Nox4: A Hydrogen Peroxide-Generating Oxygen Sensor

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Supporting Information

ABSTRACT: Nox4 is an oddity among members of the Nox family of NADPH oxidases [seven isoenzymes that generate reactive oxygen species (ROS) from molecular oxygen] in that it is constitutively active. All other Nox enzymes except for Nox4 require upstream activators, either calcium or organizer/activator subunits (p47phox, NOXO1/p67phox, and NOXA1). Nox4 may also be unusual as it reportedly releases hydrogen peroxide (H₂O₂) in contrast to Nox1–Nox3 and Nox5, which release superoxide, although this result is controversial in part because of possible membrane compartmentalization of superoxide, which may prevent detection. Our studies were undertaken (1) to identify the Nox4 ROS product using a membrane-free, partially purified preparation of Nox4 and (2) to test the hypothesis that Nox4 activity is acutely regulated not by activator proteins or calcium, but by cellular pO₂, allowing it to function as an O₂ sensor, the output of which is signaling H₂O₂. We find that approximately 90% of the electron flux through isolated Nox4 produces H₂O₂ and 10% forms superoxide. The kinetic mechanism of H₂O₂ formation is consistent with a mechanism involving binding of one oxygen molecule, which is then sequentially reduced by the heme in two one-electron reduction steps first to form a bound superoxide intermediate and then H₂O₂; kinetics are not consistent with a previously proposed internal superoxide dismutation mechanism involving two oxygen binding/reduction steps for each H₂O₂ formed. Critically, Nox4 has an unusually high Kᵢₑₗ for oxygen (~18%), similar to the values of known oxygen-sensing enzymes, compared with a Kᵢₑₗ of 2–3% for Nox2, the phagocyte NADPH oxidase. This allows Nox4 to generate H₂O₂ as a function of oxygen concentration throughout a physiological range of pO₂ values and to respond rapidly to changes in pO₂.

Nox enzymes comprise a family of oxygen- and NADPH-dependent oxidoreductases that produce superoxide and/or hydrogen peroxide in a variety of cell types and tissues, often in response to hormones, growth factors, or immune mediators.1–3 The classical NADPH oxidase, the Nox2 system, is strongly expressed in phagocytic cells such as neutrophils and macrophages in which the enzyme generates high levels of ROS as a major mechanism of antimicrobial host defense. Nox2, the catalytic subunit, is membrane-associated and binds to a second membrane protein, p22phox. The latter provides a proline-rich domain (PRD) that serves as a docking site for the "organizer" subunit p47phox, which in turn binds to the activating subunit p67phox.5,6 The small GTPase Rac also participates in activation7 by binding to p67phox. Upon exposure of phagocytes to microbes or inflammatory mediators that act upon cell surface receptors, these components along with p40phox assemble at the membrane, triggered in part by phosphorylation of p47phox and GTP binding to Rac, resulting in activation of Nox2.

Nox1 and Nox3 but not Nox4 are regulated in a manner analogous to that of Nox2 involving regulatory subunits that are homologous to p47phox and p67phox.9–14 Like Nox2, Nox1 is acutely activated by receptor-linked agonists (see, e.g., refs 15 and 16) and mediates various cellular responses, for example, in vascular smooth muscle and epithelial cells.3 Acute regulation of Nox3 is less well documented. While Nox1–Nox4 all require p22phox,13,17 p22phox functions in a different manner for Nox4 for which the p22phox PRD docking domain is not required for binding to regulatory subunits but is needed for stability, perhaps conformational integrity, and/or maturation/localization.18–20 Rather, Nox4 activity does not require regulatory subunits. Activation of Nox1–Nox3 but not Nox4 also requires the small GTPase Rac1.10,21,22 Similarly, Nox5, Duox1, and Duox2 are all acutely activated by receptor-linked stimuli that elevate cellular calcium levels via their calcium-binding domains.23–25

Nox4 is expressed at its highest levels in the kidney26,27 but is also widely expressed in many other cell types2 and hence may have a cellular function that is more general than those of some other Nox enzymes whose tissue distributions are more restricted. For example, Nox3 is expressed almost exclusively in the inner ear where it functions in the development of otoliths.28 The activity of Nox4 can be modestly stimulated by a DNA polymerase-interacting protein POLDIP2,29 which was first suggested to regulate Nox1 and Nox4 on the basis of its
binding in a yeast two-hybrid screen to p22phox; however, the biological significance of this interaction is unclear, and Nox4 is not generally considered to be acutely regulated by subunit interactions. Rather, the most striking difference between Nox4 and other Nox/Duox enzymes is that Nox4 is constitutively active\(^{27,30}\) in the absence of regulatory subunits or calcium-elevating stimuli. This has led to the concept that Nox4-dependent ROS generation is regulated primarily by its expression level.\(^{31,32}\) This study explores the hypothesis that in addition to expression levels, the activity of Nox4 can be acutely regulated not by subunits or calcium but by tissue P2O, and that its output of ROS serves as a signal that reports cellular oxygen levels.

