Myeloperoxidase Delays Neutrophil Apoptosis Through CD11b/CD18 Integrins and Prolongs Inflammation

Driss El Kebir,* Levente József,* Wanling Pan, János G. Filep

Abstract—Polymorphonuclear neutrophil granulocytes have a central role in innate immunity and their programmed cell death and removal are critical for efficient resolution of acute inflammation. Myeloperoxidase (MPO), a heme protein abundantly expressed in neutrophils, is generally associated with killing of bacteria and oxidative tissue injury. Because MPO also binds to neutrophils, we investigated whether MPO could affect the lifespan of neutrophils. Here, we report that MPO independent of its catalytic activity through signaling via the adhesion molecule CD11b/CD18 rescued human neutrophils from constitutive apoptosis and prolonged their life span. MPO evoked a transient concurrent activation of extracellular signal-regulated kinase and Akt, leading to phosphorylation of Bad at both Ser112 and Ser136, prevention of mitochondrial dysfunction, and subsequent activation of caspase-3. Consistently, pharmacological inhibition of extracellular signal-regulated kinase, Akt, or caspase-3 reversed the antiapoptosis action of MPO. Acute increases in plasma MPO delayed murine neutrophil apoptosis assayed ex vivo. In a mouse model of self-resolving inflammation, MPO also prolonged the duration of carrageenan-induced acute lung injury, as evidenced by enhanced alveolar permeability and accumulation of neutrophils parallel with suppression of neutrophil apoptosis. Our results indicate that MPO functions as a survival signal for neutrophils and thereby contribute to prolongation of inflammation. (Circ Res. 2008;103:0-0.)

Key Words: apoptosis ■ neutrophil granulocytes ■ myeloperoxidase ■ integrins ■ inflammation

Recruitment and activation of polymorphonuclear neutrophil granulocytes is among the principal defense mechanisms of innate immunity. However, neutrophil-derived proteases and reactive oxygen species, which are required for the elimination of microbes,1-3 are also capable of inflicting tissue damage.4 Myeloperoxidase (MPO), a heme protein abundantly expressed in the azurophilic granules,5 plays a central role in these events. MPO catalyzes the formation of hypochlorous acid, a potent oxidant that has been implicated in killing bacteria6 and tissue destruction through induction of necrosis and apoptosis.4,7 MPO, through formation of secondary oxidants and nitration of protein tyrosine residues, could modulate intercellular signaling in the vasculature7-9 and affect the activation state of neutrophils.10

Neutrophil trafficking into inflamed tissues is intimately linked to prolonged survival. Mature neutrophils have the shortest half-life (2-7 hours) among leukocytes and die rapidly via apoptosis.11-13 This constitutively expressed cell death program renders neutrophils unresponsive to proinflammatory stimuli and promotes their removal from inflamed areas by scavenger macrophages11 with minimal damage to the surrounding tissue, thereby facilitating the resolution of inflammation.14,15 Neutrophil survival is contingent on rescue from apoptosis by signals, such as lipopolysaccharide or proinflammatory cytokines, from the inflammatory microenvironment.16 Markedly suppressed neutrophil apoptosis has been detected in patients with inflammatory diseases, including acute respiratory distress syndrome,17 sepsis,18 and acute coronary artery disease,19 that are also associated with elevated intravascular MPO levels.20,21 However, the link between MPO and the fate of neutrophils is unclear. H2O2 or tumor necrosis factor triggers apoptosis of neutrophilic HL60 leukemia cells through MPO-dependent downregulation of FLIPS.22 In mice, MPO deficiency reduces ischemia/reperfusion-induced renal dysfunction and neutrophil accumulation but fails to abrogate apoptosis during early phases of reperfusion.23 Understanding the role of MPO in regulating neutrophil survival and apoptosis will provide important information regarding development of novel targeted therapies for dampening inflammation underlying a variety of diseases.

In the present study, we investigated whether MPO can influence neutrophil survival and apoptosis in vitro and consequently the inflammatory response in vivo. Here, we report that MPO signals through the b2 integrin CD11b/CD18 to rescue neutrophils from apoptosis by preventing mitochondrial dysfunction and subsequent activation of caspase-3. We also show that acute increases in plasma MPO level lead to...
delayed murine neutrophil apoptosis and that MPO suppression of neutrophil apoptosis prolongs acute inflammation in carrageenan-induced acute lung injury.

