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Electrochemical evidence for neuroglobin activity on NO at physiological concentrations

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Running title: NGB electro-re-reduction in the presence of NO and O_2

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ABSTRACT

The true function of neuroglobin (Ngb) and, particularly, human Ngb (NGB) has been under debate since its discovery 15 years ago. It has been expected to play a role in oxygen binding/supply, but a variety of other functions have been put forward, including NO dioxygenase activity. However, *in vitro* studies that could unravel these potential roles have been hampered by the lack of an Ngb-specific reductase. In this work, we used electrochemical measurements to investigate the role of an intermittent internal disulfide bridge in determining NO oxidation kinetics at physiological NO concentrations. The use of a polarized electrode to efficiently interconvert the ferric (Fe^{3+}) and ferrous (Fe^{2+}) forms of an immobilized NGB showed that the disulfide bridge both defines the kinetics of NO dioxygenase activity and regulates appearance of the free ferrous deoxy-NGB, which is the redox active form of the protein in contrast to oxy-NGB. Our studies further identified a role for the distal histidine, interacting with the hexacoordinated iron atom of the heme, in oxidation kinetics. These findings may be relevant *in vivo*, for example in blocking apoptosis by reduction of ferric cytochrome *c*, and gentle tuning of NO concentration in the tissues.

Neuroglobin (Ngb) is the vertebrate globin that has been hypothesized to be involved in e.g. O_2 binding/supply, the metabolism of reactive nitrogen and oxygen species, apoptosis through different pathways, intracellular signaling, and cell protection during hypoxia and ischemia (1-6). Besides the central and peripheral nervous system and retina, Ngb is also expressed in endocrine tissues, hematopoietic stem cells, the gastrointestinal tract, and cancer cells (7,8). Although the first publication on the subject was in 2000, the *in vivo* role of Ngb is still uncertain. Studies on Ngb knock-out mice and regional gene expression did not clarify it further (3,9-13), but most of the reports in the topic supported its neuroprotective function at least under conditions of neuroglobin overexpression (11,14,15). Some histological data additionally indicated that Ngb can be involved in regulation of the circadian rhythm (sleep-wake cycle) (12,16) and protection of neurons from neurodegenerative disorders, such as Alzheimer's disease (17-19). Obviously, further *in vivo* and *in vitro* studies of Ngb are necessary to clarify its molecular mechanisms of action.

As other globins, e.g. myoglobin and hemoglobin, Ngb displays the three-over-three α-helical sandwich structure. However, Ngb structurally differs somewhat from myoglobin and hemoglobin, suggesting a different

functional destination for Ngb compared to the classic globins (20). Both its weak O_2 binding affinity under physiological conditions (21) and its hexacoordinated structure of the iron atom of the heme leading to a possible intrinsic binding competition with external gaseous ligands such as O_2, CO and NO, support the hypothesis that Ngb is not constructed to transport or store O_2 (22). Unclear mechanism of action encourages researchers for detailed studies of Ngb structure and properties.

The well-defined spectral properties of the heme in globins provide opportunities for studies by UV/Vis and EPR (20,23-25). Previously, myoglobin and hemoglobin have been extensively studied using electrochemical methods (26-30). However, electrochemistry has not yet been explored in studies of Ngb. Compared with other techniques, the electrochemical approach affords reduction or oxidation of Ngb by applying a potential to a working electrode without introduction of supplementary redox reagents.

Previously, two attempts were made to link NGB to electrode surfaces using modified gold and nanoporous indium tin oxide electrodes (31,32). Although electric communication of NGB with the electrodes was confirmed through spectral changes in the immobilized protein, voltammetry measurements were impossible because of low protein surface coverages and slow electron transfer kinetics. Recently we designed an efficient protocol for immobilization and electrochemical measurements of small hydrophilic proteins including NGB (33). It created the opportunity for kinetic studies of NGB using voltammetry techniques.

Due to reactivity of the heme iron, NGB can act through multiple molecular mechanisms which seem to be closely related to the redox and ligation states of the iron (21,34-50) (Fig. 1). Globins can express NO dioxygenase activity (oxidation of NO to nitrate in the presence of O_2 as shown in Fig. 1, reaction **d**). However, the relatively rapid autoxidation of Ngb (Fig. 1, reaction **c**) compels the introduction of a reductant or enzymatic reducing system to recover the ferrous form (Fig. 1, reaction **i**), which may interfere with measurements. Moreover, UV/Vis assays need a 5–10 μM concentration of globins and an excess of NO, which exceeds by approximately two orders of magnitude the NO concentration *in vivo* (51). The advantage of the electrochemical approach is that Ngb can be rapidly converted from the ferric (Fe^{3+}) to the ferrous (Fe^{2+}) form at a polarized electrode, which facilitates control of the redox state of the protein and monitoring following chemical reactions in the presence of possible substrates such as O_2 and NO. Moreover, when the protein is immobilized in a thin layer at the electrode surface, a very low equilibrium concentrations of substrates can be introduced into the measuring cell without concern of its possible change because of reaction with the protein.

RESULTS

Electrochemical behavior of NGB — The internal disulfide bridge between Cys46 and Cys55 in NGB defines oxygen-binding properties through the affinity of the distal histidine His64 (Fig. 1). The thiol/disulfide couple in NGB has a reduction potential of −0.194 V measured through equilibrium redox titration with glutathione (40). This value suggests that in a cell at normal conditions the disulfide bond is rather reduced (40), while the cysteine residues in the isolated protein are oxidized in air forming the disulfide bridge (21,34).

