Damage-Associated Molecular Pattern S100A9 Increases Bactericidal Activity of Human Neutrophils by Enhancing Phagocytosis

Jean-Christophe Simard, Marie-Michelle Simon, Philippe A. Tessier and Denis Girard

*J Immunol* 2011; 186:3622-3631; Prepublished online 16 February 2011; doi: 10.4049/jimmunol.1002956

http://www.jimmunol.org/content/186/6/3622

---

**Supplementary Material**

http://www.jimmunol.org/content/suppl/2011/02/14/jimmunol.1002956.DC1

**References**

This article cites 65 articles, 36 of which you can access for free at:
http://www.jimmunol.org/content/186/6/3622.full#ref-list-1

**Subscription**

Information about subscribing to *The Journal of Immunology* is online at:
http://jimmunol.org/subscription

**Permissions**

Submit copyright permission requests at:
http://www.aai.org/About/Publications/JI/copyright.html

**Email Alerts**

Receive free email-alerts when new articles cite this article. Sign up at:
http://jimmunol.org/alerts
Damage-Associated Molecular Pattern S100A9 Increases Bactericidal Activity of Human Neutrophils by Enhancing Phagocytosis

Jean-Christophe Simard,* Marie-Michelle Simon,* Philippe A. Tessier,†,‡ and Denis Girard*‡

The damage-associated molecular-pattern S100A9 is found at inflammatory sites in infections and various autoimmune diseases. It is released at very high concentrations in the extracellular milieu by activated neutrophils and monocytes in response to various agents. This proinflammatory protein is found in infected mucosae and tissue abscesses where it acts notably as a potent neutrophil activator. In this study, we examined the role of S100A9 in the control of infections. S100A9 was found to increase human neutrophil bactericidal activity toward *Escherichia coli*. Although S100A9 induced the accumulation of reactive oxygen species over time through the activation of NADPH oxidase, its antimicrobial activity was mediated mainly by enhancing the efficiency of neutrophil phagocytosis. Interestingly, S100A9 did not act by increasing cell surface expression of CD16, CD32, or CD64 in neutrophils, indicating that its biological effect in FcR-mediated phagocytosis is independent of upregulation of FcγR levels. However, S100A9-induced phagocytic activity required the phosphorylation of Erk1/2, Akt, and Syk. Taken together, our results demonstrate that S100A9 stimulates neutrophil microbicidal activity by promoting phagocytosis. The Journal of Immunology, 2011, 186: 3622–3631.

Neutrophils kill microorganisms by phagocytosis and liberation of reactive oxygen species (ROS) or antimicrobial peptides stored in granules (1). Phagocytosis occurs through direct binding of bacteria and is facilitated by opsonization with Ig (2) or complement components (3). This is an active process that requires the reorganization of the actin cytoskeleton (4) and signal transduction from the cell membrane (5). Additionally, recognition and phagocytosis of invaders often induces the production of ROS. Although the major source of ROS in phagocytes is NADPH oxidase activation, mitochondria and cyclooxygenase enzymes are also responsible for the production of oxygen species (6).

Among the various molecules produced by phagocytes after pathogen recognition, the recently identified damage-associated molecular patterns S100A8 (MRP8), S100A9 (MRP14), and S100A12 (MRP6) are increasingly gaining interest. These proteins are highly expressed in neutrophils, representing close to 40% of total cytoplasmic proteins (7). Their expression is also inducible by multiple factors in monocytes (8), macrophages (9), and endothelial cells (10). These proteins are liberated as homo- or heterodimers after phagocyte activation (11), cell necrosis, or by the formation of neutrophil extracellular traps (12), where they act as danger signals for the organism presumably by activating TLR4 (13) or the receptor for advanced glycation end products (14).

There is a correlation between chronic inflammatory diseases and high concentrations of S100A8, S100A9, and S100A12. Their role in pathogenesis or in exacerbation of diseases such as rheumatoid arthritis and inflammatory bowel diseases are becoming more and more apparent (15, 16). For instance, Loser and et al. (17) have recently demonstrated a key role for S100A8 and S100A9 in the development of autoreactive CD8 T cells in a lupus model. Additionally, we and others have demonstrated important roles for these proteins in neutrophil activation and migration toward inflammatory sites. For instance, S100A8, S100A9, and S100A12 are chemotactic for neutrophils and promote their adhesion to fibrinogen, whereas S100A9 induces adhesion to fibronectin and vitronectin matrices via activation of β2 integrins (18–21). More recently, we demonstrated that S100A9 induces neutrophil degranulation, corroborating the important role of this protein in general phagocyte biology and migration (22).