**Materials and Methods**

Myeloperoxidase purified from human neutrophils was obtained from Athens Research and Technology (purity >98% by SDS-PAGE, RZ of 0.82, no detectable eosinophil peroxidase contamination). Lactoferrin and elastase prepared from human leukocytes were from Sigma.

**Neutrophil Isolation and Culture**

Neutrophils were isolated from the venous blood of healthy volunteers who had denied taking any medication for at least 2 weeks. The Clinical Research Committee approved the experimental protocols. Neutrophils (5×10⁶ cells/mL, purity >96%, viability >98%) were cultured in Hanks’ balanced salt solution supplemented with 10% autologous serum on a rotator. Neutrophils were preincubated for 20 minutes with PD98059 (50 mmol/L), LY294002 (1 mmol/L), SB203580 (1 mmol/L), z-VAD-fmk (z-Val-Ala-dl-Asp-fluoromethylketone, 20 mmol/L), or z-FA-fmk (20 mmol/L, Calbiochem), an anti-CD11b antibody (20 mg/mL, clone ILRF44, BD Biosciences) or 4-aminoazonobenzoic acid hydrazide (20 mmol/L) and then challenged with MPO (10 to 160 nmol/L) at 37°C in 5% CO₂ atmosphere. In some experiments, MPO pretreated with 4-aminoazonobenzoic acid hydrazide (20 mmol/L) or 3-amino-1,2,4-triazole (5 mmol/L) plus H₂O₂ (100 mmol/L) was used. At the designated time points, cells were processed as described below.

**Assessment of Apoptosis**

Apoptosis was assessed with flow cytometry using fluorescein isothiocyanate (FITC)-conjugated annexin V (BD Biosciences) in combination with propidium iodide (Molecular Probes) and the percentage of cells with hypoploid DNA. The percentage of morphological changes characteristic of apoptosis was confirmed by light microscopy following staining of neutrophils with hematoxylin/eosin. DNA cleavage was shown by detection of cytoplasmic histone-associated DNA fragments with Cell Death ELISA (Roche) and gel electrophoresis.

**Caspase-3 Activity**

Release of 7-amino-4-methyl-coumarin from N-acetyl-asp-Glu-Val-Asp-7-amino-4-methyl-coumarin (BD Biosciences) by human neutrophils lysates, prepared from 10⁷ cells, was measured using a CaluBio microplate reader (PE Biosystems) with excitation and emission wavelengths of 340 nm and 460 nm, respectively. In murine neutrophils, activated caspase-3 was detected with flow cytometry using FITC-labeled DEVD-Fmk (Calbiochem) according to the protocol of the manufacturer.

**Mitochondrial Transmembrane Potential (ΔΨₘ)**

Neutrophils (5×10⁶ cells) were incubated for 15 minutes at 37°C with the lipophilic fluorochrome chloride-methyl-X-rosamine (CMXRos) (200 mmol/L, Molecular Probes). The fluorescence was analyzed in a FACScan flow cytometer.

**Cytochrome c Release**

Mitochondrial and cytosolic fractions were prepared using the Mitochondria Isolation kit (Pierce) and cytochrome c levels were measured by an ELISA (Active Motif). The intraassay and interassay coefficient of variation were <10%.

**Western Blotting**

Protein extracts prepared from 10⁷ neutrophils were resolved by SDS-PAGE and transferred to poly(vinylidene difluoride) membranes. Blots were blocked with 5% skimmed milk powder in Tris-buffered saline plus Tween and probed with antibodies to phosphorylated extracellular signal-regulated kinase (ERK)1/2, Akt, p38 mitogen-activated protein kinase (MAPK), Bad(Ser112), and Bad(Ser136) (all from Cell Signaling Technologies) or b-actin (Sigma-Aldrich).