The NGB with the disulfide bridge will be referred to as NGB_{SS}. To ease the study of NGB with the reduced disulfide bridge *in vitro*, a model protein with mutated surface cysteines (NGB*) was created (21,52). NGB* behaves in a similar way to NGB with the reduced disulfide bond, but it allows to work without precautions against oxidation of the thiols into the disulfide bridge (21). In this work we compared the behavior of NGB_{SS} and NGB* to assess the effect of the disulfide bridge on the properties and mechanisms of action of NGB.

Under N_2 atmosphere, NGB* showed highly reversible electrochemical behavior when either dissolved in solution or immobilized on the electrodes (Fig. 2). The redox process at a formal potential $E°'$ of -0.136 ± 0.005 V corresponds to $Fe^{3+/2+}$ transition in the heme unit of NGB*. Owing to hexacoordination of the iron, the heme unit undergoes little structural reorganization

during the reduction/oxidation transition, enhancing electron transfer kinetics (50,53). NGB_{SS} behaved similarly with a formal potential $E°'$ of −0.126 ± 0.006 V, which we reported recently (33). A similar value was obtained by means of redox titration (−0.118 ± 0.004 V) (54). A slightly higher reduction potential of -0.103 V was assessed by spectroelectrochemical measurements of the protein adsorbed at a transparent nanoporous indium tin oxide electrode (32).

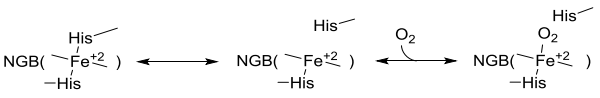
In equilibrium conditions, the protein will be reduced at potentials of the working electrode (E) lower than the formal potential ($E°'$) and oxidized at higher ones according to the Nernst equation:

$$E = E°' + 0.058 \cdot \lg([Ox]/[Red]),$$

where [Ox] and [Red] are the equilibrium concentrations of the oxidized and reduced forms.

It has been reported that NGB binds reversibly to O_2 (Fig. 1, reaction **a**) with a half-saturation pressure (P_{50}) of 1–8 mm Hg depending on pH, temperature and the state of the internal disulfide bond (21). When the measuring buffer was saturated with air, the peak current of the heme unit in NGB* was suppressed (Fig. 2C and D) due to formation of the oxy-form of NGB*. The loss of the redox activity is related to the formation of the charge-transfer state involving orbitals of Fe^{2+} and O_2 (55), which precludes the transition from Fe^{2+} to Fe^{3+} in the presence of O_2.

Effect of O_2 concentration — The process of O_2 binding in NGB is preceded by a relatively slow distal histidine dissociation (k = 7 s^{-1} for NGB* and 0.6 s^{-1} for NGB_{SS} as measured by flash photolysis (34)) as represented in following scheme:



The slow O_2 association/dissociation kinetics allowed us to perform voltammetry measurements of the ferrous deoxy-NGB without a noticeable shift in the equilibrium between oxy and deoxy forms during the measurements. The constant position of the peak potential at different levels of O_2 suggests that the kinetics of O_2 dissociation are relatively slow compared to the time scale of the performed electrochemical measurements (56). However, faster scan rates can be applied if necessary. Thus, the peak current must be proportional to the amount of deoxy-NGB and can be converted to the fraction of deoxy-NGB as $I_p/I_{p,0}$ or to the fraction of oxy-NGB as $(1 - I_p/I_{p,0})$, where $I_{p,0}$ is the peak current in the absence of O_2 and I_p is the peak current at a given level of O_2.

Fig. 3 shows the effect of oxygen concentration on the peak current for both NGB* and NGB_{ss}, obtained by DPV method. The plot of the oxy-NGB fraction against O_2 concentration is shown in Fig. 3C. The P_{50} was determined from the curves as 1.4 ± 0.5 Torr for NGB_{SS} and 6.1 ± 1.3 Torr for NGB*. Similar values were previously assessed in other studies (Table 1) based on flash photolysis and UV/Vis measurements (21,34).

Effect of nitric oxide — The effect of submicromolar NO concentration on NGB* and NGB_{SS} was studied in the presence of 30 Torr (50 μM) O_2, which is close to the normal level of O_2 in the brain (57). Fig. 4A and B represents the corresponding data. When 50 μM O_2 was introduced into the measuring cell, the peak current of NGB* was suppressed because of binding of NGB* with O_2 as described in the previous section.

Introduction of NO into the cell restored the peak current proportional to the NO concentration (Fig. 4A and B). The increase in the peak current implies the increase of the steady-state concentration of the ferrous NGB*, that was accumulated because of slow distal histidine dissociation during the oxygen-binding reaction becoming the rate-limiting step of the ongoing reaction (Fig. 5A). In the concentration range of 0.50−0.75 μM NO approximately 85% of NGB* was accumulated in the ferrous form (Fig 4C). In these conditions the process was completely limited by O_2 binding and did not depend on NO concentration. At lower NO concentrations the amount of ferrous NGB was strictly proportional to the amount of NO.

It is noteworthy that NO concentrations higher than 1 μM resulted in a partial decrease in the ferrous NGB* fraction, which can be explained by inhibition of the heme by

strongly bound NO (Fig. 1, reaction **b**). Fig. 4D shows the long-term effect of 1 μM NO in the presence of 30 μM O_2. Because of the high affinity and stability of the NGB*–NO complex (36), the level of ferrous NGB* decreased by 60%. The initial level could not be restored by increasing O_2 concentration or N_2 purging, probably because of slow NO dissociation (k_{off} = $2 \cdot 10^{-4}$ s^{-1}) from the complex (36).