S100A8, S100A9, and S100A12 are highly expressed in tissue abscesses and infected mucosa (23–27) where they are presumed to exert major roles in the control of infection by chelating Zn2+ and other ions (28). Additionally, S100A8/A9 heterodimers (=calprotectin) are crucial for the clearance of infection after challenge with *Candida albicans* (12). In contrast, blockade of S100A8 and S100A9 with neutralizing Abs inhibits phagocyte migration to the alveoli in a mouse model of streptococcal pneumonia (29). Taken together, these results suggest an essential role for S100A9 in the control of infection both in the recruitment of neutrophils and in the control of microbial growth. However, the mechanism of action of these proteins during infection remains to be clarified.

In this study, we investigated the role of S100A9 in acute infection by examining its effect on the antibacterial functions of neutrophils. We report that S100A9 increases the bactericidal activity of human neutrophils. Although S100A9 induced ROS...
accumulation over time through NADPH oxidase activation, that damage-associated molecular pattern protein mainly mediated its effect by increasing the rate of neutrophil phagocytosis via the activation of Syk, PI3K/Akt, and Erk1/2. These results further support a crucial role for S100A9 in the control of microbial infection.

Materials and Methods

Reagents

Human recombinant S100A8, S100A9, and S100A12 were produced as previously described (20, 30) and found to contain <1 pg endotoxin/µg protein. PD98059, SB203580, piceatannol, PMA, and superoxide dismutase (bovine erythrocytes) were purchased from Sigma-Aldrich (St. Louis, MO). JNK inhibitor II and U0126 were purchased from Calbiochem (San Diego, CA). Wortmannin and Syk inhibitor (Syki) II were obtained from EMD Biosciences (San Diego, CA). Mouse IgG1 isotype-ITTC, mouse anti-human CD16-ITTC, mouse anti-human CD64-ITTC, and mouse anti-human CD64-ITTC were all obtained from BD Biosciences (San Diego, CA). SRBCs were purchased from Quelab (Montreal, Quebe, Canada). Anti-human CD64-FITC were all obtained from Upstate Biotechnology (Lake Placid, NY). Mouse monoclonal Syk polyclonal Erk1/2 and anti–phospho-specific tyrosine Abs were obtained were purchased from BioSource International (Camarillo, CA). Rabbit anti–phospho-specific Erk1/2 and anti-phosphoserine Abs anti-total form of Akt Abs were purchased from Cell Signaling Technology (Danvers, MA). Anti–phospho-specific Erk1/2 and anti-phosphoserine Abs were purchased from BioSource International (Camarillo, CA). Rabbit polyclonal Erk1/2 and anti–phospho-specific tyrosine Abs were obtained from Upstate Biotechnology (Lake Placid, NY). Mouse monoclonal Syk Ab (clone 4D10), as well as goat polyclonal anti-p47phox (C-20) and rabbit polyclonal anti-p47phox (H-195) Abs, was obtained from Santa Cruz Bio-technology (Santa Cruz, CA). 5-(and-6)-Carboxy-2

Cell surface expression of CD16, CD32, and CD64

Cell surface expression of CD16, CD32, and CD64 was monitored by flow cytometry. Neutrophils were resuspended in a final volume of 100 µl following addition of agonists. After stimulation, the cells were centrifuged and washed twice with cold PBS. Nonspecific binding of Abs was prevented by incubating cells with PBS plus 20% decomplemented human autologous serum for 30 min on ice. After several washes with PBS, the cells were incubated with FITC-coupled Abs (CD16, CD32, CD64, or IgG isotype) for 30 min on ice. After three washes, the cells were resuspended in PBS for FACS analysis on a BD FACScan apparatus (BD Biosciences).