**Intravenous Injection of MPO to Rats**

The protocols were approved by the Animal Care and Use Committee. Male Wistar rats (weighing 246 to 316 g, Charles River Laboratories) were first implanted with arterial and venous catheters as described. Four days later, after recovery from the surgery, they received MPO (5 mmol/kg body weight) or saline intravenously. Mean arterial blood pressure and heart rate were monitored continuously. At 60 minutes post-MPO injection, under isoflurane anesthesia, blood was collected by cardiac puncture. Total and differential white blood cell counts were determined. Cell viability and apoptosis were assessed in freshly isolated neutrophils and in neutrophils cultured for up to 24 hours by staining with propidium iodide and FITC-conjugated annexin V, respectively. Two-color fluorescence was analyzed in a FACScan flow cytometer.

**Plasma MPO Levels**

Plasma MPO levels were determined by ELISA as described. Rat plasma was analyzed for MPO by using an ELISA according to the instructions of the manufacturer (Assay Design). The intraassay coefficient of variation was <6%.

**Carrageenan-Induced Acute Lung Injury**

The protocols were approved by the Animal Care and Use Committee. Female BALB/c mice (aged 8 to 12 weeks, Charles River Laboratories) were injected intratracheally with 0.1 mL of 0.25% l-carrageenan (Fluka) with or without 10 mL of 16 mmol/L MPO or saline as a control. At 1, 2, 3, 4, and 5 days post-MPO, the mice were killed and the lungs were lavaged 5 times with 1 mL of saline solution containing 0.5% heparin. The supernatant of the first milliliter of bronchoalveolar lavage (BAL) fluid was used for measurements of protein concentration. The remaining pooled BAL fluid was centrifuged, and the cells were resuspended in PBS. Total and differential leukocyte counts in BAL fluid samples were assessed by standard light microscopy techniques. Neutrophil viability and apoptosis were assessed with flow cytometry following staining with propidium iodide and FITC-conjugated annexin V, respectively. In separate groups of mice, the lungs were removed without lavage, fixed in 4% formaldehyde, and embedded in paraffin, and 2-mm-thick sections were stained with hematoxylin and eosin. Lung tissue MPO activity was measured using o-dianisidine as a substrate.

**Statistics**

Results are presented as means±SEM. Statistical comparisons were made by ANOVA using ranks (Kruskal–Wallis test), followed by Dunn’s multiple contrast hypothesis test to identify differences between various treatments or by Mann–Whitney U test (2-tailed). P<0.05 was considered statistically significant.

**Results**

Myeloperoxidase Delays Human Neutrophil Apoptosis by Signaling Through CD11b/CD18 Integrins

To investigate whether MPO can affect apoptosis directly, human neutrophils were cultured up to a 96-hour period with MPO purified from human neutrophils. MPO markedly suppressed neutrophil apoptosis in a time-dependent (Figure 1A) and concentration-dependent (Figure 1B) manner. After 24 hours of culture with MPO, an increased number of annexin V- and propidium iodide−negative cells were present and these cells could be identified morphologically as intact neutrophils (Figure 1C). Electrophoretic analysis confirmed the ability of MPO to attenuate DNA fragmentation (Figure 1D). Considerable proportions of MPO-treated neutrophils...
retained a nonapoptotic phenotype even after 48 hours in culture; however, cell viability decreased to <19% and <2% by 72 and 96 hours, respectively. Other azurophilic granule constituents, elastase (1 to 100 milliunits/mL) and lactoferrin (0.01 to 1 mg/mL), were without effects (data not shown).

Because anti-CD11b antibodies were found to block MPO binding to neutrophils and subsequent degranulation and superoxide production,10,11 we established whether the antiapoptosis action of MPO also involved this pathway. Indeed, pretreatment with an anti-CD11b antibody prevented the MPO suppression of neutrophil apoptosis, whereas the MPO inhibitor 4-aminobenzoic acid hydrazide was without effects (Figure 2). Pretreatment of MPO with 4-aminobenzoic acid hydrazide or the mechanism-based inhibitor 3-amino-1,2,4-triazole plus H₂O₂, which resulted in >95% and 71% inhibition of catalytic activity, respectively, failed to affect the antiapoptosis action of MPO (Figure 2). MOPC-21, a class-matched irrelevant antibody, did not affect neutrophil responses to MPO (data not shown). These findings corroborate that neutrophil responses to MPO are mediated via binding to CD11b, rather than by secondary generation of reactive oxidants.