Surprisingly, NGB_{SS} demonstrated only a minor increase of the ferrous NGB_{SS} fraction with the NO concentration in the same conditions as NGB* (Fig. 4C). The fraction of ferrous deoxy-NGB_{SS} was 13% and 18% for 0.5 μM and 1.0 μM NO, respectively. As Fig. 5B illustrates, the disulfide bridge increased the rate of HisE7 dissociation and, apparently, shifted the rate-limiting step from O_2 binding to the NO-oxidation.

DISCUSSION

A reductase that is capable of rapidly reducing NGB is not yet known. This problem limits assay studies because of autoxidation of NGB in the presence of O_2. In this work we employed a polarized electrode as the reducing system which can recover the ferrous NGB from the oxidized ferric form. Such an approach allowed rapid reduction of the protein without introduction of any chemicals and simplified the study.

The technique for studying redox proteins on an electrode, also known as protein film voltammetry (58,59), was previously widely used for mechanistic studies of redox proteins. However, small hydrophilic proteins can easily desorb and dissolve in bulk. Thus, an appropriate immobilization technique must be used. Recently, we developed a gentle immobilization procedure based on a bis-silane cross-linker dissolved in water medium (33). Immobilized proteins including NGB could be retained at the surface without loss of redox activity or a noticeable shift of their redox potentials. Fast electron transfer kinetics allows us to reduce the protein rapidly and without diffusion limitation. Moreover, because of the small amount of the protein (approximately 0.04 pmol per electrode) and the large bulk volume, the consumption of O_2 and NO from the bulk is negligible even when their concentrations are low. It permits reliable measurements for low concentration of NO and O_2, while in assays using about 10 μM protein concentration, studies in the presence of submicrololar NO would be impossible. Thus, the suggested approach allows (1) rapid electrochemical reduction of NGB and (2) equilibrium and kinetic measurements in low NO and O_2 concentration ranges.

It is known that the disulfide bridge regulates the affinity of NGB to bind oxygen (34). To study this effect a comparison was made between the wild type NGB (NGB_{SS}) and NGB with mutated cysteines (NGB*) (21,34). As ferrous NGB alone is electroactive but its complex with O_2 is not, we could titrate the protein by adding O_2 similar to the method used in UV/Vis assays but without introduction of any reduction agents. The obtained values of P_{50} were 6.1 ± 1.3 and 1.4 ± 0.5 Torr for NGB* and NGB_{SS}, respectively, which is in good agreement with other reports (Table 1).

It should be mentioned that the published P_{50} values demonstrate a noticeable distribution. Moreover, one may notice a difference in reports regarding the temperature dependence of O_2 affinity in NGB measured by equilibrium titration and flash photolysis (21,60). The results obtained in UV/Vis assays could depend on the rate of autoxidation of NGB and efficiency of the reducing system used at particular pH and temperature. The suggested electrochemical approach is free from these complications and can be further used for more detailed studies of the affinity of NGB to bind O_2 or other gases in different conditions.

Affinity to O_2 that is regulated through the disulfide bond is an intriguing feature of NGB but its role in O_2 supply/storage is unlikely for many reasons (3,4). The role of NGB as a possible NO dioxygenase is more supported since such a function is well-known for hemoglobin, myoglobin and especially for flavohemoglobin (61).

To the best of the authors' knowledge, only two works have been published with regard to an *in vitro* test of dioxygenase function in Ngb in the presence of O_2,

conducted with mouse Ngb in air-saturated buffer (37) and with human NGB in the presence of 4% (30 Torr) O_2 (38). In both works the authors reported rapid NO oxidation by oxy-Ngb ($k \approx 300\ s^{-1}$), which followed the rate-limiting distal histidine dissociation and O_2 binding ($k \approx 0.4\ s^{-1}$) (37). The measurements with mouse Ngb were performed with 10 and 250 μM NO, and the total kinetics were independent of NO concentration (37). The measurements with NGB by Smagghe et al. were conducted in the presence of 40 μM NO (38). The ability to catalytically scavenge NO was directly related to the recovery rate of the ferrous form by the reduction system used. No data regarding physiologically relevant NO concentrations or an effect of the disulfide bond have yet been reported.

In contrast to the previous works (37,38), we were able to do measurements in a low NO concentration range and overcome the limitation of the slow re-reduction of NGB from its ferric form.

As a result, we found that O_2 binding kinetics in NGB* are comparable to an NO oxidation rate up to 0.5 μM NO concentration, which resulted in a split of the NGB* into deoxy- and oxy-NGB* fractions proportional to NO concentration. When the NO concentration was 0.5 μM or higher, the kinetics of the dioxygenase activity were fully limited by O_2 binding, and almost all NGB* was accumulated in the free ferrous form. In the same conditions, NGB_{SS} did not show a similar effect, most probably because of the faster formation of the oxy form owing to tenfold faster distal histidine dissociation (34).

In conclusion, we demonstrated a new approach to study NGB in the presence of O_2 and NO that overcomes the limitation related to autoxidation of the protein and allows to work with submicromolar concentrations of effectors. The approach can be potentially extended to other hexacoordinate globins.

If we postulate the existence of a rapid reducing system for NGB *in vivo* (which should exist because of noticeable autoxidation of the protein in the presence of O_2), then not only affinity to bind O_2 but also the rate of NO oxidation to NO_3^- and accumulation of the ferrous NGB is defined by the state of the internal disulfide bridge and NO concentration.