The identity of the reactive oxygen product of Nox4 has been a matter of debate. Recent studies reported that the major product from Nox4 is H\(_2\)O\(_2\),\(^{33}\) although other studies (e.g., refs 27, 34, and 35) have detected superoxide. While some of the discrepancies may have resulted from the use of nonspecific assay reagents in detecting ROS\(^{36-38}\) some groups have suggested that the failure to detect superoxide results from membrane compartmentalization of Nox4-generated superoxide. While many Nox/Duox enzymes are localized at least in part at the cell surface where they can release their reactive oxygen products into the extracellular milieu, Nox4 is localized within the cell where it is reportedly localized to internal membranes such as the endoplasmatic reticulum, nuclear membrane, and mitochondria.\(^{33,39-43}\) While the exact subcellular location of Nox4 is controversial, association with any of these internal membranes is expected to direct reactive oxygen products into the membrane-enclosed cavity. Because superoxide is charged and unable to pass through lipid membranes while hydrogen peroxide is neutral and can readily traverse membranes and/or aquaporin channels, external probes should not detect the superoxide and would detect only hydrogen peroxide. According to this scenario, the cryptic superoxide dismutates within a membrane-limited cavity to form hydrogen peroxide, which escapes and is detected by ROS probes. To identify the ROS product of Nox4 in the absence of confounding membrane compartments, we have used a detergent-solubilized, partially purified preparation of Nox4.

Table 1. Partial Purification of His\(_6\)-Nox4 Using Ni\(^{2+}\)-Bead Affinity Chromatography\(^{4a}\)

<table>
<thead>
<tr>
<th>sample</th>
<th>total protein (mg)</th>
<th>heme (pmol/mg)</th>
<th>total heme (nmol)</th>
<th>specific activity (nmol of H(_2)O(_2)/min)</th>
<th>purification (x-fold)</th>
<th>total activity (nmol of H(_2)O(_2)/min)</th>
<th>yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cell lysate</td>
<td>26</td>
<td>16</td>
<td>0.42</td>
<td>0.35</td>
<td>1</td>
<td>9.1</td>
<td>100.0</td>
</tr>
<tr>
<td>NEF/LSP</td>
<td>6.7</td>
<td>25</td>
<td>0.17</td>
<td>1.1</td>
<td>3.1</td>
<td>7.2</td>
<td>79</td>
</tr>
<tr>
<td>His(_6)-Nox4</td>
<td>0.027</td>
<td>480</td>
<td>0.013</td>
<td>94</td>
<td>10</td>
<td>270</td>
<td>28</td>
</tr>
</tbody>
</table>

\(^{4a}\)NADPH-dependent hydrogen peroxide generating activity was measured by Amplex Red oxidation and heme content by oxidized-minus-reduced difference spectroscopy as detailed in Materials and Methods. Samples are those indicated in Figures 2 and 3 of the Supporting Information.

Materials and Methods

Materials. Full-length cDNA encoding human Nox4 (amino acid residues 1–578) and N-terminally His\(_6\)-tagged Nox4 were cloned into pcDNA 3.1 and pCIG vectors, respectively (Invitrogen). cDNA encoding N- or C-terminal His\(_6\)-tagged full-length p22phox was cloned into pCIR (Invitrogen). The rabbit polyclonal antibody against a C-terminal synthetic peptide within the segment of amino acid residues 500–578 of human Nox4 was from Novus Biologicals, Inc.; mouse monoclonal antibody 2366 to His\(_6\) was from Cell Signaling Technologies, and mouse monoclonal antibody 44.1 against human p22phox was from Santa Cruz Biotechnology. Rabbit polyclonal antibodies to human lamin A (ab8980), calreticulin (ab4-100), and cadherin (ab6529-200) were obtained from Abcam. Goat anti-rabbit IgG and anti-mouse secondary antibodies linked to horseradish peroxidase were from Bio-Rad and Promega, respectively. Ni-NTA agarose was purchased from Qiagen, and amyllose agarose and Factor Xa protease were from New England Biolabs. Protease inhibitor cocktail (EDTA-free) and Amplex Red were from Roche and Invitrogen, respectively. FAD, NADPH, diphenyleneiodonium (DPI), phenylmethanesulfonyl fluoride (PMSF), protein A-agarose Fast Flow [50% (v/v)], 3,3′-diaminobenzidine, and nuclei EZ lysis buffer were purchased from Sigma-Aldrich (St. Louis, MO). Percoll was from GE Healthcare Bio-Science AB. HEK293 cells stably transfected with Nox4 were the kind gift of R. P. Brandes (Goethe University, Frankfurt am Main, Germany). Micromat Gas tanks containing various oxygen/nitrogen mixtures were from Matheson Tri-Gas (Hilliard, OH).

Transient Transfection of Nox4. HEK293 cells were seeded at a density of 1 × 10\(^6\) cells/plate (10 cm diameter) and grown for 24 h to 40–50% confluence in Dulbecco’s modified Eagle’s medium with 10% fetal serum, 100 units/mL penicillin, and 0.1 mg/mL streptomycin. Cells were transfected 48 h prior to use with mammalian expression vectors encoding Nox4, His\(_6\)-Nox4, His\(_6\)-Nox4(P437H), His\(_{6}\)p22phox, or empty vector, using FuGENE6 (Roche Molecular Biochemicals).