Myeloperoxidase Prevents Mitochondrial Dysfunction and Caspase-3 Activation

To assess the downstream intracellular signaling pathways, we studied the activation of several MAPKs known to regulate neutrophil survival and monitored mitochondrial function and caspase-3 activation. MPO induced a rapid phosphorylation of ERK1/2 and Akt relative to unstimulated controls (Figure 3A). Culture of neutrophils resulted in time-dependent phosphorylation of p38 MAPK that was further enhanced in the presence of MPO (Figure 3B). To confirm the role of these kinases, we used selective pharmacological inhibitors. Both PD98059 and the phosphonositide (PI)3-kinase (the up-stream regulator of Akt activation) inhibitor LY294002, which inhibited MPO-induced phosphorylation of ERK1/2 and Akt, respectively (Figure 3C), almost completely blocked the responses to MPO (Figure 3D). By contrast, blockade of p38 MAPK

Figure 1. MPO prolongs survival of human neutrophils by suppressing apoptosis. A and B, Kinetic analysis (A) and concentration dependence (B) of the MPO effects. Neutrophils (5 × 10⁶ cells/mL) were incubated with 160 nM MPO for the indicated times (A) or with increasing concentrations of MPO for 24 hours (B). Viability was assessed by propidium iodide staining; apoptosis was assessed by annexin V–FITC binding and analysis of nuclear DNA content. Data represent the means with increasing concentrations of MPO for 24 hours (B). Viability was assessed by propidium iodide staining; apoptosis was assessed by annexin V–FITC binding and analysis of nuclear DNA content. Data represent the means ± SEM of 5 to 7 experiments with different blood donors. *P < 0.05, **P < 0.01 vs untreated. C, MPO suppression of morphological changes indicative of neutrophil apoptosis. Left, Morphology of freshly isolated neutrophils. Middle, Arrows indicate typically apoptotic morphology, showing condensed nuclei. D, MPO attenuates DNA fragmentation in neutrophils maintained in culture for 24 hours. The left lane represents DNA standards, and values of selected standards are shown at the left margin.

Figure 2. Prevention of the antiapoptosis action of MPO with an antibody against CD11b but not by the MPO inhibitor 4-aminobenzoic acid hydrazide (4-ABAH) or 3-amino,12,4-triazole (3-AT). A. Inhibition of the catalytic activity of MPO (160 nM/mL) by 4-ABAH (20 mM/mL) or 3-AT (5 mM/mL) plus H₂O₂ (100 mM/mL). MPO activity was measured using o-dianisidine as a substrate (n = 3). B. Human neutrophils were preincubated with an anti-CD11b antibody (20 mg/mL) or 4-ABAH (20 mM/mL) for 20 minutes and then challenged with MPO (160 mM/mL) or with MPO pretreated with 4-ABAH or 3-AT plus H₂O₂ for 24 hours (n = 5 to 6). *P < 0.01 vs untreated; †P < 0.05; ††P < 0.01 vs MPO-treated.
Involvement of ERK and PI3-kinase in mediating the antiapoptotic effect of MPO in human neutrophils. A, B, D, and E, Effects of MPO on phosphorylation of Akt, ERK1/2, p38 MAPK, and the proapoptotic protein Bad. Neutrophils (10^7 cells/mL) were lysed immediately after isolation (0 hour) or after challenge with MPO (160 nmol/L) for the indicated time periods (A and B) or for 30 minutes (D and E). Proteins were subjected to immunoblotting with antibodies to phosphorylated kinases, β-actin, phosphorylated Bad, or Bad. Blots are representative of 4 independent experiments. C, Pharmacological blockade of MAPK/ERK kinase and PI3-kinase attenuates the apoptosis delaying action of MPO. Neutrophils (5×10^6 cells/mL) were cultured for 24 hours in the presence of PD98059 (50 nmol/L), LY294002 (1 mmol/L), or SB203580 (1 mmol/L) with or without MPO (160 nmol/L). Cell viability and apoptosis were assessed by staining with propidium iodide and annexin V-FITC, respectively. Data represent the means ± SEM (n=5 to 7). *P<0.05; **P<0.01 vs untreated. †P<0.05, ††P<0.01 vs MPO-treated.

with SB203580 significantly increased the number of viable cells and reduced apoptosis. Cotreatment of neutrophils with MPO and SB203580 resulted in similar changes as those observed with either MPO or SB203580 alone (Figure 3D). MPO induced phosphorylation of Bad at both Ser112 and Ser136, a downstream target for ERK and Akt, respectively (Figure 3E).