Immunoprecipitation

Polymorphonuclear leukocytes (7 × 106 cells/condition) were treated with the indicated agonists for the indicated period of time at 37˚C, centrifuged, and lysed in nonniedemulating cold lysis buffer (50 mM Tris-HCl [pH 7.4], 100 mM NaCl, 1% Triton X-100, 0.1% SDS, 1 mM orthovanadate, 1 mM PMSF, 10 µg/ml trypsin inhibitor, aprotinin, leupeptin, and pepstatin) for 1 h on ice and sonicated three times for 20 s. The lysates were preincubated with protein G-Sepharose (Amersham Biosciences, Piscataway, NJ). After 1 h, samples were centrifuged to remove Sepharose beads and then incubated with 2 µg/ml goat anti-human p47phox for 4˚C with gentle agitation overnight. Protein G-Sepharose was then added for 4 h with gentle agitation at 4˚C. The solid matrix was collected and washed three times with lysis buffer before adding an equivalent volume of sample buffer. The samples were then boiled at 100˚C for 10 min. Immunoprecipitates were electrophoresed on a SDS-polyacrylamide gel, followed by Western blot analysis.

Western blot analysis

Neutrophils (40 × 106 cells/ml in RPMI 1640 supplemented with 25 mM HEPES, 100 U/ml penicillin, and 100 µg/ml streptomycin) were stimulated with PMA (10−7 M) for 5 min, GM-CSF (65 ng/ml) for 10 min, and with S100A9 (40 µg/ml) or the diluent HBSS for 1–60 min at 37˚C. In some experiments, cells were preincubated for 30 min at 37˚C with the following inhibitors: wortmannin (10 nM), piceatannol (30 µM), Syki II (1 µM), PD98059 (5 µM), or U0126 (5 µM). At the end of the incubation period, the cells were lysed in 4× Laemmli’s sample buffer (0.25 M Tris-HCl [pH 6.8], 8% SDS, 40% glycerol, and 2% 2-ME), and aliquots of extracts corresponding to 1 × 106 cells were loaded onto 10% SDS-PAGE and transferred to nitrocellulose membranes for the detection of p-Syk, p-Akt, Akt, p-Erk1/2, Erk1/2, and p-Tyr. For detecting the phosphorylated form of p47phox, p47phox immunoprecipitates were electrophoresed on 15% SDS-PAGE gel and transferred to nylon membranes. Membranes were blocked for 1 h at room temperature in TBS-Tween containing 5% nonfat dry milk or 3% BSA. After washing, the anti–phospho-specific Syk, Erk1/2, and Akt Abs were added at a final dilution of 1:1000 in TBS-Tween 0.15% containing 3% BSA. The anti–phospho-specific Ab directed against tyrosine residues and the Ab against total Syk were added at a final concentration of 1:4000. Anti–phospho-specific serine Ab was added at a final dilution of 1:750. A dilution of 1:1000 in 3% BSA was used for total Akt Ab. The membranes were kept overnight at 4˚C, then washed with TBS-Tween and incubated for 1 h at room temperature with a goat anti-rabbit IgG HRP secondary Ab (Jackson ImmunoResearch Laboratories, West Grove, PA) diluted 1:20,000 in TBS-Tween plus 5% nonfat dry milk, or a goat anti-mouse IgG HRP secondary Ab (Jackson ImmunoResearch Laboratories) diluted 1:20,000 in TBS-Tween plus 5% nonfat dry milk. Immunoreactive bands were visualized with the enhanced chemiluminescence detection system (Amersham Biosciences). Membranes were stripped and reprobed to confirm equal loading of proteins.
Preparation of bacteria

Bacteria were prepared essentially as previously described (34), with few modifications. Briefly, *E. coli* MG1655 was grown overnight in a shaking incubator at 37°C. Bacteria were centrifuged at 1000 × g for 5 min and washed twice with PBS. The final pellet was resuspended in HBSS and the concentration of bacteria was calculated by measuring the OD at 550 nm using an established standard curve. Bacteria were opsonized by suspending 1 × 10^8 CFU in 1 ml HBSS containing 10% autologous serum and by rotating the solution end over end for 20 min at 37°C.

