6]^{3-/4-}$ in phosphate buffer (pH 6.0) at 100 mV/s.

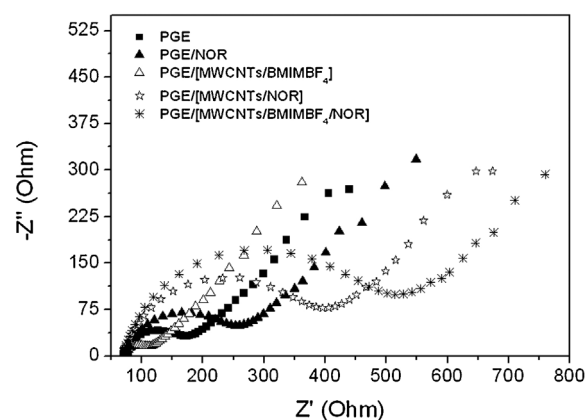
while a tenfold increment was noticed between the R_{ct} values of PGE/[MWCNTs/BMIMBF₄ (33.8 Ω) and PGE/[MWCNTs/BMIMBF₄/NOR] (360 Ω). In agreement with previous studies, the inclusion of the enzyme on the proposed nanocomposite promoted a significant increase of the semi-circle in the impedimetric plots [44]. A similar R_{ct} of 300 Ω was reported by Karimi et al. [45] for another biosensor based on cholesterol oxidase incorporated in NH_2 -MWCNTs/BMIMBF₄ nanocomposite and adsorbed onto a glassy carbon electrode [45]. NOR at pH 6.0 is positively charged [46] and hence can bind to BMIMBF₄ and the MWCNTs through ionic interactions. Additionally, BMIMBF₄ may interact with the carbon nanotubes by π - π , π -cationic and/or hydrophobic-hydrophobic interactions [47,48]. For that reason, the selected IL combined with the MWCNTs had an essential role in NOR entrapment.

3.1.2. Morphological characterization

Since the electrochemical responses are also dependent of the surface morphology, SEM characterization of each modified electrode (PGE/MWCNTs, PGE/[MWCNTs/BMIMBF₄] and PGE/[MWCNTs/



(A)



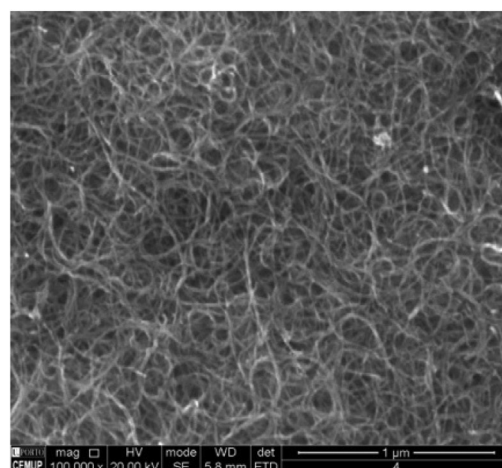
(B)

Fig. 2. Effect of enzyme immobilization on (A) cyclic voltammetric behavior and (B) Nyquist plots of the PGE, PGE/MWCNTs and PGE/[MWCNTs/BMIMBF₄] in 5.0 mmolL⁻¹ [Fe(CN)₆]^{3-/4-} in phosphate buffer (pH 6.0). Cyclic voltammetry parameters: scan rate of 100 mV/s and step potential of 3 mV. Electrochemical impedance spectroscopy conditions: frequency range from 10⁻¹ to 10⁵ Hz with an amplitude perturbation of 5 mV and 0.2 V as conditioning potential.

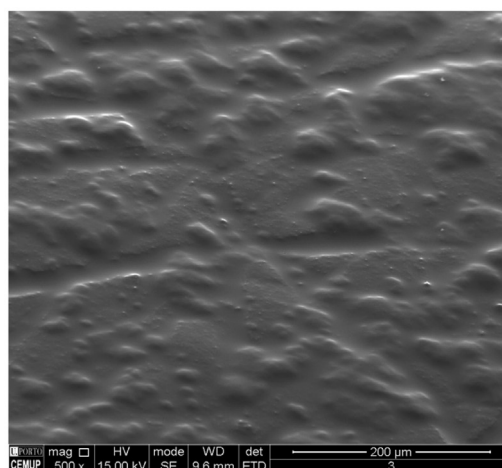
BMIMBF₄/NOR]) was performed to complement the electrochemical data. Representative SEM images spectra are exhibited in Fig. 3. Fig. 3 (A) shows the typical morphology of well-dispersed functionalized MWCNTs onto the electrode surface, which displays a spaghetti-like porous reticular structure with MWCNTs entangled in one another [47]. After mixing BMIMBF₄ with MWCNTs (Fig. 3(B)), the pores of the MWCNTs network were fully eliminated and filled with the viscous IL increasing the uniformity and smoothness of the film, being in accordance with previous studies [47]. This layer (MWCNTs/BMIMBF₄), as it can be noticed in Fig. 3(C), provided an adequate microenvironment for NOR entrapment by combining the solvation ability (and high ionic conductivity) of the selected IL with the high tensile strength (and electric conductivity) of MWCNTs [42,45,47].