Reductions in mitochondrial transmembrane potential (ΔΨm) precede development of apoptotic morphology in neutrophils undergoing constitutive programmed cell death. Thus, following 24 hours of culture, >60% of neutrophils exhibited reduced ΔΨm (Figure 4A) compared with >44% annexin V–positive cells (Figure 1A). Consistent with suppression of development of apoptotic morphology, MPO partially prevented disruption of ΔΨm in a concentration-dependent fashion (Figure 4B) and attenuated subsequent release of cytochrome c from the mitochondrion into the cytosol (Figure 4C). This was associated with concentration-dependent decreases in caspase-3 activity (Figure 4D). Both PD98059 and LY294002 attenuated the caspase-3 inhibitory action of MPO, although complete reversal was not achieved, not even in the presence of both PD98059 and LY294002 (Figure 4E). Pretreatment of neutrophils with the pan-caspase inhibitor z-VAD-fmk effectively suppressed apoptosis and increased the number of viable cells (Figure 4F). The combination of MPO and z-VAD-fmk produced similar inhibition than MPO or z-VAD-fmk alone, indicating that MPO and z-VAD-fmk inhibited the same pathway. Neither z-FA-fmk (a negative control) nor the vehicle (0.1% dimethyl sulfoxide) elicited any detectable effects (data not shown).

Figure 3. Involvement of ERK and PI3-kinase in mediating the antiapoptotic effect of MPO in human neutrophils. A, B, D, and E, Effects of MPO on phosphorylation of Akt, ERK1/2, p38 MAPK, and the proapoptotic protein Bad. Neutrophils (10^7 cells/mL) were lysed immediately after isolation (0 hour) or after challenge with MPO (160 nmol/L) for the indicated time periods (A and B) or for 30 minutes (D and E). Proteins were subjected to immunoblotting with antibodies to phosphorylated kinases, β-actin, phosphorylated Bad, or Bad. Blots are representative of 4 independent experiments. C, Pharmacological blockade of MAPK/ERK kinase and PI3-kinase attenuates the apoptosis delaying action of MPO. Neutrophils (5×10^6 cells/mL) were cultured for 24 hours in the presence of PD98059 (50 nmol/L), LY294002 (1 mmol/L), or SB203580 (1 mmol/L) with or without MPO (160 nmol/L). Cell viability and apoptosis were assessed by staining with propidium iodide and annexin V-FITC, respectively. Data represent the means ± SEM (n=5 to 7). *P<0.05; **P<0.01 vs untreated. †P<0.05, ††P<0.01 vs MPO-treated.