Subcellular Fractionation by Differential Centrifugation. Stable or transiently transfected HEK293 cells (typically ∼1.5 × 10\(^6\) cells) cultured in ∼25 tissue culture plates (10 cm) were harvested, washed twice in PBS, suspended in nuclei EZ lysis buffer (pH 7.4) (Sigma-Aldrich) containing protease inhibitor cocktail (Complete Mini, Roche Diagnostics) with 0.2 mM PMSF, and disrupted using a glass homogenizer with a loose fitting pestle (3 min at 4 °C). The homogenate was centrifuged at 800g for 5 min in a Beckman TL-100 rotor at 4 °C to collect a nuclei-enriched fraction (NEF), and the supernatant was centrifuged at 10000g in a Beckman TL-100 rotor for 30 min to obtain the low-speed pellet (LSP). The supernatant (Sn) was centrifuged at 105000g for 60 min to yield the high-speed pellet (HSP) and the high-speed supernatant (HSS).

Partial Purification of His\(_6\)-Nox4. From 25 to 30 mg of total lysate protein, the combined NEF and LSP were resuspended by homogenization on ice in buffer B [25 mM Heps (pH 7.4) with 130 mM NaCl, 0.1 mM MgCl\(_2\), 10% glycerol, 1 μg/mL protease inhibitor cocktail, 0.5 mM PMSF, 20 μM FAD, 1% Nonidet P-40, and 0.2% deoxycholate] and then stirred gently for 30 min at 4 °C. The extract was centrifuged at 105000g for 60 min at 4 °C in a Beckman TL-
100 rotor, and the supernatant was applied to a Ni-NTA affinity column (10 mm × 15 mm) equilibrated with buffer B. The column was washed with 15 mL each of buffer B and then buffer B containing 10 mM imidazole. His<sub>6</sub>-Nox4 was eluted with buffer B containing 100 mM imidazole, and 0.2 mL fractions were collected. Fractions showing NADPH-dependent Amplex Red oxidizing activity were pooled, concentrated by Amicon Ultra-4 filtration, and dialyzed with two buffer changes against 250 mL of buffer B for 24 h at 4 °C to remove imidazole. The final material was characterized as described in Results and Discussion (Table 1 and Figure 4 of the Supporting Information).

**Isolation of Human Neutrophils.** Normal human neutrophils were obtained from peripheral blood of normal healthy donors after obtaining informed consent as described previously and suspended in 0.9% saline at a density of 1–2 × 10<sup>8</sup> cells/mL. Human neutrophils were washed by centrifugation and resuspended in PBS (pH 7.4) containing 10 mM glucose. 

**Preparation of Plasma Membrane and Cytosolic Fractions from Human Neutrophils.** After disruption of cells by sonication (3 × 5 s) on ice, cytosolic and plasma membrane-enriched fractions were separated by centrifugation at 105000g in a Beckman TL-100 rotor for 30 min at 3 °C using a Percoll density gradient as described previously to obtain a plasma membrane-enriched fraction and a cytosolic fraction.

**Measurement of Superoxide.** Cytochrome c (final concentration of 100 μM) was added to a 0.8 mL cuvette containing 4.2 × 10<sup>5</sup> neutrophils in PBS (pH 7.4), and cells were activated at 25 °C with 0.12 μM PMA in the absence and presence of superoxide dismutase (300 units/mL). As described previously, the rate of cytochrome c reduction was monitored for 10 min by the increase in absorption at 550 nm, monitored using an Ultraspex 3000 spectrophotometer (Pharmacia Biotech) and quantified using an extinction coefficient of 19.5 mM<sup>−1</sup> cm<sup>−1</sup> correcting for the low rate of cytochrome c reduction in the presence of SOD. Cytochrome c reduction by 2.1 × 10<sup>6</sup> Nox4-transfected cells was monitored using the same method, without activation by PMA. Neutrophil cell-free cytochrome c reductase activity was assayed in 0.8 mL of a reaction mixture consisting of PBS (pH 7.4), 20 μM GTPγS, 20 μM FAD, 100 μM NADPH, 100 μM cytochrome c, and 5 mM MgCl<sub>2</sub> without or with 300 units/mL SOD, using 25 μg of protein of plasma membrane fraction with 0.2 mg of protein cytosol. The Nox2 system was activated by the addition of arachidonate (final concentration of 200 μM). Cytochrome c reduction by lysates or cell fractions from Nox4-expressing HEK293 cells in PBS (pH 7.4) containing 10 mM glucose was measured by the same method, except that the final cytochrome c concentration was 40 μM and GTPγS was omitted.

In some experiments, superoxide was also measured by dihydroethidium, according to ref 47 and using the same conditions that were used for cytochrome c reductase measurements.