3.2. Direct electron transfer behavior of NOR on the PGE/[MWCNTs/BMIMBF₄/NOR] biosensor

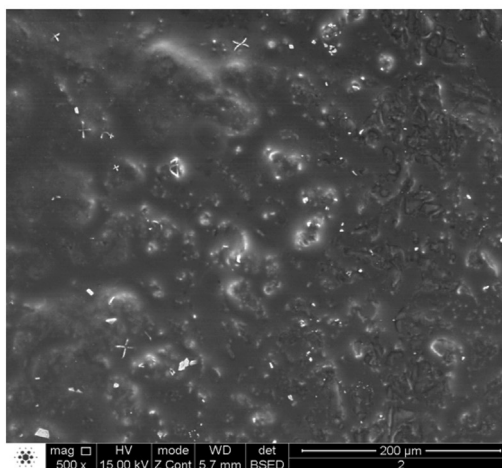
The DET behavior of NOR on the proposed biosensor immersed in 100 mmolL⁻¹ phosphate buffer, 0.02% DM and 0.01% PE at pH 6.0 is presented in Fig. 4. Since enzymatic activity is markedly influenced by the pH, all assays were executed at the optimum pH for NOR, i.e. 6.0 [14]. The electrochemical response of NOR corresponded to a pair of



(A)



(B)



(C)

Fig. 3. Scanning electron microscopy images of (A) PGE/MWCNTs, (B) PGE/[MWCNTs/BMIMBF₄] and (C) PGE/[MWCNTs/BMIMBF₄/NOR].

well-defined cathodic and anodic peaks (Fig. 4 at -0.261 ± 0.003 and -0.249 ± 0.002 V (formal potential of -0.255 ± 0.003 V), respectively, at scan rate of 0.25 V/s, which is ascribed to the heme *b*₃ center

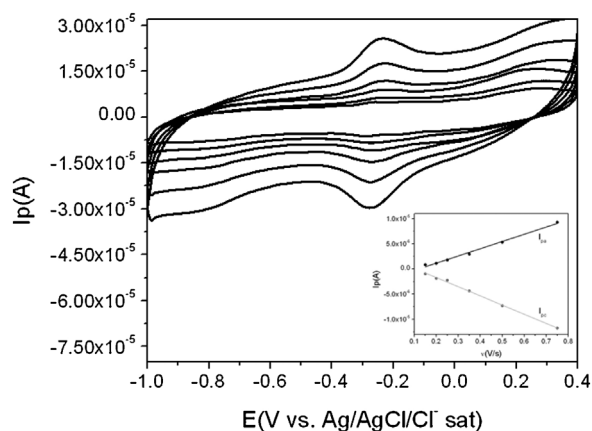


Fig. 4. Cyclic voltammograms of direct electrochemical behavior of NOR on PGE/[MWCNTs/BMIMBF₄/NOR] biosensor in 100 mmolL⁻¹ of phosphate buffer with 0.02% n-dodecyl-β-D-maltoside and 0.01% 2-phenylethanol (pH 6.0) at several scan rates (150, 200, 250, 350, 500 and 750 mV/s). Inset: Anodic (*I*_{pa}) and cathodic (*I*_{pc}) peak current vs the scan rate.

in the bi-nuclear site of NOR [14]. Good linearity was obtained between the peak current and the scan rate (0.150 – 0.750 V/s) for both anodic and cathodic signals (Fig. 4) (*I*_{pa} (A) = $1.44 \times 10^{-5} \pm 6.14 \times 10^{-7} \nu$ (V/s) - $1.73 \times 10^{-6} \pm 2.58 \times 10^{-7}$; *r*² = 0.991; *n* = 6 and *I*_{pc} (A) = $-1.82 \times 10^{-5} \pm 4.53 \times 10^{-7} \nu$ (V/s) + $1.92 \times 10^{-6} \pm 1.90 \times 10^{-7}$; *r*² = 0.997; *n* = 6) indicative of a characteristic surface-controlled electrochemical process as anticipated for immobilized structures [49]. Moreover, the formal potential was not dependent of the scan rate pointing to a facile charge transfer kinetic in the tested range of scan rates (150–750 mV/s) [47].