Figure 4. MPO prevents loss of mitochondrial transmembrane potential (ΔΨm), cytochrome c release and activation of caspase-3 in human neutrophils. Freshly isolated neutrophils (0 hour) or neutrophils (5×10^6 cells/mL) cultured for 24 hours in the presence or absence of inhibitors with or without MPO (160 nmol/L) were analyzed. A, Representative dot plots of neutrophils stained with CMXRos. Decreases in CMXRos fluorescence indicate loss of ΔΨm. The percentages indicate cells with reduced ΔΨm. Preincubation of neutrophils with the uncoupling agent carbonyl cyanide m-chlorophenylhydrazone (5 mmol/L) completely abolished ΔΨm. B, Concentration dependency of the MPO action on ΔΨm was assayed following 24 hours of culture. Results are means ± SEM (n=5 to 6). *P<0.05, **P<0.01 vs untreated. C, Cytochrome c was measured in mitochondrial and cytosolic fractions by ELISA (n=5). *P<0.01. D, Caspase-3 activity was determined in neutrophil lysates and expressed as relative fluorescence units (RFU). No fluorescence was detected in the presence of AC-DEVD-Ala-d-Ala-Val-Asp-d-Val-Asp-7-amido-4-methylcoumarin (AC-DEVD-AMC), an inhibitor of caspase-3 activity. Results are means ± SEM (n=4). *P<0.05 vs untreated. E, Pharmacological blockade of ERK and PI3-kinase reverses MPO suppression of caspase-3 activity. Caspase-3 activity was determined in lysates of neutrophils cultured for 24 hours with PD98059 (50 mmol/L), LY294002 (1 mmol/L), or MPO (n=4). *P<0.05 vs untreated; †P<0.05 vs MPO-treated. F, The caspase inhibitor z-VAD-fmk (20 mmol/L) reverses the apoptosis-suppressing action of MPO. Neutrophil viability and apoptosis were assessed following 24 hours of culture (n=6). **P<0.01 vs untreated; ††P<0.01 vs MPO-treated.
tracheal injection of MPO alone produced only minimal airspace (Figure 6A) and alveolar edema (Figure 6C). Intra-
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MPO on the resolution of neutrophil-mediated inflammation
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Having shown in vitro and ex vivo that neutrophil apoptosis
Prolongs Acute Inflammation
MPO Suppression of Neutrophil Apoptosis
Acute Elevations of Plasma MPO Delay Neutrophil Apoptosis
To study the impact of acute elevations in plasma MPO on
neutrophil survival, we injected human MPO intravenously
into conscious chronically catheterized rats. This resulted in
plasma concentrations of MPO in rats to levels comparable to
human neutrophils in vitro. We confirmed that increasing
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granule constituents lactoferrin and elastase failed to affect
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Consistent with the commitment of neutrophils to apopto-
sis, MPO at clinically relevant concentrations delayed, rather
than blocked apoptosis, resulting in prolonged survival of
human neutrophils in vitro. We confirmed that increasing
plasma concentrations of MPO in rats to levels comparable to
those detected in patients with inflammatory vascular diseases
was sufficient to retard the apoptotic machinery in

Discussion
Our results uncovered an unexpected role for MPO to
influence the fate of neutrophils and consequently the dura-
tion of inflammation. By suppressing the constitutive cell
death program, MPO prolonged the life span of neutrophils,
thereby delaying the resolution of inflammation. These ac-
tions were specific for MPO, because other azurophilic
granule constituents lactoferrin and elastase failed to affect
neutrophil apoptosis.

Consistent with the commitment of neutrophils to apopto-
sis, MPO at clinically relevant concentrations delayed, rather
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human neutrophils in vitro. We confirmed that increasing
plasma concentrations of MPO in rats to levels comparable to
those detected in patients with inflammatory vascular diseases
was sufficient to retard the apoptotic machinery in

inflammatory cell accumulation, whereas it prolonged
carrageenan-induced inflammation (Figure 6A). Thus, the
number of neutrophils in the BAL fluid (Figure 6B), BAL
fluid protein levels (Figure 6C), and tissue MPO content (an
indicator of neutrophil influx into tissues) (Figure 6D) were
still markedly elevated at day 5 after carrageenan plus MPO
as compared with mice that were injected carrageenan only.
The percentage of annexin V–positive neutrophils (Figure
6E), DNA fragmentation (Figure 6F) and caspase-3 activity
(Figure 6G) were markedly lower in carrageenan plus MPO-
treated mice than in carrageenan-treated mice. Consistently,
mice injected with carrageenan or carrageenan plus MPO had
marked inflammatory infiltrate at Day 1 (Figure 7). By day 5,
the lungs appeared to be almost normal in carrageenan-
treated mice, whereas the inflammation persisted in mice that
had received carrageenan plus MPO (Figure 7).

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Figure 5. Acute increases of plasma MPO retard neutrophil apoptosis in conscious rats. Human MPO (5 nmol/kg body weight) or its
vehicle (saline) was injected intravenously to conscious chronically catheterized rats. A and B, MPO did not affect heart rate (HR), mean
arterial blood pressure (MABP), blood leukocyte, and neutrophil counts. C and D, MPO-induced suppression of neutrophil apoptosis.
Sixty minutes after injection of MPO or saline, blood was collected by cardiac puncture under isoflurane anesthesia. Cell viability and
staining with annexin V (C), and DNA fragmentation and caspase-3 activity (D) were assayed immediately after isolation of neutrophils
(within 3 hours of blood collection) and at 2 and 24 hours of culture of isolated neutrophils. Data are means±SEM (n=5 to 6). *P<0.05;
**P<0.01.