**Measurement of Hydrogen Peroxide.** For intact cells, 100 μM Amplex Red final and 0.6 unit/mL HRP were included in place of cytochrome c, and the reaction was initiated by the addition of cells or fractions containing Nox4. The linear increase in the absorption of resorufin produced by oxidation of Amplex Red was measured at 572 nm. For experiments monitoring fluorescence, respective excitation and emission wavelengths of 572 and 583 nm, respectively, were used for cuvette measurements or fixed excitation and emission ranges of 540 ± 40 and 620 ± 40 nm, respectively, for microplate measurements. Reactions were monitored at 25 °C for 10 min using a Synergy 2 Multi-Model Microplate Reader and Gen 5, version 2.00 (Bio Tek), or, in oxygen dependence experiments, using a Pharmacia Biotec Ultraspec 3000 or a Hitachi F-4500 fluorescence spectrophotometer. For cell lysates, a final protein concentration of 0.25 mg/mL was added to a reaction mixture containing 20 μM FAD, 50 μM glucose 6-phosphate, and 50 μM NADP<sup>+</sup>. Endogenous glucose 6-phosphate dehydrogenase (G6PDH) was sufficient to support the NADPH oxidase reaction in lysates. For the isolated NEF/LSP cell fractions and for partially purified His<sub>6</sub>-Nox4, the same protocol was used, except that the indicated concentrations of enzyme or protein were added, and commercial G6PDH (0.25 unit/mL) was included. For cell-free measurements of Amplex Red oxidation, there is a well-documented interference by reduced pyridine nucleotides. However, we have found that the inclusion of an NADPH-regenerating system consisting of glucose 6-phosphate and G6PDH, along with NADP<sup>+</sup>, markedly decreased the background rate. The remaining low residual rate of enzyme-independent Amplex Red oxidation was then subtracted to obtain corrected rates. The concentration of Amplex Red oxidized was calculated using an extinction coefficient at 572 nm of 54 M<sup>−1</sup> cm<sup>−1</sup>, or when fluorescence was measured using a standard curve generated from the addition of known amounts of hydrogen peroxide.

In some experiments, hydrogen peroxide was quantified using an Apollo 4000 Free Radical Analyzer (World Precision Instruments), equipped with a hydrogen peroxide electrode. The electrode system was used according to the manufacturer’s instructions and allowed omission of HRP from assay mixtures.

**Regulation of the Oxygen Concentration.** The gas equilibration system consisted of a tightly capped 1.5 mL cuvette with a gas delivery needle and a gas exit needle that also served as a delivery port for addition of reagents. All experiments were conducted at 25 °C in a total volume of 0.8 mL. The mixture was equilibrated by gentle bubbling (approximately one bubble per second) with the indicated percent of oxygen/nitrogen gas mixtures, with continuous gentle stirring for 10 min using a magnetic stirrer. Concentrated stocks of activators (either PMA or arachidonate) were pre-equilibrated by being continuously bubbled with N<sub>2</sub> gas, and cells or cell fractions were activated by injecting 10 μL of activator through the gas exit needle with a 20 μL Hamilton syringe. Absorption, fluorescence, or luminescence measurements were taken as described above.

**Immunoprecipitation and Western Blot Analysis.** HEK293 cells were incubated in lysis buffer containing 1% Nonidet P-40 and 10% glycerol as described previously. The mixture was gently mixed by rotation for 1 h at 4 °C with antibody (30 μg) against Nox4 with 25 μL of protein A-agarose Fast Flow beads (50% slurry). The beads were washed three times with lysis buffer, and bound proteins were eluted into 30 μL of Laemmli sample buffer (Bio-Rad). Proteins were separated via sodium dodecyl sulfate–polyacrylamide gel electrophoresis (4 to 15% gel) and transferred to an Immobilon PVDF membrane (Millipore). Proteins were visualized by being incubated with primary antibodies overnight at 4 °C with gentle shaking and then with horseradish peroxidase-linked secondary antibody (1:3000 dilution, 2 h). Bands were visualized by chemiluminescence after the addition of Super...
Signal West Pico Chemiluminescent Substrate (Thermo Scientific), according to the manufacturer’s instructions.

**Spectrophotometric Determination of Heme.** Solubilized cell lysate, combined NEF/LSP fractions, or partially purified proteins in buffer B were centrifuged at 105,000g for 30 min at 4 °C to remove any particulate matter. Reduced-minus-oxidized difference spectra were recorded at 5 min intervals after the addition of a few crystals of sodium dithionite until a stable spectrum was achieved. The concentration of heme was determined from the difference spectrum near the Soret peak using a difference extinction coefficient of 426 minus 410 nm of 200 mM⁻¹ cm⁻¹.30