The NOR surface coverage (τ^* , mol/cm²) of the biosensor was estimated based on Eq. (1):

$$Q = nFA\tau^* \quad (1)$$

where *Q* (A.s) is the charge involved in the reaction, *A* (cm²) is the geometric area of the working electrode, *n* is the number of the electron transferred, and *F* (s.A/mol) is the Faraday constant [50]. The obtained τ^* value (2.04×10^{-10} mol/cm²) indicated a high quantity of adsorbed NOR due to the large specific surface area of the nanocomposite-modified PGE. This is the first time that NOR was used to prepare a biosensor, but some previous catalytic studies, with NOR directly adsorbed onto the PGE, reported a one order of magnitude lower value of surface coverage (1.52×10^{-11} - 2.37×10^{-11} mol/cm²) [12–14] evidencing the advantages of the proposed immobilization approach. Moreover, the previously reported τ^* for enzymatic and heme-based-biosensors that included BMIMBF₄ ranged from 4.18×10^{-12} to 9.07×10^{-9} mol/cm² and 1.39×10^{-11} to 6.81×10^{-8} mol/cm², respectively (Tables 1S-2S, Supplementary Material). Both lowest values of surface coverage were obtained for biosensors that did not include nanomaterials in their construction [51,52]. On the other hand, the higher loadings were reported when enzyme immobilization involved carbon nanomaterials [31,53]. Recently, Kang et al. [31] reported very high τ^* (6.81×10^{-8} to mol/cm²) for a carbon ionic liquid electrode modified with a biocomposite composed by myoglobin, BMIMBF₄, graphene and cobalt oxide nanoflower, possibly due to the porous and three-dimensional structure of the nanoflowers combined with the use of other nanomaterials. Comparable values as the one reached in this study were reported for biosensors based on catalase [47], horseradish peroxidase [54] and hemoglobin [55] developed for hydrogen peroxide detection.

According to Laviron theory [56], and since the potential separation of the peaks was less than 200 mV, the electron transfer rate constant (*k*_s, s⁻¹) was calculated using Eq. (2):

$$k_s = mnF\nu/RT \quad (2)$$

where *m* is the parameter related to peak potential separation (V), *n* the number of electrons involved in the reaction, ν is the scan rate (V/s) and all other symbols have their usual meanings. A *k*_s value of 0.35 s⁻¹ was obtained being in the same range as those described for some enzymatic biosensors (0.51 s⁻¹ for glucose oxidase [42]; 0.55 [57] and 0.655 s⁻¹ [58] for horseradish peroxidase; 0.7 s⁻¹ for chloroperoxidase [59]; and 0.78 s⁻¹ for choline oxidase based-biosensor [53]) and heme-based biosensors (0.406 s⁻¹ [60], 0.5525 s⁻¹ [61], 0.63–0.70 s⁻¹ [55] and 0.725 s⁻¹ [62] for hemoglobin based-biosensors; 0.610 s⁻¹ [63] and 0.675 s⁻¹ [31] for myoglobin based devices) with BMIMBF₄ (Table 1S-2S, Supplementary Material). This information demonstrated that the electron transfer between NOR and the modified electrode is efficiently mediated by the developed nanocomposite.