MPO Suppression of Neutrophil Apoptosis
Prolongs Acute Inflammation
Having shown in vitro and ex vivo that neutrophil apoptosis
was markedly delayed by MPO, we investigated the impact of
MPO on the resolution of neutrophil-mediated inflammation
in mice. We used a model of acute lung injury induced by low
concentration of intratracheal inoculation with carrageenan,
which is useful to study resolution of inflammation.29
Carrageenan injection evoked acute pulmonary inflammation
characterized by massive infiltration of neutrophils into the
airspace (Figure 6A) and alveolar edema (Figure 6C). Intra-
tracheal injection of MPO alone produced only minimal

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neutrophils as assayed ex vivo. Furthermore, MPO also suppressed apoptosis in neutrophils that had emigrated into the airways and delayed resolution of inflammation in a mouse model of carrageenan-induced acute lung injury.

Neutrophils bind to MPO-coated surfaces or “free” circulating MPO through CD11b/CD18 integrins, leading to degranulation and superoxide production. Our results indicate that the apoptosis delaying action of MPO also involves this pathway and is independent of its catalytic activity. Previous studies have shown that MPO upregulates surface expression of CD11b on neutrophils and evokes MPO release from neutrophils, implicating an autocrine and paracrine mechanism for perpetuation of the inflammatory response. In addition, following engagement with CD11b/CD18, MPO extends survival and thus the pool of functional neutrophils. Neutrophil-derived MPO may also impact function of other leukocytes, including monocytes and NK cells that express CD11b/CD18.

Figure 6. MPO prolongs carrageenan-induced lung inflammation. Acute lung inflammation was induced in female BALB/c mice by intratracheal instillation of 100 mL of 0.25% carrageenan with or without 10 mL of 16 mmol/L MPO. Mice were killed at the indicated times and BAL fluid total leukocyte number (A) and neutrophil number (B), BAL fluid protein concentration (C), lung tissue MPO activity (D), the percentage of annexin V-positive neutrophils in BAL fluid (E), DNA fragmentation (F), and neutrophil caspase-3 activity (G) were determined. Data represent the means ± SEM (n=8 mice per group). ** P < 0.01 vs carrageenan-injected.

Figure 7. Lung tissue sections from naive mice (day 0) or from mice 1 and 5 days after intratracheal instillation of saline, carrageenan, or carrageenan + MPO. Hematoxylin/eosin stain. Bar=100 mm.
The β2 integrin CD11b/CD18 is best known for mediating neutrophil adhesion and transmigration across the endothelium and for promoting phagocytosis of microbes. CD11b/CD18-mediated “outside-in” signaling provokes neutrophil degranulation and contributes to suppression of apoptosis during endothelial transmigration. However, β2 integrin-mediated neutrophil adhesion per se is not a prerequisite to generate survival signals for antibody cross-linking of CD11b/CD18 in cells in suspension signals survival cues. Neutrophil apoptosis is controlled by a complex network of signaling pathways, including the ERK, Akt, and p38 MAPK pathways. MPO-induced phosphorylation of p38 MAPK, which mediates activation of NADPH oxidase, did not generate a survival signal under our experimental conditions. Indeed, selective pharmacological blockade of p38 MAPK retarded apoptosis both in the absence and presence of MPO. We identified ERK1/2 and Akt-dependent prevention of mitochondrial dysfunction as the key mechanism by which MPO rescued neutrophils from constitutive apoptosis. The delay of neutrophil apoptosis in response to intercellular adhesion molecule-1 adhesion is attributed to Akt activation, whereas promotion of neutrophil survival by another CD11b/CD18 ligand fibrinogen requires activation of both Akt and ERK. Previous studies also showed that transient activation of PI3-kinase without ERK activation may not be sufficient to delay neutrophil apoptosis. Compelling evidence suggests that ERK and Akt-mediated phosphorylation of the proapoptotic protein Bad prevents its association with the Bcl-2 homolog Mcl-1 expressed in neutrophils. This would allow expression of the antiapoptotic actions of Mcl-1, including prevention of mitochondrial membrane potential transition and loss in DYm that occurs in cells irreversibly committed to apoptosis. The present results confirmed that MPO activated this signaling cascade, leading to prevention of cytochrome c release from the mitochondria and activation of caspase-3; MPO and the pan-caspase inhibitor z-VAD-fmk did not produce additive suppression of neutrophil apoptosis, further highlighting the biological importance of MPO reduction of caspase-3 activation. In contrast to these previous results, MPO was found to mediate apoptosis in HL60 leukemia cells, indicating differences in primary and leukemic cell responses to MPO. Although the involvement of Mac-1 in the proapoptotic action of MPO has not been addressed in these previous studies, in the presence of proapoptotic signals, such as tumor necrosis factor, phagocytosis of opsonized bacteria, Mac-1 engagement and concomitant intracellular generation of reactive oxygen species would lead to activation of caspase-8, a signature of receptor-mediated cell death. Thus, Mac-1 could play a dual role in determining the fate of neutrophils.