**RESULTS AND DISCUSSION**

**Reactive Oxygen Product of Nox4.** Consistent with earlier publications, Figure 1A demonstrates that in intact HEK293 cells stably expressing Nox4, the major product is H₂O₂ and very little superoxide is seen. In addition to the use of the Amplex Red method, this result was confirmed using a hydrogen peroxide electrode system. The electrode system reported approximately the same static concentrations of H₂O₂ as did Amplex Red when cells were removed but detected a rate of hydrogen peroxide formation in the presence of cells that was approximately 1/3 of that of the Amplex Red method. This was presumably due to the “trapping” effect of HRP in the Amplex Red assay, which allows detection of all of the released H₂O₂, whereas the electrode measures a rate of H₂O₂ that is decreased because of the competing metabolism by cellular catalase and peroxidases. This is in contrast to the case for neutrophils (Figure 1B), which express Nox2 but not other isoforms and show superoxide as the major product, with a neutrophils (Figure 1B), which express Nox2 but not other catalase and peroxidases. This is in contrast to the case for decreased because of the competing metabolism by cellular data con-artifactually generate superoxide,36 nonselectivity for ROS/RNS and redox cycling that can some earlier studies can be subject to certain artifacts such as there was no detectable di-reduction is not mediated by superoxide. In these preparations, reductases such as P450 reductase for which cytochrome c reduction was seen that was only slightly inhibited by SOD. This is likely due to the presence of endogenous cytochrome c reductases such as P450 reductase for which cytochrome c reduction is not mediated by superoxide. In these preparations, there was no detectable difference in cytochrome c reduction in Nox4-expressing versus control cells. In contrast, H₂O₂ was readily detected in Nox4-expressing but not control cells, with the H₂O₂ identity validated by inhibition by catalase but not SOD (Figure 1 of the Supporting Information). Because of the very limited amounts of material available and the large volume needed for measurements using the H₂O₂ electrode system, it was not feasible to use the electrode system for measurements in broken cell or purified preparations.

It can be argued that because of its transmembrane topology with its NADPH-binding site located on the cytosolic side of the membrane and the oxygen-reducing heme (heme B) located near the membrane-enclosed lumen, Nox4 might release superoxide into the interior of a membrane compartment where it is trapped due to its charge and therefore inaccessible to membrane-impermeant probes. There, it would be expected to undergo spontaneous and/or SOD-catalyzed dismutation to form H₂O₂. The latter might then diffuse through the membrane where it is detected by an extracellular
probe. Measurements made in both cell lysates and isolated membrane-containing cell fractions are also subject to the same theoretical concerns.

We therefore measured superoxide and hydrogen peroxide in a detergent-solubilized, partially purified preparation of Nox4 in which compartmentalization is not a concern. Details of the purification methods are provided in the Supporting Information and are summarized in Table 1. Briefly, cells and lysates from His6-Nox4-transfected cells were first verified to generate H$_2$O$_2$ at a rate nearly the same as the rate of cells and lysates from cells transfected with wild-type Nox4, and H$_2$O$_2$ generation was verified to be largely inhibited by the general flavoprotein dehydrogenase inhibitor diphenyleneiodonium (DPI) (Figure 2 of the Supporting Information). The NADPH-binding site mutant His$_6$-Nox4(P437H), which is inactive, was used as a negative control and showed levels of H$_2$O$_2$ generation nearly the same as those of nontransfected cells. Cells were fractionated by centrifugation and density methods into a nucleus-enriched fraction (NEF), a low-speed pellet (LSP), a high-speed pellet (HSP), and a high-speed supernatant (HSS), as shown in Figure 3 of the Supporting Information. Anti-His$_6$, anti-Nox4, and anti-p22phox immunoreactivity was seen primarily in the NEF and LSP fractions, which also showed the highest level of DPI-inhibited H$_2$O$_2$ production. These two fractions also stained for the nuclear marker Lamin A. While the colocalization of overexpressed Nox4 with nuclear markers does not definitively imply the nuclear localization of Nox4 in a natively expressing cell, it is interesting to note that Nox4 has been reported in several studies to be associated with nuclei; nevertheless, other studies have reported localizations in other subcellular locations, including the endoplasmic reticulum, plasma membrane, and mitochondria. NADPH enrichment was not used as an indicator of purification, which also showed the highest level of DPI-inhibited H$_2$O$_2$ generation. This is consistent with the idea that superoxide is an intermediate in the formation of H$_2$O$_2$ by Nox4 and that occasionally this intermediate is released and can be detected. Because the oxygen-reducing heme group is an obligate one-electron donor, a superoxide intermediate is mechanistically plausible, whereas the direct formation of H$_2$O$_2$ without a superoxide intermediate is mechanistically implausible. It should be pointed out that the measured rate of turnover of Nox4 is only 10–20% of that of Nox2. While this value is still quite respectable (e.g., some P450 enzymes show rates below 10 min$^{-1}$), we speculate that the rate of Nox2 that is much higher than that of Nox4 may represent an evolutionary adaptation to allow production of cytotoxic levels of H$_2$O$_2$ for microbial killing, compared with the lower concentrations of H$_2$O$_2$ that are likely to be needed for signal transduction.

**Oxygen Dependence of Nox4.** Herein, we explore the hypothesis that Nox4 activity is regulated not only by its expression level but also by oxygen availability and that it therefore functions as an oxygen sensor. For an enzyme to function as an oxygen sensor, it must fulfill two criteria. First, a *sine qua non* of an oxygen-sensing enzyme is an unusually high $K_m$ for oxygen that allows it to respond to physiological ranges of oxygen concentrations, which in tissues can range from 2–5% to around 20% in the lung, with intermediate concentrations in the circulatory system. Second, its enzymatic activity must be linked to an effect or signal that can be translated into a cellular response. While Nox4 has been speculated to function in this manner,

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tissue pO2 values, it cannot respond dynamically to changes in pO2; in contrast, a high K_m enzyme operating at a subsaturating pO2 will change its activity dynamically with changes in pO2.