When the bridge is reduced, NGB can exist in the ferrous form even at high O_2 concentrations when a near micromolar or submicromolar amount of NO is present. This could be meaningful *in vivo*. For example, reduction of ferric cytochrome *c*, which has been hypothesized as an anti-apoptotic mechanism of action for NGB (46,47), can be accomplished only by the ferrous deoxy-NGB. Moreover, the ligand binding induces structural transition in NGB that prevents formation of the stable complex with $G\alpha_i$ (41) and, probably, other apoptosis related proteins (Fig. 1, reaction **g**). In the conditions of severe hypoxia, NGB–O_2 adduct can dissociate to form ferrous NGB. However, it may probably lose ability to interact with the apoptosis related proteins due to binding of NO whose concentration is elevated under hypoxia conditions. Our data suggest that ferrous (Fe^{+2}) NGB can appear at a certain ratio of NO/O_2 concentrations and thus, reduce the ferric cytochrome *c* or bind the proteins involved in apoptosis (41-45), thus, leading to protection against neuronal death.

Finally, it is worth noting that NO plays multiple roles in the nervous system and in the pathophysiology of several neurological disorders (62). It can be assumed that NGB gently regulates NO concentration or acts as a sensor of NO/O_2 ratio in cells, generating a redox active form of NGB from the redox inactive oxy-form which exists at normal O_2 and very low NO concentrations.

EXPERIMENTAL PROCEDURES

Materials — Recombinant human Ngb (NGB) and the triple mutant with replaced cysteine residues (Cys46Gly, Cys55Ser and Cys120Ser; NGB*) were expressed and purified as described previously (52). Briefly, the recombinant expression plasmid with the pET3a vector was transformed in the *E. coli* strain BL21(DE3)pLysS. The cells were grown overnight at 37°C in 6 mL L-Broth containing ampicillin and chloramphenicol. Then, the culture was transferred into 250 mL TB medium containing ampicillin,

chloramphenicol and δ-aminolevulinic acid. After reaching A_{600} = 0.8, the expression was induced by isopropyl-1-thio-D-galactopyranoside and continued overnight. After the preparation of a crude protein extract, NGB was purified using DEAE Sepharose Fast Flow and Sephacryl S-200 High Resolution chromatography, dialyzed against 5 mM pH 8.5 Tris-HCl and concentrated.

Inorganic salts, NaOH, H_2SO_4, 1,2-bis(trimethoxysilyl)ethane were purchased from Sigma-Aldrich (Belgium). 6-Mercapto-1-hexanol (>98.0 %) was sourced from TCI Europe N.V. (Belgium).

Preparation of electrodes — The commercial gold disk electrodes, 1.6 mm diameter (BASi, West Lafayette, IN, USA) were polished first on nylon pads (Buehler, Lake Bluff, IL, USA) using diamond suspensions of 3, 1 and 0.25 μm particle size (DP-Spray, Struers, Ballerup, Denmark) in a supplier recommended lubricant (DP-Lubricant, Struers, Ballerup, Denmark), and on soft pads (Buehler, Lake Bluff, IL, USA) using a water based γ-alumina slurry of 50 nm particle size (SPI Supplies, West Chester, PA, USA). The electrodes were sonicated in ethanol and ultrapure water after each polishing step. Next, the electrodes were electrochemically treated in 0.5 M NaOH and 0.5 M H_2SO_4 until a repetitive voltammogram of polycrystalline gold was achieved (63,64). Finally, the electrodes were left in 8 mM 6-mercapto-1-hexanol solution in ultrapure water for approximately 20 h.

Afterwards, 1.8 μL of a mixture consisting of 15 μM protein and 10 mM 1,2-bis(trimethoxysilyl)ethane in 50 mM pH 7 KH_2PO_4 buffer was placed on the electrodes and dried at room temperature for 1 h. The obtained surface coverage of the surface-confined NGB was approximately 2 pmol/cm^2.

Cyclic (CV) and differential pulse voltammetry (DPV) were conducted in pH 7.4 PBS buffer using a conventional three-electrode cell and μAutolab III electrochemical interface (Metrohm-Autolab BV, the Netherlands). A saturated calomel electrode (Radiometer, Denmark; +0.244 V vs standard hydrogen electrode at 25°C) and a glassy carbon rod were used as reference and counter electrode, respectively. All potentials are given versus the standard hydrogen electrode (SHE).

Background CV behavior of MH modified electrodes was carefully checked to ensure the quality of the electrode preparation and stability of the electrodes. Contaminated electrodes and electrodes with a defective MH layer (which could be disclosed due to an increased background current under N_2 atmosphere) demonstrated inappropriate long-term stability and were discarded.

O_2 binding — The measuring buffer (30 mL) was purged with N_2 for 1 h in advance and for at least 20 min after the protein electrodes were inserted into the thermostatic (25.0 ± 0.2 °C) electrochemical cell. CV and DPV performances of the electrodes were recorded to ensure good stability and appropriate immobilization of NGB. Next, DPV curves were sequentially recorded starting from −0.3 V till +0.05 V with a conditioning step of 1 min before each measurement, when the potential was set again to −0.3 V to keep the protein in the reduced form. After recording at least five consecutive DPV curves under N_2 to ensure stable peak intensity, a certain volume of the air-saturated buffer, equilibrated at the same temperature, was injected using an air-tight syringe. For each concentration the measurements were repeated at least twice to ensure the stable value of the peak current after introduction of O_2.

