Hydrogen peroxide regulation of endothelial exocytosis by inhibition of N-ethylmaleimide sensitive factor

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Although an excess of reactive oxygen species (ROS) can damage the vasculature, low concentrations of ROS mediate intracellular signal transduction pathways. We hypothesized that hydrogen peroxide plays a beneficial role in the vasculature by inhibiting endothelial exocytosis that would otherwise induce vascular inflammation and thrombosis. We now show that endogenous H$_2$O$_2$ inhibits thrombin-induced exocytosis of granules from endothelial cells. H$_2$O$_2$ regulates exocytosis by inhibiting N-ethylmaleimide sensitive factor (NSF), a protein that regulates membrane fusion events necessary for exocytosis. H$_2$O$_2$ decreases the ability of NSF to hydrolyze adenosine triphosphate and to disassemble the soluble NSF attachment protein receptor complex. Mutation of NSF cysteine residue C264T eliminates the sensitivity of NSF to H$_2$O$_2$, suggesting that this cysteine residue is a redox sensor for NSF. Increasing endogenous H$_2$O$_2$ levels in mice decreases exocytosis and platelet rolling on venules in vivo. By inhibiting endothelial cell exocytosis, endogenous H$_2$O$_2$ may protect the vasculature from inflammation and thrombosis.

Introduction

Reactive oxygen species (ROS) play a critical role in vascular signaling, mediating cellular responses to ligands such as growth factors and cytokines (Finkel and Holbrook, 2000; Griendling et al., 2000; Xu et al., 2002). Elevated levels of ROS that are associated with cardiovascular diseases such as diabetes, hypertension, and atherosclerosis promote vascular inflammation by modulating proinflammatory transcription factors, by oxidizing LDL, and by limiting the bioavailability of nitric oxide (NO; Griendling and Alexander, 1997; Maytin et al., 1999; Harrison et al., 2003). However, low levels of ROS play a physiological role by acting as second messengers (Goldschmidt-Clermont and Moldovan, 1999; Griendling and Harrison, 1999; Cai and Harrison, 2000; Finkel, 2000). Extracellular ligands activate production of intracellular ROS, which modulate specific signal transduction pathways (Sundaresan et al., 1995; Bae et al., 1997; Hampton and Orrenius, 1997; Irani et al., 1997; Ushio-Fukai et al., 1998; Goldhaber and Qayyum, 2000; Irani, 2000; Har et al., 2002; Liu and Gutterman, 2002; Meng et al., 2002). Low concentrations of ROS may protect the vasculature from inflammation.

Weibel-Palade body exocytosis is one mechanism by which endothelial cells promote vascular inflammation (Weibel and Palade, 1964; Wagner, 1993). Weibel-Palade bodies are endothelial cell granules that contain von Willebrand’s factor (vWF) and P-selectin (Wagner et al., 1982; McEver et al., 1989; Vischer and Wagner, 1993). A variety of proinflammatory agonists trigger endothelial cell exocytosis of Weibel-Palade bodies, releasing vWF into the lumen, which promotes platelet adhesion and aggregation, and translocates P-selectin to the luminal surface, which facilitates leukocyte rolling. Weibel-Palade body exocytosis is regulated by members of the SNARE superfamily and NSF (Jahn and Sudhof, 1999; Mellman and Warren, 2000; Sollner, 2003). We recently discovered that NO regulates exocytosis by S-nitrosylating cysteine residues on NSF (Matsushita et al., 2003). Because low levels of ROS may protect the vasculature from inflammation, we hypothesized that hydrogen peroxide modulates exocytosis by regulating NSF.

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Abbreviations used in this paper: 3-AT, 3-amino-triazole; HAEC, human aortic endothelial cells; NAC, N-acetyl-cysteine; NO, nitric oxide; ROS, reactive oxygen species; SOD, superoxide dismutase; vWF, von Willebrand’s factor.
Results

To explore the effect of H$_2$O$_2$ on granule exocytosis, we studied thrombin-induced exocytosis of Weibel-Palade bodies from human aortic endothelial cells (HAEC). We pretreated HAEC with H$_2$O$_2$ for 10 min, and then stimulated the cells with thrombin, and measured the amount of vWF released into the media. Thrombin induces the rapid release of vWF from HAEC (Fig. 1, A and B). However, exogenous H$_2$O$_2$ blocks the effects of thrombin in a dose-dependent manner (Fig. 1, A and B). We next examined the effect of the antioxidant N-acetyl-cysteine (NAC) on Weibel-Palade body exocytosis. HAEC were incubated with NAC for 4 h, washed, treated with H$_2$O$_2$, and finally stimulated with media or thrombin, and exocytosis was measured with an ELISA for vWF. NAC counteracts the inhibitory effect of H$_2$O$_2$ (Fig. 1 C).