The oxygen dependence for Nox2- versus Nox4-dependent ROS generation is compared in Figure 2. Nox2-dependent superoxide generation in either intact human neutrophils or a cell-free system shows a K_m for oxygen of 3.1 or 2.3%, respectively, corresponding to the range of K_m values seen in enzymes that participate in metabolic or cellular housekeeping functions. Because inflamed or infected tissues are often moderately hypoxic, this would allow the Nox2 system to continue to function at a significant rate under these conditions. On the other hand, Nox4 in both intact cells and lysates shows an oxygen K_m value for H_2O_2 generation of 16–20%, corresponding to the K_m range seen for other known oxygen-sensing enzymes. Under our assay conditions, the rate of Nox4-dependent H_2O_2 generation at both 21 and 1% oxygen was approximately linear for up to 3 h and was inhibited by DPI (data not shown). Because tissue oxygen concentrations are often on the order of 2–3%, this means that Nox4 will generate H_2O_2 approximately in direct proportion to oxygen at concentrations below ~10%, making it a sensitive reporter of tissue oxygenation.

**Mechanism of H_2O_2 Generation.** Two mechanisms are possible for the generation of H_2O_2 by Nox4. Because the FAD domain does not conduct this reaction directly, both possible mechanisms require single electron transfers from heme to oxygen. According to a “superoxide dismutase” mechanism that was previously suggested, two superoxide molecules are formed in sequence and retained at the active site, and their sequestered dismutation before release from the enzyme results in H_2O_2 formation. Such a mechanism is shown in Figure 3 (bottom), along with its rate equation. The oxygen dependence for such a mechanism involves two oxygen binding events and predicts a sigmoidal oxygen dependence, as shown by the dashed line in Figure 3. According to an internal superoxide reduction mechanism (Figure 3, top mechanism and rate equation), a single oxygen binds and is reduced in two sequential electron transfer steps from the heme, using a retained superoxide intermediate. Because there is a single oxygen binding event, such a mechanism predicts a simple hyperbolic Michaelis–Menten curve as shown by the solid black line in the top panel of Figure 3. Data replotted from Figure 2 show an excellent fit to the theoretical line predicted by a mechanism involving a single oxygen binding event for each H_2O_2 formed (i.e., a mechanism in which sequential electrons are introduced into the oxygen from the heme), while they do not conform to the internal superoxide dismutation mechanism that would require two distinct oxygen binding events for each H_2O_2 formed. Therefore, while either mechanism could account for a small production of superoxide (depending on the relative rate of dissociation compared with those of subsequent steps), kinetics are consistent only with a mechanism involving a single bound superoxide intermediate.
Inhibition of the production of superoxide generation in Nox4-expressing cells shows an unusually high factor that activates one of the Nox isoforms, rather than by finding that Nox4 was itself functioning as the oxygen sensor or was permissive in the response. These studies provide data consistent with an oxygen sensor role, the $K_m$ of Nox4 for oxygen was not previously determined, and it was therefore not clear to us whether Nox4 was itself functioning as the oxygen sensor or was permissive in the response. These studies provide this missing information and show that Nox4 activity is responsive to physiological ranges of oxygen tension. This may be relevant in normal physiology, for example, in skeletal muscle, wherein oxygen levels can dramatically and rapidly change with exercise. In addition, pathological ischemic conditions may also modulate Nox4 activity.

For an enzyme to function as an oxygen sensor, its enzymatic activity must be linked to a signal or an effector system that can mediate a downstream metabolic or cellular response. $H_2O_2$ has been long implicated as a cellular signal and has been linked to a variety of cellular responses, including regulation of transcription, enzymatic activity, and ion channels. In most signaling studies related to Nox enzymes, the cellular response is triggered by a receptor-linked hormone or growth factor that activates one of the Nox isoforms, rather than by oxygen concentration per se. Thus, the finding that Nox4 shows an unusually high $K_m$ for oxygen and that it generates mostly hydrogen peroxide means that Nox4, rather than responding to external signals via intermediate signaling mechanisms such as changes in cellular calcium or phosphor-

### SUMMARY

**Nox4 and Oxygen Sensing.** Nox4 was proposed to participate in oxygen sensing on the basis of its localization in kidney, which secretes the hormone erythropoietin in response to hypoxia. Although the HIF-1α system that regulates erythropoietin secretion had been proposed in earlier studies to respond to oxygen radicals, the oxygen-regulated enzymes prolyl hydroxylase and FIH-1 were subsequently discovered to be major regulators of the HIF-1α system and Nox4 is not currently thought to be involved. More recent studies have shown that responses of some ion channels to hypoxia require Nox4. The potassium channel TASK-1 is inhibited at 21% oxygen in Nox4-expressing cells (but not in Nox4-RNAi cells), and this inhibition is relieved by hypoxia. Likewise, the activity of the smooth muscle ryanodine receptor Ca$^{2+}$ release channel (RyR1) was oxygen-dependent and required Nox4, and the channel activity correlated with the oxidation of specific cysteine thiols in RyR1. While these studies provide data consistent with an oxygen sensor role, the $K_m$ of Nox4 for oxygen was not previously determined, and it was therefore not clear to us whether Nox4 was itself functioning as the oxygen sensor or was permissive in the response. These studies provide this missing information and show that Nox4 activity is responsive to physiological ranges of oxygen tension. This may be relevant in normal physiology, for example, in skeletal muscle, wherein oxygen levels can dramatically and rapidly change with exercise. In addition, pathological ischemic conditions may also modulate Nox4 activity.