NO metabolism — A saturated water solution of NO was prepared as previously described (65,66). Briefly, 2 M H_2SO_4 was carefully added drop-wise into saturated $NaNO_2$ preliminarily purged with nitrogen. The disproportional reaction resulted in the formation of NO which was directed to pass through a washing bottle containing 30% NaOH and two vials with ultrapure water. The solution from the second vial was used in the experiments. Under room temperature (22 °C) and normal pressure conditions, the saturated concentration of NO in water is close to 2.0 mM (67). Saturated NO solution was added to the electrochemical cell using an air-tight Hamilton syringe to get NO concentrations in the range from 0.05 to 1.25 μM. The measurements were done in the presence of 50 μM (30 Torr) O_2 at 25°C.

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CONFLICT OF INTEREST
The authors declare that they have no conflicts of interest with the contents of this article.

AUTHOR CONTRIBUTIONS
KDW and ST designed research and analyzed all data; ST conducted most of the experiments and wrote most of the paper; MdJ conducted preliminary experiments on the immobilization and electrochemical characterization of NGB; EL purified and characterized samples of NGB and NGB*, SD contributed to interpretation of data and revised the paper.

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FOOTNOTES

The abbreviations used are: Ngb, neuroglobin; NGB, human neuroglobin; NGB*, NGB with mutated surface cysteines; NGB_{SS}, NGB with the internal disulfide bridge; EPR, electron paramagnetic resonance; PBS, phosphate-buffered saline; CV, cyclic voltammetry; DPV, differential pulse voltammetry; UV/Vis, ultraviolet-visible spectrophotometry.

FIGURE LEGENDS

FIGURE 1. The relation of the redox and ligation states of the heme iron and NGB reactivity. (**a**) Ferrous (Fe^{2+}) NGB reacts with O_2 to form the O_2 adduct. The dissociation of the distal histidine limits the binding kinetics due a low dissociation rate constant of 0.6 s^{-1} and 7 s^{-1} for NGB with reduced and oxidized state of the internal disulfide bridge respectively (34,35). The P_{50} value was reported in the range of 1-8 Torr depending on pH, temperature and the state of the internal disulfide bound (21). (**b**) Ferrous NGB reacts with NO leading to the nitrosyl ligated form with $K_d \approx 1$ nM and a slow dissociation rate constant $k_{off} \approx 10^{-4} - 10^{-3}$ s^{-1} (37). (**c**) NGB-O_2 adduct is prone to autoxidation with $k \approx 0.17$ min^{-1} (21). Similar to myoglobin and hemoglobin, NGB has been reported as a scavenger of reactive oxygen and nitrogen species (ROS, RNS): (**d**) NGB shows NO dioxygenase activity with $k_{cat} \approx 300$ s^{-1} (37,38); (**e**) nitrosyl ferrous NGB but not ferric (Fe^{3+}) NGB can scavenge peroxynitrite with $k_{cat} \approx 1.3 \cdot 10^5$ M^{-1} s^{-1}

(39); (**f**) ferrous (Fe^{2+}) NGB can reduce nitrite (NO_2^-) although with a relatively low rate constant of 0.06 and 0.12 M^{-1} s^{-1} for NGB with the reduced and oxidized state of the disulfide bridge respectively (40). The role of NGB in blocking apoptosis through binding other proteins has been also suggested in the literature: (**g**) NGB can bind to the GDP-bound form of the α-subunit of heterotrimeric G-protein ($G\alpha_i$) with $K_d \approx 6 \cdot 10^2$ nM (41). Immunoprecipitation technique revealed binding of NGB to voltage-dependent anion channel (VDAC) (42), Flotillin-1 (43), two members of the Rho GTPase family (Rac1 and Rho A), as well as the Pak1 kinase (44), and a subunit of the mitochondrial complex III Cytochrome *c*1 (45). It has been found that the conformational transition in NGB upon binding ligands such as O_2 and NO can prevent NGB binding to $G\alpha_i$. Similar mechanisms may regulate binding to other proteins. (**h**) Moreover, ferrous NGB is capable to reduce rapidly ferric Cytochrome *c* (Cyt *c*) with a kinetic constant of $2 \cdot 10^7$ $M^{-1}s^{-1}$ (46), which seems to be facilitated by an appropriate docking between two proteins (47,48). Interaction between Cyt *c* and NGB goes through a rapid transient binding with a relatively high dissociation constant $K_d \approx 120$ μM (48), which decreases in low ionic strength buffer suggesting that the interaction is largely electrostatic in nature (48,49). (**i**) The reaction that is responsible for one-electron reduction of the ferric (Fe^{3+}) to ferrous (Fe^{2+}) form is not known yet. It can be driven by an enzyme process or a low molecular weight redox compound/mediator. Noteworthy, hexacoordination of the heme iron favors reduction kinetics comparing to pentacoordinated analogues (50).

FIGURE 2. CV and DPV behavior of NGB* in PBS buffer solution (A, B) and immobilized on the gold electrodes (C, D). Concentration of the dissolved NGB*, 20 μM; surface density of the immobilized NGB*, 2 pmol/cm^2; CV scan rate, 20 mV/s; DPV modulation amplitude, 20 mV; modulation time, 0.05 s; interval time, 0.5 s. The arrows denote scan directions. Blank voltammograms are shown by dashed lines (in green) and curves recorded in the air-saturated buffer are presented by dashed-dotted lines (in blue).

FIGURE 3. Behavior of NGB in the presence of different levels of O_2. (A, B) Change in voltammograms with increase of O_2 level in the presence of NGB* and NGB_{SS}; (C) determined fraction of the oxygenated NGB in equilibrium with the ferrous (Fe^{+2}) NGB as a function of O_2 concentration. Error bars show standard deviation for three consecutive measurements. PBS pH 7.4, 25°C.