One-step and two-step killing assay

To measure neutrophil bactericidal activity, a one-step assay was used in which neutrophils were not separated from uningested bacteria (34). Neutrophils (3 × 10^6 cells) were stimulated with 40 μg/ml S100A8, S100A9, S100A12, or the equivalent volume of the diluent (HBSS) for 30 min at 37°C. Cells were then washed twice with ice-cold PBS while pooling the supernatants (uninduced bacteria). Each sample was diluted further into water. Pellets and Supernatants were then resuspended in 2.5 ml H2O (pH 11). Neutrophils were lysed for 5–10 min at room temperature, then vortexed vigorously for 10 s to disperse bacteria. Each sample was diluted further into water (pH 11) and spread on Luria-Bertani agar plates at 150 CFU per plate in duplicate. Plates were incubated overnight at 37°C and the numbers of colonies formed were counted. Results were expressed as percentage of survival. This killing assay provided a composite measure of both phagocytosis and killing. For the two-step assay, 50-μl samples were taken from 10, 20, and 30 min and diluted with 950 μl ice-cold PBS to stop neutrophil activity. Samples were centrifuged at 100 × g for 5 min at 4°C. Supernatants were collected and pellets were washed twice with ice-cold PBS while pooling the supernatants (uningested bacteria). The pellets were then resuspended in 2.5 ml H2O (pH 11). Neutrophils were lysed for 10 min and then vortexed to disperse bacteria. Each sample was diluted further into water. Pellets and supernatants were spread separately on Luria-Bertani agar plates at ~100–150 CFU per plate (i.e., two plates were used for each sample). Plates were incubated overnight at 37°C and the number of colonies formed was counted. Colony counts were converted to original bacterial densities by multiplying with the appropriate dilution factor. Growth adjustment, phagocytosis rate constant (k), and killing rate constant (K) values were calculated according to the formula described by Green et al. (34).

Detection of intracellular and mitochondrial ROS

Cells were resuspended in HBSS containing 10 μM CM-H2DCFDA or 10 μM mitochondrial superoxide indicator MitoSOX at 1 × 10^6 cells/ml for 15 min at 37°C. Cells were then washed twice with PBS before being incubated in the presence or absence of S100A9 (40 μg/ml) for the indicated period of time. PMA (10^-7 M) was used as a positive control. For some experiments, S100A9-stimulated cells were incubated with opsonized SRBCs as phagocytic stimuli, and ROS production was measured for the indicated periods of time. Fluorescence was recorded using a FACScan. ROS production was expressed as MFI.

Detection of extracellular O2

Superoxide production was monitored by the reduction of ferrocyanochrome c, as previously reported (35, 36) with few modifications. Briefly, neutrophils (1 × 10^6 cells/ml) were suspended in HBSS (supplemented with 1.6 mM CaCl_2) with or without 10 μg/ml superoxide dismutase with 150 μM ferrocyanochrome c for 5–180 min at 37°C in the presence of 40 μg/ml S100A8, S100A9, S100A12, buffer, diluent, or PMA (10^{-7} M). The reduction of ferrocyanochrome c was monitored at 550 nm, and the concentration of superoxide anions (O_2^-) produced was calculated from the difference between corresponding wells either with or without superoxide dismutase using a molar coefficient extinction of 21.1 l mol^{-1} cm^{-1}. 

Immunofluorescence microscopy

Following phagocytosis of Alexa Fluor 488-labeled *E. coli*, as described before, cells were washed twice in ice-cold PBS and then cytocentrifuged on glass coverslips (Fisher Scientific). Cells were fixed and permealized in 3% paraformaldehyde plus 0.1% digitonin at room temperature for 20 min. After three washes, cells were incubated with 2 U phallolidin-Alexa Fluor 568 at 37°C for 30 min to detect F-actin filaments. After three washes, coverslips were mounted with Vectashield plus DAPI (Vector Laboratories, Burlington, Ontario, Canada). Fluorescent-labeled cells were captured from high-power field (×400) and observed with a Leica microscope equipped with an eqb 100 de epifluorescent condenser. Images were taken with a Cooke Sensicam high-performance camera (Applied Scientific Instrumentation) coupled to the Image-Pro Plus program (version 4.0; Media Cybernetics).

Statistical Analysis

Experimental data are expressed as means ± SEM. Repeated-measures ANOVA (Dunnett multiple-comparison test) were performed using GraphPad Prism (version 5.01). Differences were considered statistically significant as follows: *p ≤ 0.05, **p ≤ 0.01, and ***p ≤ 0.005 versus buffer or the appropriate diluent. Densitometric analyses were performed using Quantity One, version 4.6.6 (Bio-Rad, Hercules, CA).