For an enzyme to function as an oxygen sensor, its enzymatic activity must be linked to a signal or an effector system that can mediate a downstream metabolic or cellular response. $H_2O_2$ has been long implicated as a cellular signal and has been linked to a variety of cellular responses, including regulation of transcription, enzymatic activity, and ion channels. In most signaling studies related to Nox enzymes, the cellular response is triggered by a receptor-linked hormone or growth factor that activates one of the Nox isoforms, rather than by oxygen concentration per se. Thus, the finding that Nox4 shows an unusually high $K_m$ for oxygen and that it generates mostly hydrogen peroxide means that Nox4, rather than responding to external signals via intermediate signaling mechanisms such as changes in cellular calcium or phosphor-

(termed a "sequential one-electron reduction mechanism" in Figure 3). Because such a mechanism has certain features in common with a superoxide reductase enzymatic activity, we also investigated the effects of azide and cyanide on $H_2O_2$ and superoxide generation in Nox4-expressing cells. A bacterial superoxide reductase shows inhibition of the production of $H_2O_2$ by these agents, with accumulation of superoxide. The superoxide reductase shows inhibition of the production of superoxide generation in Nox4-expressing cells. A bacterial that Nox2 is not inhibited by azide or cyanide. Thus, azide inhibition may point to differentiating features of the oxygen-binding heme site in Nox2 versus Nox4.

These data allow us to suggest a role for a critical histidine (His-222) residue for $H_2O_2$ generation. Mutation of this histidine, which is localized in an extracellular loop adjacent to heme B, converts Nox4 from a predominantly $H_2O_2$-generating enzyme to a predominant superoxide generator. We confirmed the switch to predominantly superoxide generation upon mutation of His-222 in intact cells (data not shown). On the basis of thermodynamic considerations, transfer of a second electron to the negatively charged $O_2^-$ itself is energetically unfavorable, but donation of a histidyl proton to the $O_2^-$ intermediate (bound at the heme B site) to form the neutral $HO_2^-$ should greatly facilitate transfer of a second electron, which (along with a solvent proton) forms $H_2O_2$. Mutation of this proton-donating histidine (which is absent in superoxide-generating Nox isoforms) should then favor release of superoxide rather than $H_2O_2$. We are currently investigating such a mechanism.

**Figure 3.** Analysis of the kinetic models for $H_2O_2$ generation. Data from Figure 2D are replotted, normalized to the percentage of $V_{max}$. The solid line was calculated from the kinetic rate equation corresponding to a “sequential one-electron reduction mechanism” (top equation and scheme), while the dashed line is that calculated from the equation corresponding to an “internal superoxide dismutation mechanism” (bottom equation and scheme). The former mechanism involves binding of a single oxygen, which is then reduced sequentially by heme B in two one-electron reduction steps. Depending on the rate of dissociation of superoxide compared with that of a second electron transfer step, the enzyme will release either superoxide or hydrogen peroxide. If the second electron transfer is more rapid than dissociation of the superoxide, then the primary product will be $H_2O_2$. The internal superoxide dismutation mechanism involves two discrete oxygen binding steps, each producing a superoxide at the active site. Both superoxide molecules are retained at the active site (indicated by the dashed box), and dismutation then results in the release of $H_2O_2$. Inhibition of the production of superoxide by these agents, with accumulation of superoxide. The superoxide reductase shows inhibition of the production of superoxide generation in Nox4-expressing cells. Therefore, azide reduction step per se. Likewise, $1 mM$ KCN failed to increase the overall Nox4 enzyme activity rather than a superoxide increase in superoxide production, suggesting that azide inhibits Nox4-dependent $H_2O_2$ generation but did not cause any instability, $0.6 mM$ sodium azide produced 70% inhibition of use cyanide using the electrode system because of signal used to allow for high sensitivity. While it was not possible to detection, because these agents inhibit the HRP that is needed from Figure 2D are replotted, normalized to the percentage of corresponding to a “sequential one-electron reduction mechanism” (top equation and scheme), while the dashed line is that calculated from the equation corresponding to an “internal superoxide dismutation mechanism” (bottom equation and scheme). The former mechanism involves binding of a single oxygen, which is then reduced sequentially by heme B in two one-electron reduction steps. Depending on the rate of dissociation of superoxide compared with that of a second electron transfer step, the enzyme will release either superoxide or hydrogen peroxide. If the second electron transfer is more rapid than dissociation of the superoxide, then the primary product will be $H_2O_2$. The internal superoxide dismutation mechanism involves two discrete oxygen binding steps, each producing a superoxide at the active site. Both superoxide molecules are retained at the active site (indicated by the dashed box), and dismutation then results in the release of $H_2O_2$. Inhibition of the production of superoxide by these agents, with accumulation of superoxide. The superoxide reductase shows inhibition of the production of superoxide generation in Nox4-expressing cells. Therefore, azide reduction step per se. Likewise, $1 mM$ KCN failed to increase the overall Nox4 enzyme activity rather than a superoxide increase in superoxide production, suggesting that azide inhibits Nox4-dependent $H_2O_2$ generation but did not cause any instability, $0.6 mM$ sodium azide produced 70% inhibition of use cyanide using the electrode system because of signal used to allow for high sensitivity. While it was not possible to detection, because these agents inhibit the HRP that is needed from Figure 2D are replotted, normalized to the percentage of corresponding to a “sequential one-electron reduction mechanism” (top equation and scheme), while the dashed line is that calculated from the equation corresponding to an “internal superoxide dismutation mechanism” (bottom equation and scheme). The former mechanism involves binding of a single oxygen, which is then reduced sequentially by heme B in two one-electron reduction steps. Depending on the rate of dissociation of superoxide compared with that of a second electron transfer step, the enzyme will release either superoxide or hydrogen peroxide. If the second electron transfer is more rapid than dissociation of the superoxide, then the primary product will be $H_2O_2$. The internal superoxide dismutation mechanism involves two discrete oxygen binding steps, each producing a superoxide at the active site. Both superoxide molecules are retained at the active site (indicated by the dashed box), and dismutation then results in the release of $H_2O_2$.
ylation of regulatory subunits, responds directly and acutely to oxygen tension with the output of the signal molecule H$_2$O$_2$.