Endogenous H$_2$O$_2$ inhibits exocytosis

We next examined the role of endogenous H$_2$O$_2$ in the regulation of Weibel-Palade body exocytosis. First, we showed that thrombin increases endogenous H$_2$O$_2$ production. We transduced HAEC with adenoviral vectors expressing β-galactosidase or catalase and measured cellular levels of H$_2$O$_2$ before and after thrombin treatment. Thrombin increases endogenous H$_2$O$_2$ production in control cells, but transduction with adenovirus-catalase blocks thrombin stimulation of endogenous H$_2$O$_2$ production (Fig. 2 A). These data suggest that thrombin activates endogenous H$_2$O$_2$ production and catalase decreases endogenous H$_2$O$_2$ levels.

We used these adenoviral vectors to determine the effect of endogenous H$_2$O$_2$ on Weibel-Palade body exocytosis. Thrombin stimulates control HAEC to release vWF (Fig. 2 B). Expression of β-galactosidase has no effect on vWF release. However, expression of catalase increases vWF release from resting cells and from thrombin-stimulated cells (Fig. 2 B). Furthermore, expression of superoxide dismutase (SOD) decreases the release of vWF (Fig. 2 B). These data suggest that endogenous H$_2$O$_2$ produced in response to thrombin inhibits Weibel-Palade body exocytosis.

We next pretreated HAEC with angiotensin II to activate endogenous production of H$_2$O$_2$ (Ku et al., 1993; Papaspetroulos et al., 1997; Dimmelser et al., 1999; Fulton et al., 1999). Treatment with 10$^{-7}$ M angiotensin II for 30 min decreases thrombin-stimulated vWF release (Fig. 2 C). Catalase or an angiotensin II antagonist peptide blocks the effects of angiotensin II treatment, implying that H$_2$O$_2$ mediates angiotensin II inhibition of exocytosis (Fig. 2 C). These data suggest that endogenous H$_2$O$_2$ regulates endothelial cell exocytosis.

H$_2$O$_2$ inhibits NSF

How does H$_2$O$_2$ inhibit exocytosis? We hypothesized that H$_2$O$_2$ inhibits NSF, a protein that regulates granule exocytosis, by activating endogenous H$_2$O$_2$ production and catalase decreases endogenous H$_2$O$_2$ levels.

Figure 1. Exogenous H$_2$O$_2$ inhibits exocytosis from HAEC. [A] Dose response. HAEC were pretreated with increasing amounts of exogenous H$_2$O$_2$ for 10 min, and then treated with 1 U/ml thrombin, and the amount of vWF released into the media was measured by an EUSA (n = 3 ± SD; *, P < 0.05 vs. thrombin; **, P < 0.01 vs. thrombin). (B) Time course. HAEC were pretreated with exogenous H$_2$O$_2$ for 10 min, and then treated with 1 U/ml thrombin, and the amount of vWF released into the media at increasing times was measured by an EUSA (n = 3 ± SD). (C) NAC decreases exogenous H$_2$O$_2$ inhibition of thrombin-triggered vWF release. Cells were incubated with 10 mM NAC for 4 h, washed, treated with H$_2$O$_2$, and stimulated with media or thrombin, and the amount of released vWF was measured (n = 3 ± SD; **, P < 0.01 vs. H$_2$O$_2$ alone).