3.3. Nitric oxide reduction on the PGE/[MWCNTs/BMIMBF₄/NOR] biosensor

To investigate the electrocatalytic activity of NOR towards NO reduction, SWV voltammograms (at the optimal conditions of 10 Hz frequency, 20 mV amplitude and 3 mV step potential) were executed in 100 mmolL⁻¹ phosphate buffer, 0.02%DM and 0.01% PE (pH 6.0). The obtained results are illustrated in Fig. 5. NOR entrapped on MWCNTs/BMIMBF₄ acts as an effective catalyst towards reduction of NO, with an irreversible peak at -0.68 ± 0.03 V (Fig. 5). Moreover, the biosensor response to 0.50–6.98 μmol L⁻¹ of NO was evaluated. Linearity with low dispersion of data (*I*_{pc} (A) = $-4.29 \times 10^{-7} \pm 2.48 \times 10^{-8}$ [NO] (μmolL⁻¹) - $1.24 \times 10^{-7} \pm 6.84 \times 10^{-8}$; *n* = 6) and appropriate correlation coefficient (0.991) was perceived till 4.76 μmol L⁻¹, which was followed by saturation of the signal tending to a plateau after 5.88 μmol L⁻¹ (characteristic of enzymatic kinetics of second order [63]) (Fig. 5). The limit of detection (LOD) and limit of quantification (LOQ) were assessed as being 0.07 and 0.23 μmolL⁻¹, respectively, based on 3*Sy-intercept/slope (for LOD) and 10*Sy-intercept/slope (for LOQ), where Sy-intercept is the standard deviation of the y-intercept [65]. Satisfactory sensitivity of 0.429 μA/μmolL⁻¹ was also established. These data compare favorably with those described by Xu et al. [66] for hemoglobin and myoglobin-based biosensors using HIMIMPF₆ and didodecyl-dimethylammonium bromide (linear ranges from 1.8 to 21.6 and 1.8–23 μmolL⁻¹ with no reported LOD and LOQ) and by Zhang et al. [41] for a basal plane graphite electrode modified by successive layers of nafion/ethanol, EMIMBF₄/ethanol and myoglobin (linearity between 0.7–7.0 μmol L⁻¹ and a LOD of 0.2 μmol L⁻¹). Only these two studies

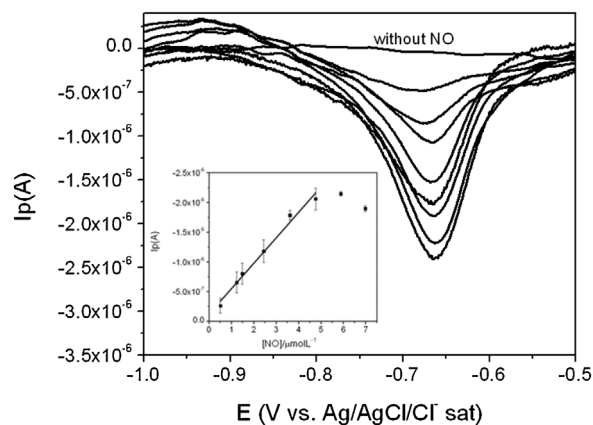


Fig. 5. Square wave voltammograms obtained with PGE/[MWCNTs/BMIMBF₄/NOR] biosensor in the absence of NO and in the presence of standard NO concentrations of 0.50, 1.23, 1.48, 2.44, 3.61 and 4.76 μmolL⁻¹ in 100 mmolL⁻¹ of phosphate buffer with 0.02% n-dodecyl-β-D-maltoside and 0.01% 2-phenylethanol (pH 6.0). Inset: Peak current vs NO concentration and respective linearity zone. Experimental conditions: frequency of 10 Hz, amplitude of 20 mV and step potential of 3 mV.

were found concerning NO biosensors that include an IL and heme-proteins in their construction. The immunological function and the pathological effects of NO are associated with high nanomolar to low micromolar concentrations [67,68]. Thus, the attained figures of merit are appropriate to allow application of the developed biosensor to detect NO levels in real biological samples, namely those related with modulation of blood flow, cardiovascular pathologies, neurodegenerative diseases, among others [6,7,68]. Few heme-based biosensors were tested in rat liver, brain and raw blood describing concentrations ranging from 0.6 to 2.5 $\mu\text{mol L}^{-1}$ [69–73]. Higher concentrations, in the range of 3.91–4.92 $\mu\text{mol L}^{-1}$ NO, were reported by Abdelwahab et al. [70], demonstrating that the proposed biosensor could also be used in gastric adenocarcinoma and colon adenocarcinoma diagnosis.

The affinity of a substrate for the enzymatic centre can be assessed by the Michaelis-Menten constant (K_m , mol L^{-1}), which decreases as the enzyme affinity increases [64]. Biochemically, it indicates a higher probability of formation of the NOR-NO intermediate, which originates an increased NO concentration to be electrochemically reduced. K_m was estimated by the Lineweaver–Burk Eq. (3):