Consistent with the results obtained in human neutrophils, intravenous injection of MPO into rats also suppressed neutrophil apoptosis. Because neutrophils undergoing apoptosis are rapidly removed from the circulation on expression of phosphatidylserine (the “eat me” signal for macrophages) on their surface, we assessed neutrophil apoptosis ex vivo at 60 minutes post-MPO. Our in vitro data point to a direct effect of MPO on neutrophils, although we cannot exclude the possibility that other mechanism(s) may have contributed to its antiapoptotic action in vivo. In addition, MPO suppressed neutrophil apoptosis in a mouse model of carrageenan-induced lung injury parallel with prolongation of the inflammatory response. This model was chosen for its clinical relevance and because of the self-resolving nature of neutrophil-dependent inflammation. We have shown that MPO delayed self-resolution of carrageenan-induced lung injury, further suggesting that this process is intimately linked to acceleration of neutrophil apoptosis and the removal of apoptotic neutrophils by macrophages.

Our results showing MPO suppression of neutrophil apoptosis add a novel facet to the MPO biology in addition to MPO-mediated generation of reactive oxygen species and tissue injury. Of note, some studies could not show a significant direct contribution for MPO or its derived oxidants to the induction of apoptosis and necrosis in vivo. Indeed, K+ flux-mediated activation of proteases has been implicated in mediating the killing activity of neutrophils. Interestingly, MPO−/− mice exhibit lower pulmonary bacterial colonization, reduced lung injury, and greater survival following intraperitoneal Escherichia coli injection compared with wild type mice. MPO deficiency is also associated with elevated basal pulmonary inducible NO synthase expression and NO production that partially compensate for the lack of HOCl-mediated bacterial killing. The mechanism of upregulation of inducible NO synthase expression in MPO−/− mice, as well as the impact of acute suppression of inducible NO synthase expression by MPO on the resolution of lung inflammation, remains to be investigated. Absence of MPO-derived oxidant production during E coli septicemia in MPO−/− mice could reduce lung injury and mortality. However, it is not known whether MPO deficiency could affect the longevity of neutrophils, thereby contributing to protection against lung inflammation in this model of sepsis. Recent evidence indicates that prolonged neutrophil survival adversely affect the duration of the inflammatory response. It is intriguing that MPO prolonged the life span of neutrophils, the predominant source of this enzyme. The apoptosis-delaying and neutrophil-activating properties of MPO are reminiscent of those of proinflammatory cytokines and bacterial constituents and indicate an important role for MPO in regulating the inflammatory response, as we showed in a mouse model of acute lung injury. These findings lend strong support to the notion that neutrophil apoptosis is among the critical determinants of the outcome of the inflammatory response in vivo, including models of carrageenan-induced acute lung injury, pleurisy, and arthritis, and, therefore, is a potential target for therapeutic interventions. Thus, suppression of neutrophil apoptosis may ensue prolonged inflammation, whereas induction of neutrophil apoptosis would enhance resolution of inflammation.

In summary, the present study identifies MPO as a survival signal for neutrophils by delaying intrinsic apoptosis, thereby modulating the outcome of acute inflammation. Future studies are, thus, warranted to define whether these actions of MPO represent novel therapeutic targets for dampening inflammation.
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Disclosures
None.

References


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