Figure 2. Endogenous H$_2$O$_2$ inhibits exocytosis from HAEC. [A] Catalase inhibits endogenous H$_2$O$_2$ production. HAEC were transduced with adenoviral vectors and stimulated with thrombin. The amount of H$_2$O$_2$ released from cells was measured by monitoring the increase in fluorescence of N-acetyl-3,7-dihydroxyphenoxazine (n = 3 ± SD; **, P < 0.01 vs. control). (B) Endogenous H$_2$O$_2$ decreases thrombin-triggered vWF release. HAEC were transduced with adenoviral vectors and, after 48 h, treated with thrombin, and vWF was measured with an EUSA (n = 3 ± SD; **, P < 0.01 vs. none). (C) Angiotensin II induction of endogenous H$_2$O$_2$ decreases vWF release. HAEC were stimulated with 10$^{-7}$ M angiotensin II for 30 min, and then incubated with thrombin and 500 U/ml catalase or 10 mM angiotensin II antagonist peptide. The amount of vWF released from cells into the media was measured by an EUSA (n = 3 ± SD; **, P < 0.01 vs. control).
hydrolyzing ATP and by interacting with SNARE molecules (Block et al., 1988; Malhotra et al., 1988; Mellman and Warren, 2000). We first examined the effect of H₂O₂ on the ATPase activity of NSF, which is critical for NSF function (Whiteheart et al., 1994). H₂O₂ was added to 10 μg of recombinant NSF, and the ATPase activity of NSF was measured by a colorimetric assay. H₂O₂ significantly inhibits NSF hydrolysis of ATP (Fig. 3 A).

If H₂O₂ reversibly oxidizes NSF cysteine residues, then the reducing agent DTT would be predicted to reduce oxidized cysteine residues and restore NSF ATPase activity. To test this prediction, we treated recombinant NSF with H₂O₂, added DTT, and measured the ATPase activity of NSF. H₂O₂ inhibits NSF ATPase activity, and DTT restores ATPase activity of NSF exposed to H₂O₂ (Fig. 3 B).

We next explored the effect of H₂O₂ on NSF disassembly activity. NSF interacts with SNARE molecules using α-SNAP as an adaptor (Jahn and Sudhof, 1999; Mellman and Warren, 2000). ATP-γS locks NSF onto the SNARE complex; however, ATP enables NSF to separate from and disassemble the SNARE complex. Accordingly, we examined the effect of H₂O₂ on NSF disassembly of recombinant NSF molecules. Recombinant (His)₆-NSF was pretreated or not with H₂O₂. Then, (His)₆-NSF and (His)₆-α-SNAP were incubated with recombinant SNARE polypeptides that regulate Weibel-Palade body exocytosis: GST-syntaxin-4 as well as nontagged VAMP-3 and SNAP-23. ATP or ATP-γS was added to the mixture, the mixture was precipitated with glutathione-sepharose beads, and precipitated proteins were fractionated by SDS-PAGE and immunoblotted with antibody to the NSF tag, syntaxin, and VAMP-3.

ATP-γS increases the interaction of NSF with SNARE polypeptides. ATP decreases the interaction of NSF with SNARE polypeptides (Fig. 3 C). However, H₂O₂ blocks NSF disassembly of the SNARE complex in the presence of ATP (Fig. 3 D). H₂O₂ inhibits disassembly activity of wild-type NSF in a dose-dependent manner (Fig. 3 D). Together, these data show that H₂O₂ blocks NSF disassembly activity.

We next confirmed that NSF is an intracellular target of H₂O₂. We treated HAEC with H₂O₂, and then permeabilized the cells and added recombinant NSF. H₂O₂ blocks exocytosis as before (Fig. 3 E). Recombinant NSF restores exocytosis to cells inhibited with H₂O₂ (Fig. 3 E). Furthermore, oxidized NSF cannot restore exocytosis to HAEC (Fig. 3 E). As an additional control, we added to HAEC either wild-type NSF or a mutant NSF(C264A) with decreased ATPase activity. Although wild-type NSF restores secretion to endothelial cells, the kinase-dead mutant NSF does not (Fig. 3 F). These data demonstrate that NSF is an intracellular target of H₂O₂.

Specific cysteine residues mediate NSF sensitivity to H₂O₂

H₂O₂ may regulate NSF by oxidizing cysteine residues. To determine which of the nine cysteine residues of NSF are targets of H₂O₂, we expressed in bacteria and purified wild-type NSF polypeptides with each of the nine individual cysteine residues. We added H₂O₂ to wild-type and mutant NSF polypeptides and measured ATPase activity. Mutation of cysteine residues 21, 91, 264, and 334 decreases NSF ATPase activity (Fig. 4 A). H₂O₂ treatment inhibits ATPase activity of all mutant NSF except mutants C21A and C264A (Fig. 4 A). These data suggest that cysteine residues C21 and C264 mediate H₂O₂ inhibition of NSF ATPase activity.