FIGURE 4. Behavior of NGB in the presence of 30 Torr O_2 and submicromolar NO concentrations: (A) change in DPV curves for NGB*; (B) the DPV curves after baseline correction; (C) dependence of the steady state deoxy-NGB fraction on NO concentration in the presence of 30 Torr O_2. Average values of three separate titration curves are plotted, with the standard deviation values. (D) Stability of deoxy-NGB* in the presence of 20 Torr O_2 and 1 μM NO. Arrows denote direction of changes. PBS pH 7.4, 25°C.

FIGURE 5. The mechanism of NGB transitions in the presence of 0.5 μM NO and 30 Torr O_2: (a) behavior of NGB* which models the protein with the opened disulfide bridge that favors the hexacoordinate ferrous form; (b) behavior of NGB_{SS} which is the protein with the disulfide bridge that favors the oxygenated form. Broken arrows indicate a rate limiting step and the bold red structures depict an accumulated form.

TABLE 1. Comparison of P_{50} values for NGB obtained by different methods

	Method	Conditions	P50 (Torr)	Reference
NGB*	Voltammetry	PBS, pH 7.4, 25°C	6.1 ± 1.3[a]	This work
NGB_{SS}	Voltammetry	PBS, pH 7.4, 25°C	1.4 ± 0.5[a]	This work
NGB*[b]	Equilibrium UV/Vis[c]	Bis-Tris//Hepes, pH 7.0, 25°C	5	Fago et al. (40)
NGB*[b]	Equilibrium UV/Vis[c]	Bis-Tris//Hepes, pH 7.6, 20°C	2.6	Fago et al. (40)
NGB_{SS}	Equilibrium UV/Vis[c]	Bis-Tris//Hepes, pH 7.6, 20°C	0.67	Fago et al. (40)
NGB*	Flash photolysis	Phosphate, pH 7.0, 25°C	10	Hamdane et al. (41)
NGB_{SS}	Flash photolysis	Phosphate, pH 7.0, 25°C	0.9	Hamdane et al. (41)
NGB+DTT	Flash photolysis	Phosphate, pH 7.0, 25°C	8.4	Hamdane et al. (41)

[a]average ± standard error (n=4); [b]No difference between NGB* and NGB+DTT was reported; [c] measured on an ultrathin layer of protein sample using a gas diffusion chamber.

Figure 1.

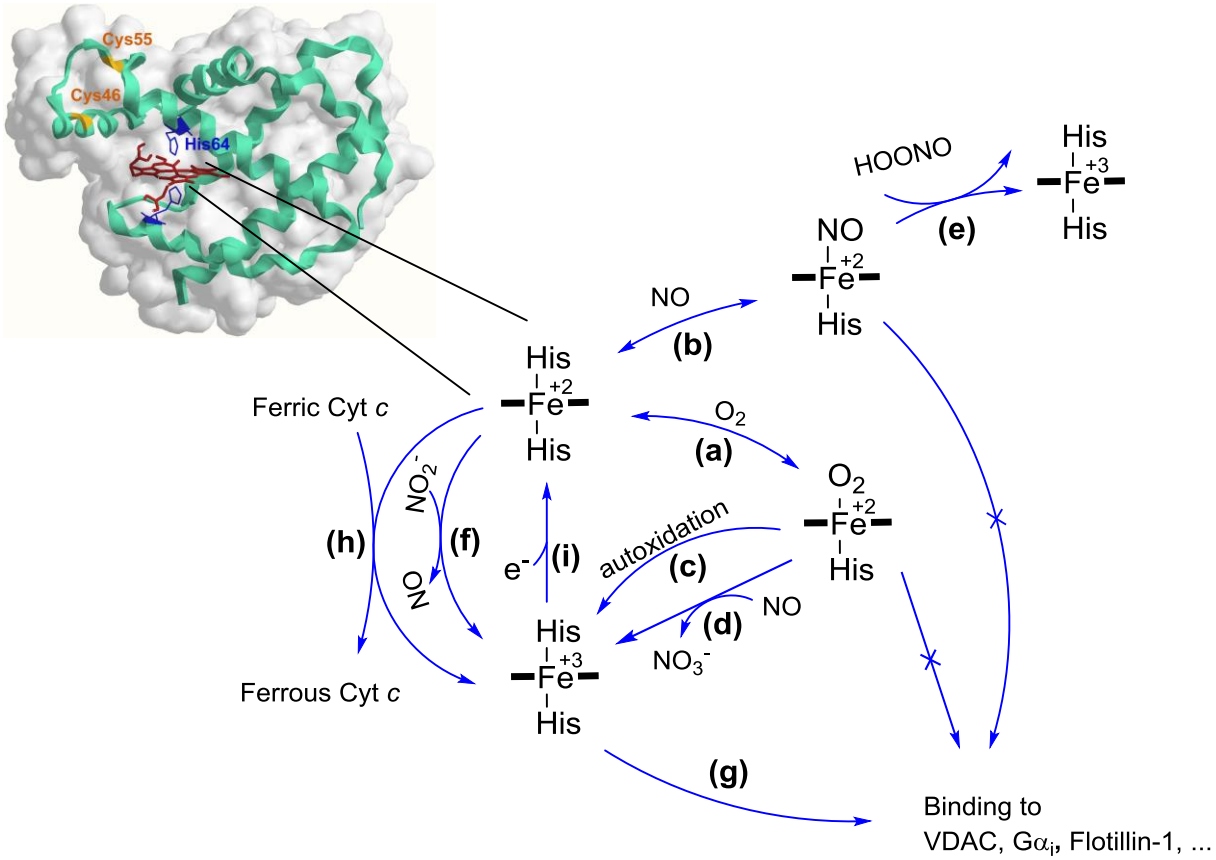


Figure 2.