$$1/I_p = K_m/I_{\max} \times 1/[\text{NO}] + 1/I_{\max} \quad (3)$$

where I_p (A) is the current after addition of the substrate; $[\text{NO}]$ (mol L^{-1}) is the concentration of the substrate and I_{\max} (A) is the maximum current measured [56]. The value obtained for the PGE/[MWCNTs/BMIMBF₄/NOR] biosensor of 2.17 $\mu\text{mol L}^{-1}$ indicated high bioactivity performance, which could be ascribed to the ionic micro-environment generated by the prepared MWCNTs/BMIMBF₄ nanocomposite, allowing NOR to retain its native structure and high affinity towards its natural substrate, and at the same time promoting efficient NOR–substrate interaction. To the best of our knowledge, no Michaelis Menten constant was yet established for NO biosensors that include the selected IL (BMIMBF₄) or other IL [41,66]. In general, the achieved K_m is significantly lower than those reported for heme-based (0.16–17870 $\mu\text{mol L}^{-1}$) and enzymatic (0.118–9800 $\mu\text{mol L}^{-1}$) biosensors using BMIMBF₄ (Table 1S–2S, Supplementary Material) with some exceptions [45,47,51,61,74–79]. The best reported affinity was reached for laccase immobilized in a BMIMBF₄/NH₂-MWCNTs nanocomposite (K_m of 0.118 $\mu\text{mol L}^{-1}$) tested for hydrogen peroxide quantification [47]; for heme-protein biosensors 0.16 $\mu\text{mol L}^{-1}$ was attained for hemoglobin incorporated in a chitosan/graphene/BMIMBF₄ matrix proposed for nitromethane biosensing [79].

The repeatability and reproducibility of the PGE/[MWCNTs/BMIMBF₄/NOR] biosensor were examined by the relative standard deviation (RSD) of several experiments. The reduction current of 2.44 $\mu\text{mol L}^{-1}$ NO was measured during six independent assays and a RSD of 9.1% was displayed showing that the proposed approach had high repeatability. Concerning reproducibility, it was tested with eight biosensors, independently prepared under equivalent experimental circumstances, and the RSD varied from 6.0% (at 4.76 $\mu\text{mol L}^{-1}$) to 11% (at 0.50 $\mu\text{mol L}^{-1}$), indicating good reproducibility. Recovery values ranged from 80 to 102% for concentrations in the 0.50–4.76 $\mu\text{mol L}^{-1}$ range. Further assays proved the high selectivity of NOR towards NO even in the presence of physiologically important species that may be simultaneously present with NO (or can be sponsors of NO production) in biological milieus, namely, ascorbic acid (20 $\mu\text{mol L}^{-1}$), sodium nitrite (200 $\mu\text{mol L}^{-1}$) and nitrate (200 $\mu\text{mol L}^{-1}$), as well as glucose (800 $\mu\text{mol L}^{-1}$). Recovery values varied from $91.4 \pm 3.0\%$ (sodium nitrite) to $98.4 \pm 8.9\%$ (glucose) confirming the non-significant interference of these compounds. In addition, the long-term stability and electroanalytical performance of the developed biosensor was intermittently (once or twice per week) characterized during one month. The results showed that the developed biosensor was active and retained 79–116% of its initial response during all the tested period. Although the hydrophobic yet hygroscopic properties of the selected IL [80], these data indicated that no significant leaching of any of the

three nanocomposite components (MWCNTs, BMIMBF₄ and NOR) occurred from the biosensing surface during one month. These results can be explained by the fact that BMIMBF₄ is not simply and directly adsorbed at the PGE surface; it is mixed with MWCNTs and NOR (28.6% (v/v/v) of BMIMBF₄ in the nanocomposite) forming a stable nanocomposite, where interactions (ionic interactions, π - π , π -cationic and/or hydrophobic–hydrophobic interactions [47,48]) between the three components occur. Moreover, the stability results attained in this study are in clear agreement with those previously reported for enzymatic and heme-based biosensors (Tables 1S and 2S; Supplementary Material). These data confirmed that NOR incorporated in the MWCNTs/BMIMBF₄ nanocomposite can efficiently maintain its bioactivity for a significant period of time.

4. Conclusions

The importance of NO in signaling and cellular physiology in humans has been increasingly recognized in biomedical sciences over the last decade, what has led to an exponential growth in the development of new methods and tools. In this work, a MWCNTs/BMIMBF₄ nanocomposite was successfully developed to entrap NOR, for the first time, and prepare a novel third-generation enzymatic biosensor for NO detection. The excellent electric conductivity, together with the large surface area of MWCNTs, combined with the suitable biocompatibility, viscosity and ionic conductivity of the selected IL provided a suitable microenvironment for the immobilization of NOR and for preservation of its activity. Synergetic effects were perceived between MWCNTs and BMIMBF₄, which facilitated the direct electron transfer between NOR and the transducer and the unmediated NOR-NO interaction. Therefore, these results suggest that this novel PGE/[MWCNTs/BMIMBF₄/NOR] biosensor can be a simple, sensitive and excellent strategy for bioelectrochemical NO biomonitoring applications.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.snb.2019.01.074>.

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