We next determined which cysteine residues mediate H₂O₂ inhibition of NSF separation from the SNARE complex.

Figure 3. H₂O₂ inhibits NSF. (A) H₂O₂ inhibits ATPase activity of wild-type NSF. H₂O₂ or control was added to recombinant wild-type NSF, and the ATPase activity of NSF was measured [n = 2 ± SD; * P < 0.05 vs. NSF; ** P < 0.01 vs. NSF]. (B) DTT restores ATPase activity of wild-type NSF inhibited by H₂O₂. H₂O₂ or control was added to recombinant wild-type NSF, buffer or 1 mM DTT was added, and the ATPase activity of NSF was measured [n = 3 ± SD; * P < 0.01 for H₂O₂ vs. H₂O₂ + DTT]. (C) H₂O₂ inhibits disassembly activity of wild-type NSF. Recombinant (His)₆-NSF was pretreated or not with 1 mM H₂O₂ and incubated with (His)₆-α-SNAP, GST-Syntaxin-4, VAMP-3, and SNAP-23. ATP or ATP-γS was added, and the mixture was precipitated with glutathione-sepharose. Precipitated proteins were immunoblotted with antibody to the NSF tag (top), to syntaxin-4 (middle), or to VAMP-3 (bottom). Experiment was repeated three times with similar results. (D) H₂O₂ inhibits disassembly activity of wild-type NSF (dose response). The NSF disassembly assay was performed, pretreating recombinant (His)₆-NSF with increasing concentrations of H₂O₂ and then mixing with (His)₆-α-SNAP, GST-Syntaxin-4, VAMP-3, and SNAP-23. Proteins precipitated with glutathione-sepharose were immunoblotted with antibody to the NSF tag (top), to syntaxin-4 (middle), or to VAMP-3 (bottom). Experiment was repeated three times with similar results. (E) Exogenous NSF restores vWF exocytosis in endothelial cells treated with H₂O₂. HAEC were pretreated with 1 mM H₂O₂ for 10 min, permeabilized with SLO, incubated with recombinant NSF or H₂O₂-treated recombinant NSF, and stimulated with thrombin, and the amount of vWF in the media was measured [n = 3 ± SD; * P < 0.01 for H₂O₂ vs. H₂O₂ + NSF]. (F) NSF mutant C264A does not restore exocytosis. HAEC were pretreated with 1 mM H₂O₂ for 10 min, permeabilized, and incubated with recombinant wild-type NSF (WT) or mutant NSF(C264A). In some cases, the recombinant NSF was treated with H₂O₂ before addition to cells. The cells were then resolated and stimulated with thrombin, and the amount of vWF in the media was measured [n = 3 ± SD; * P < 0.01 vs. H₂O₂ + Thrombin].
We used the NSF-SNARE pull-down assay, adding H$_2$O$_2$ to NSF mutants lacking individual cysteine residues, along with $\alpha$-SNAP, GST-syntaxin-4, VAMP-3, and SNAP-23. H$_2$O$_2$ blocks the ability of wild-type NSF to separate from the SNARE complex in the presence of ATP (Fig. 4 B). Mutation of cysteine residues 250 and 599 has no effect on the ability of H$_2$O$_2$ to inhibit NSF separation from the SNARE complex. The effect of H$_2$O$_2$ on cysteine residues 11, 21, 334, 568, and 582 cannot be ascertained because mutation of these residues abrogates NSF interaction with SNARE molecules. Recombinant wild-type or mutant NSF was treated with 0.1 mM H$_2$O$_2$ for 5 min, fractionated by non-denaturing PAGE, and then immunoblotted with antibody to NSF.