Results

S100A9 induces ROS production through NADPH oxidase activation

Neutrophils are key components of innate immunity against bacterial infections. In addition to sensing invading pathogens, neutrophils have developed efficient mechanisms for extracellular killing and for processing of phagocytized bacteria. One of the key mechanisms involved in bacterial killing is the production of ROS, which can occur through NADPH oxidase activation or triggered by an alteration of the mitochondria transmembrane potential in response to diverse stimuli (1). Because S100A9 is secreted during infections and is a potent neutrophil agonist, we investigated its effect on neutrophil bactericidal activity through the production of ROS. As shown in Fig. 1, S100A9 induced a significant intracellular accumulation of ROS over time (Fig. 1A), but little or no accumulation of O_2^- in the extracellular medium (Fig. 1B). This contrasts with the rapid burst of ROS detected when neutrophils were stimulated with PMA, which occurred both in the intracellular and extracellular compartments (Fig. 1A, 1B). Unlike S100A9, S100A8 or S100A12 had no effect on ROS production even when neutrophils were stimulated for longer periods of time (Fig. 1B, inset). Because S100A8/A9 was previously found to induce mitochondrial ROS production in cancer cells (37), we then investigated the origin of ROS in S100A9-induced neutrophils. Based on our results, S100A9, as well as S100A8 and S100A12, do not induce damage in mitochondria since no O_2^- has been detected in S100A9-stimulated neutrophils compared with PMA-treated cells (Fig. 1C). We next investigated whether the observed ROS production in S100A9-stimulated neutrophils was from the activation of NADPH oxidase. For this purpose, we measured the phosphorylation of p47^phox, which is the initial step in the activation of the enzyme. We demonstrated in this case that signaling cascade triggers by S100A9 led to phosphorylation of p47^phox, suggesting an activation of NADPH oxidase (Fig. 1D). Uptake of phagocytic stimuli often triggers the activation of NADPH oxidase and ROS production to kill pathogens. According to our previous data, we were interested to know whether S100A9-stimulated neutrophils can further produce ROS in response to phagocytic stimuli. Interestingly, S100A9-stimulated neutrophils have an increased capacity to generate ROS in response to opsonized SRBCs (Fig. 1E), suggesting that the bactericidal activity of those cells is more powerful.

S100A9 increases neutrophil bactericidal activity

ROS production is associated with neutrophil bactericidal activity (38, 39), and patients with deficiency in NADPH oxidase components suffer from repeated bacterial infections (40). Because we demonstrated that S100A9 induces an accumulation of intracel-
lular ROS and increases the oxidative burst in response to a phagocytic stimulus, we next investigated the possibility that it could potentiate neutrophil bactericidal activity. As illustrated in Fig. 2, S100A9-primed neutrophils showed an enhanced capacity to kill \textit{E. coli} as early as 10 min after incubation with bacteria, and this effect was sustained over time. Again, this effect was restricted to S100A9, as other S100 proteins failed to potentiate neutrophil bacterial killing (Fig. 2). Because this assay does not discriminate between phagocytosis and killing, we next proceeded to a two-step assay, allowing the distinction between intracellular (phagocytosis) and extracellular killing. As shown in Fig. 3A, cells treated with S100A9 showed more intracellular bacteria after 10 min as compared with control. Intracellular and extracellular bacteria analyses allowed the determination of $K_p$ and $K_k$. Interestingly, S100A9 increased the $K_p$ of neutrophils, but had no effect on their $K_k$ (Fig. 3B). The concentration of S100A8, S100A9, and S100A12 used in our study had no effect on \textit{E. coli} growth (data not shown). This is in agreement with a previous study showing that higher concentrations of S100A8/A9 were required to inhibit \textit{E. coli} growth (41). Because we previously demonstrated that S100A9 induced the degranulation of human neutrophils mainly through activation of the MAPK p38 (22) and that released granules can have antimicrobial activities, we tested the involvement of this pathway in S100A9-induced extracellular killing. Interestingly, inhibition experiments revealed that this pathway is not involved in overall S100A9-treated neutrophil bactericidal activity (Supplemental Fig. 1).