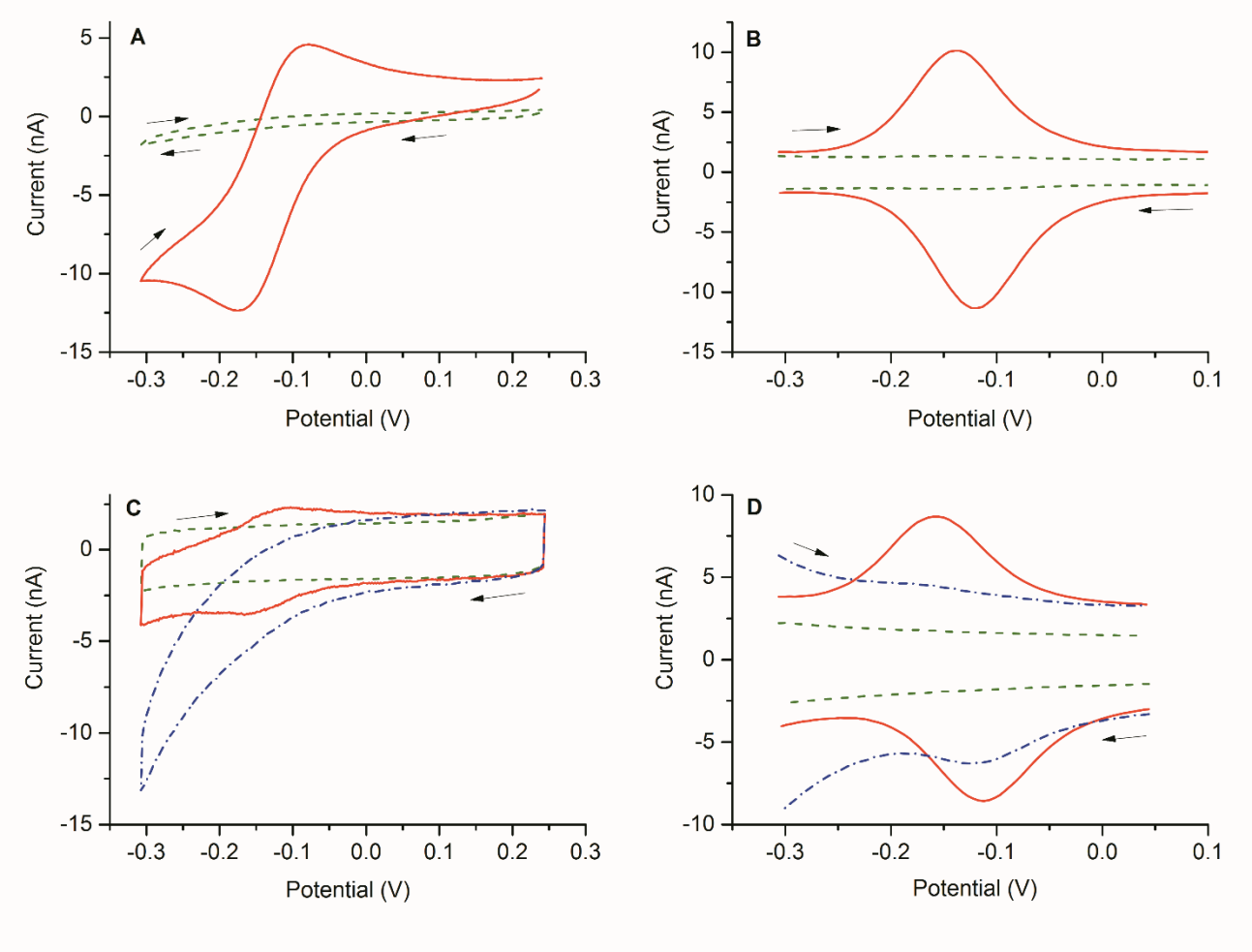


Figure 3.