We next constructed a H$_2$O$_2$-resistant NSF mutant and used it to make an endothelial cell line containing H$_2$O$_2$-resistant NSF. Our data suggested that C264 may be a redox-sensitive cysteine residue in NSF. A comparison of primary NSF amino acid sequences reveals that C264 in the Walker A box of the D1 domain of NSF may be a recent evolutionary adaptation (Sollner and Sequeira, 2003). The amino acid residue in this position is cysteine in vertebrates but is threonine in insects, plants, and yeast (Sollner and Sequeira, 2003). We hypothe-
sized that a mutant NSF(C264T) would retain NSF activity but would be resistant to H2O2. To test this idea, we constructed the NSF mutant NSF(C264T).

We first compared the effect of H2O2 on the ATPase activity of recombinant wild-type NSF and mutant NSF(C264T). The ATPase activity of the NSF(C264T) mutant is approximately the same as that of wild-type NSF, although the ATPase activity of mutant NSF(C264A) is greatly decreased (Fig. 5 A). H2O2 inhibits ATPase activity of wild-type NSF but not of mutant NSF(C264T) (Fig. 5 A).

We next compared the effect of H2O2 on the disassembly activity of wild-type NSF and mutant NSF(C264T). The disassembly activity of the NSF(C264T) mutant is similar to that of the wild-type NSF (Fig. 5 B). H2O2 inhibits disassembly activity of wild-type NSF but not of mutant NSF(C264T) (Fig. 5 B).

We then constructed endothelial cells that contain the NSF(C264T) mutant. Endothelial cells were permeabilized with SLO and then incubated with wild-type or mutant NSF. Thrombin activates exocytosis in HAEC containing wild-type NSF and mutant NSF(C264T) (Fig. 5 C). H2O2 inhibits exocytosis from cells containing wild-type NSF. In contrast, H2O2 does not affect exocytosis from endothelial cells containing NSF(C264T) (Fig. 5 C). Together, these data show that NSF residue C264 is a target of H2O2. These data also support the hypothesis that H2O2 inhibits exocytosis by oxidation of NSF.

**H2O2 inhibits exocytosis in vivo**

We also examined the physiological effects of H2O2 on exocytosis in vivo. If H2O2 inhibits exocytosis, then we would expect catalase inhibitors to increase endogenous H2O2 levels and to decrease endothelial release of vWF. We first tested this hypothesis in endothelial cells with the catalase inhibitor 3-amino triazole (3-AT). Increasing doses of 3-AT increase endothelial levels of H2O2 (Fig. 6 A). Increasing doses of 3-AT also block endothelial exocytosis (Fig. 6 B). We examined this phenomenon in mice. We administered 3-AT to mice, and examined H2O2 levels and exocytosis after 5 h. The catalase inhibitor 3-AT increases H2O2 levels in murine liver (Fig. 6 C). We examined the effect of 3-AT on platelet rolling along murine venules stimulated with FeCl3; platelet rolling is mediated in part by vWF released by endothelial exocytosis of Weibel-Palade bodies (Andre et al., 2000). Mice were treated with 3-AT or PBS, anesthetized, and injected with calcein-AM–labeled platelets. The mesentery was externalized, endothelial exocytosis was induced by superfusing with FeCl3, and platelet rolling on mesenteric venules was recorded using a digital fluorescent camera. FeCl3 activates platelet rolling in control mice (Fig. 6, D and E). However, 3-AT greatly inhibits FeCl3-activated platelet rolling in mice (Fig. 6, D and E). Together, these data suggest that H2O2 inhibits exocytosis by nitrosylating NSF (Matsushita et al., 2003). NO and H2O2 appear to have distinct effects on NSF. Both NO and H2O2 inhibit NSF disassembly activity, but only H2O2 inhibits NSF ATPase activity. Together, our data suggest that the intracellular redox state regulates exocytosis.

Thrombin not only stimulates endothelial exocytosis but also stimulates H2O2 production, which inhibits exocytosis. Other compounds that activate endothelial exocytosis also increase H2O2 production, such as epinephrine, VEGF, and ceramide (Griendling and Alexander, 1997; Goldschmidt-Clermont and Moldovan, 1999; Finkel, 2001). H2O2 may thus serve as a nitric oxide (NO) sensor for NSF. These data extend our report that NO regulates exocytosis by nitrosylating NSF (Matsushita et al., 2003). NO and H2O2 appear to have distinct effects on NSF. Both NO and H2O2 inhibit NSF disassembly activity, but only H2O2 inhibits NSF ATPase activity. Together, our data suggest that the intracellular redox state regulates exocytosis.