The role of Nox4 in oxygen sensing appears to be complex because oxygen levels can also regulate the expression of Nox4 itself. For example, the Nrf2 system transcriptionally induces antioxidant- and drug-metabolizing enzymes in response to oxidants and electrophilic compounds$^{63,64}$ as part of a pathway to adapt to cellular stresses. It is interesting that among the protein products induced by Nrf2 in response to hyperoxia is Nox4 itself, which may suggest that the induction of a Nox4-catalyzed H$_2$O$_2$ signal is part of a cellular adaptation response to oxidative stress. In this context, adaptation to cellular stresses has previously been suggested as a general function for the Nox family of proteins. Nox4 is also induced under hypoxic conditions in pulmonary artery smooth muscle cells via a HIF-1$\alpha$ pathway, suggesting that its regulation by oxygen may be complex and tissue-dependent. Nox4 is also induced by other stresses such as cardiac load-induced stress$^{65}$ and by inflammatory mediators via the NF-κB pathways$^{66}$ and in the former system has been shown to exert a beneficial effect, in contrast to the detrimental effect of Nox2 induction.$^{67}$ Thus, Nox4-derived H$_2$O$_2$ may participate in signaling by both acute oxidants and electrophilic compounds$^{63,64}$ as part of a pathway itself. For example, the Nrf2 system transcriptionally induces because oxygen levels can also regulate the expression of Nox4 generating Nox isoform.

Regardless of the stimulus, induction of Nox4 would be expected to increase the magnitude of the response of Nox4 to oxygen concentration, further enhancing Nox4-dependent H$_2$O$_2$ signaling with its consequent transcriptional induction of stress-adaptive proteins. We suggest that Nox4 is likely to participate in physiological processes, including adaptation to altitude and regulation of the delivery of oxygen to tissues, and that aberrant expression of Nox4 will lead to pathological processes, for example, related to the aberrant responses of tumors to hypoxia,$^{69}$ hypoxia-induced pulmonary hypertension,$^{70}$ and a growing list of diseases in which Nox4 has been implicated.$^{71,72}$

In summary, Nox4 has been described as being unique among the Nox family of enzymes in that it is constitutively active without the need for external signals or regulatory proteins. Rather, these studies indicate that its activity is regulated acutely by oxygen tension. Its widespread distribution, including in cells of the vascular system, suggests important physiological roles for Nox4 in the rapid response to changes in oxygen tension in the circulatory system and in tissues. In this context, the primary output of the signaling molecule H$_2$O$_2$ with minimal production of superoxide may allow for signaling with a level of production of toxic oxygen radicals lower than what would be possible with a superoxide-generating Nox isoform.

ASSOCIATED CONTENT

Supporting Information
Four figures documenting the subcellular fractionation and characterization of Nox4-containing fractions and the partial purification of a membrane-free preparation of Nox4. This material is available free of charge via the Internet at http://pubs.acs.org.

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ABBREVIATIONS

ROS, reactive oxygen species; RNS, reactive nitrogen species; NADPH oxidase; PRD, proline-rich domain; NEF, nucleus-enriched fraction; LSP, low-speed pellet; Sn, supernatant; HSP, high-speed pellet; DPI, diphenyleneiodonium; PMSF, phenylmethylsulfonyl fluoride; FAD, flavin adenine dinucleotide; G6PDH, glucose-6-phosphate dehydrogenase; NADPH, nicotinamide adenine dinucleotide phosphate (reduced form); NADP$, nicotinamide adenine dinucleotide phosphate (oxidized form); PHD, HIF1-α prolyl hydroxylase; FIH-1, HIF1-α asparaginyl hydroxylase; SEM, standard error of the mean.

REFERENCES