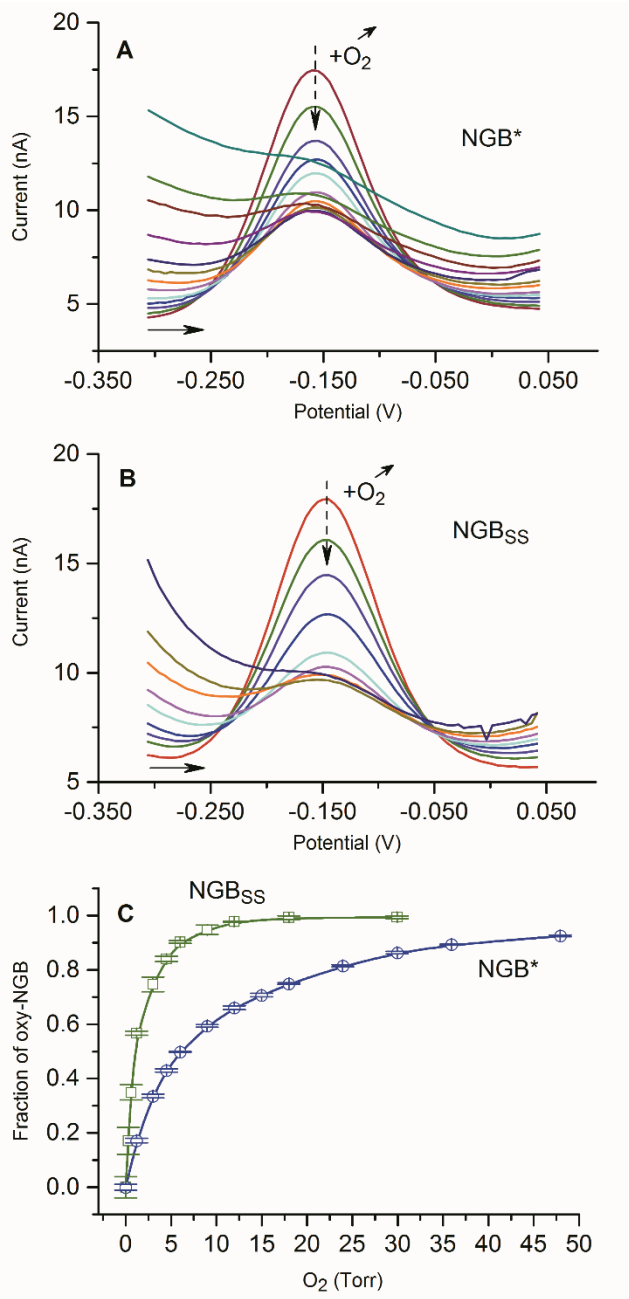


Figure 4.

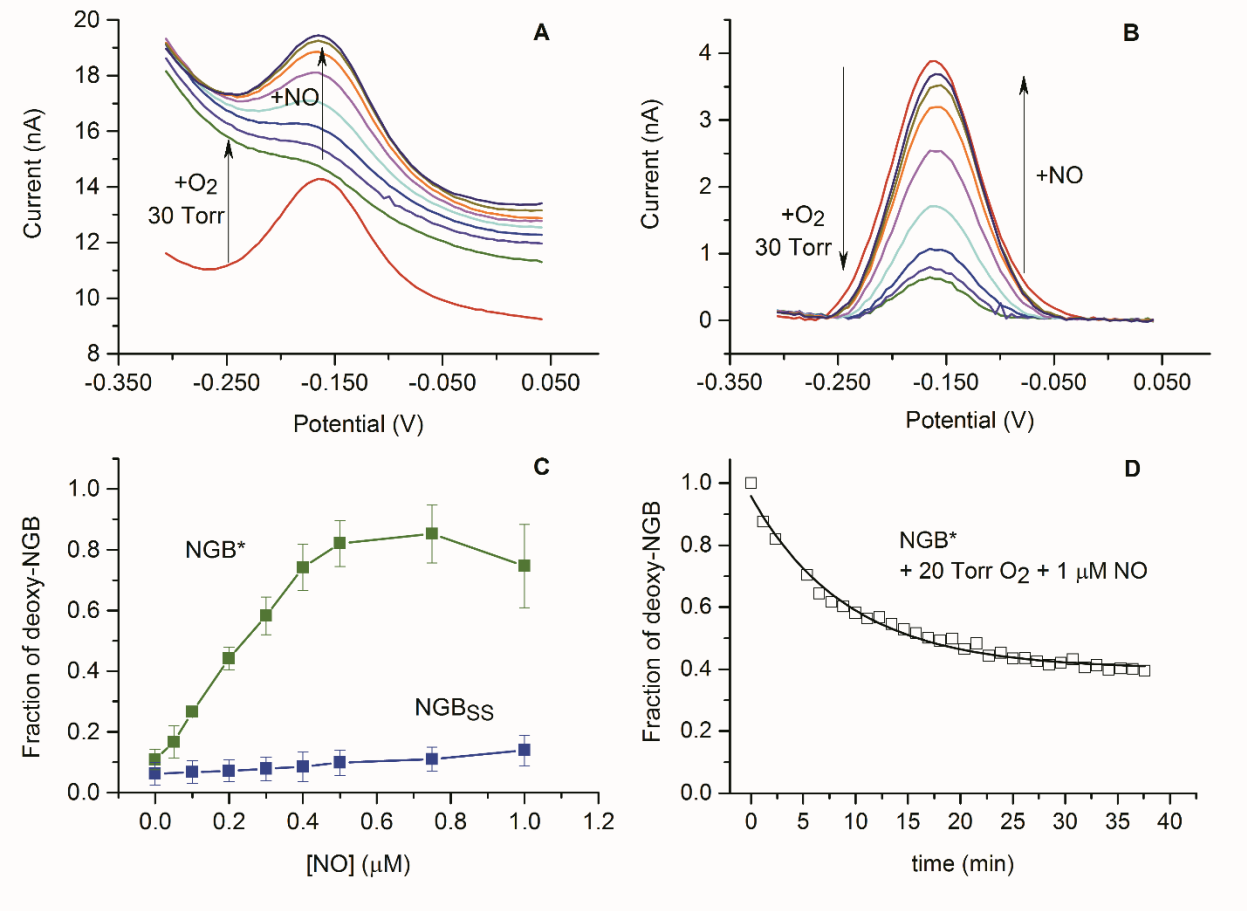
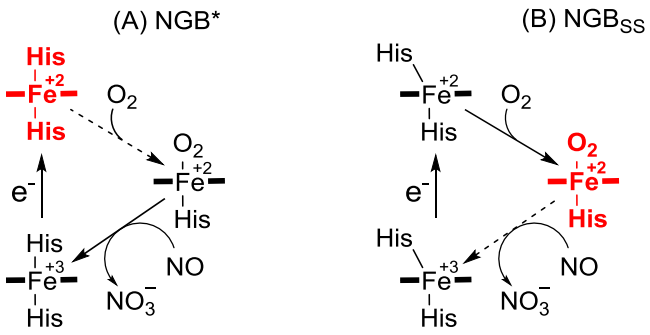


Figure 5.



Electrochemical evidence for neuroglobin activity on NO at physiological concentrations

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