**Discussion**

The major finding of our study is that H2O2 regulates exocytosis by inhibiting NSF. Construction of an H2O2-resistant mutant NSF suggests that NSF residue C264 serves as a redox sensor for NSF. These data extend our report that NO regulates exocytosis by nitrosylating NSF (Matsushita et al., 2003). NO and H2O2 appear to have distinct effects on NSF. Both NO and H2O2 inhibit NSF disassembly activity, but only H2O2 inhibits NSF ATPase activity. Together, our data suggest that the intracellular redox state regulates exocytosis.

Several large randomized clinical trials have demonstrated that antioxidants do not reduce mortality or cardiovascular outcomes (Virtamo et al., 1998; Yusuf et al., 2000; de Gaetano, 2001; Heart Protection Study Collaborative Group, 2002)
Materials and methods

Materials

Thrombin was purchased from Enzyme Research Laboratories. H₂O₂, catalase, NAC, and angiotensin II were purchased from Sigma-Aldrich. Mouse mAbs to NSF and syntaxin-4 were purchased from BD Biosciences. The cDNA for GST-syntaxin-4, GST-SNAP-23, and GST-VAMP-3 were provided by J. Pevsner (Johns Hopkins University School of Medicine, Baltimore, MD). The cDNAs of RGS-His₆-NSF and RGS-His₆-αSNAP were gifts from J.E. Rothman (Rockefeller University, New York, NY).

Preparation of recombinant adenoviruses

The replication-deficient adenovirus encoding the epitope-tagged catalase, SOD cDNA, and the adenovirus-LacZ were constructed by homologous recombination in 293 cells with use of the adenovirus-based plasmid pHM17 as previously described (Sundaresan et al., 1995; Irani et al., 1997). All viruses were amplified and tittered in 293 cells and purified on CsCl gradients.

Preparation of recombinant NSF and SNARE polypeptides

Mutation of the cysteine residues to alanine residues of NSF was performed with a kit according to the manufacturer’s instructions (Stratagene). Recombinant NSF mutant polypeptides, and resealed. We developed a permeabilization protocol specific for endothelial cells by following a method for optimization of permeabilization with SLO (Wale et al., 2001). To permeabilize HAEC, cells were grown in 96-well plates, washed with HBSS without Mg²⁺ and Ca²⁺, and incubated for 15 min at 37°C with 10 U SLO in 50 μL PBS, pH 7.4, along with 100 μg/ml NSF or NSF mutants polypeptides, and ressealed. We developed a permeabilization protocol specific for endothelial cells by following a method for optimization of permeabilization with SLO (Wale et al., 2001). To permeabilize HAEC cells, HAEC were obtained from Clonetics and grown in EGM-2 media (Clonetics). For some assays, the GST tag was cleaved off of the GST-SNARE polypeptides GST-VAMP-3 and GST-SNAP-23 with thrombin.

Cell culture and analysis of vWF release

HAEC were obtained from Clonetics and grown in EGM2 media (Clonetics). To measure the effect of H₂O₂ on vWF release, HAEC were pre-treated with buffer or H₂O₂ for 10 min in the presence or absence of catalase. The cells were washed and stimulated with 1 μM histamine, and images of platelet rolling were captured with a digital camera (Retiga Exi Fast1394; Qimaging) through a Modulation Optics objective lens with a 20× magnification. The images were collected by QCapture PRO imaging software (Qimaging) and imported into Adobe Photoshop Creative Suits on an Apple PowerPC G4 computer. Each image was adjusted with Adobe Photoshop CS to select the entire image, opening the Levels dialogue box, dragging the black Input Level slider to the leftmost cluster of pixels in the histogram, and dragging the white Input Level slider to the rightmost cluster of pixels in the histogram. Platelet rolling was determined by counting the number of platelets that remained transiently within a frame for the 30-ms collection time.

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References


2002; Morris and Carson, 2003). Our data suggest one explanation for this lack of benefit: endogenous oxidants protect the vasculature by inhibiting endothelial exocytosis that would otherwise lead to vascular inflammation and thrombosis. Future therapies aimed at modulating endogenous oxidants may have to be narrowly tailored to block the harmful effects of radicals while preserving the beneficial effects.