**FIGURE 1.** S100A9 induces intracellular ROS accumulation over time via NADPH oxidase activation in human neutrophils. Production of reactive oxygen species was assessed by (A) oxidation of carboxy-H2DCFDA, (B, E) reduction of ferrocytochrome c, and (C) oxidation of mitochondrial superoxide indicator, as described in Materials and Methods. Cells were incubated in the presence of buffer (Ctrl), diluent (0.1% DMSO), or 40 \mu g/ml S100A8, S100A9, or S100A12, or $10^{-7}$ M PMA for 5–180 min (A, inset in B and C) or 30 min (B). Results are from one experiment representative of four others (A, inset in B and C). NADPH oxidase activation was determined based on p47^{phox} phosphorylation by immunoprecipitation (IP) of p47^{phox} followed by immunoblotting with an anti-phosphoserine Ab, as described in Materials and Methods. Cells were treated in the presence of buffer (Ctrl), 40 \mu g/ml S100A9 for 60 min, or $10^{-7}$ M PMA for 5 min. E, Cells were treated with buffer (Ctrl) or S100A9 before being stimulated with opsonized SRBCs. Data represent the mean ± SEM of at least three experiments performed on cells from different donors (B, D, E).

S100A9 increases FcR-mediated phagocytosis

Because exposure to S100A9 increased $K_p$ in neutrophils, we then investigated how S100A9 modulates this process. Phagocytosis in neutrophils and macrophages generally occurs via two major distinct mechanisms, namely complement receptor-dependent and Fc receptor-dependent pathways (42). Accordingly, we first examined the effect of S100A9 pretreatment on FcR-mediated phagocytosis through the uptake of IgG-opsonized SRBCs (Fig.

**FIGURE 2.** S100A9 increases human neutrophil bactericidal activity. Killing of \textit{E. coli} was evaluated by a one-step assay, as described in Materials and Methods. Cells were incubated in the presence of buffer (Ctrl) or 40 \mu g/ml S100A9, S100A8, or S100A12 for 10–30 min before incubation with \textit{E. coli}. Data represent the mean ± SEM of four experiments performed on cells from different donors.
Treatment with S100A9 increased not only the phagocytosis rate (one or more SRBCs) (Fig. 4A), but also the phagocytosis index (three or more SRBCs/cell) (Fig. 4B). Interestingly, the effect of S100A9 was stronger than the positive control, GM-CSF (32, 43). Although concentrations of 40–100 μg/ml S100A9 were found to be optimal, concentrations as low as 1 μg/ml showed a significant effect on phagocytosis (Fig. 4C).

Because S100A9 induces neutrophil degranulation and FcγRIII (CD16) is a known component of neutrophil granules (44), we next investigated the cell surface expression of FcγRs. Fig. 5 shows that CD16 was not significantly increased in cells treated with S100A9 as compared with unstimulated cells. Additionally, S100A9 had no effect on either CD32 or CD64 cell surface expression.

S100A9 increases complement receptor-mediated phagocytosis in human neutrophils

Next, we determined whether the effect of S100A9 was restricted to FcγR-mediated phagocytosis. We thus investigated the possibility that this protein might also modulate complement receptor (CR)-mediated phagocytosis. First, the internalization of FITC-labeled microspheres was examined by flow cytometry. Exposure of neutrophils to S100A9 markedly increased the uptake of FITC-labeled microspheres as compared with untreated cells. More than 61% of neutrophils had internalized at least five latex beads compared with 35% in buffer-treated cells. More than 61% of neutrophils had internalized at least five latex beads compared with 35% in buffer-treated cells (see markers in Fig. 6A). To further support these findings, we evaluated the effect of S100A9 on the uptake of E. coli incubated in the presence of serum. Again, S100A9 markedly increased the internalization of bacteria based on flow cytometry (Fig. 6B) and immunofluorescence microscopy experiments (Fig. 6C). Therefore, stimulation of neutrophils with S100A9 enhances phagocytic processes independently of the receptors used to engulf opsonized Ags.

S100A9 induces phosphorylation events in human neutrophils

Phagocytosis and bacterial killing are complex processes involving, among other things, cytoskeleton reorganization (4) and phosphorylation of different proteins, including the Syk tyrosine kinase (45), PI3K/Akt, and Erk1/2 (46). Consequently, phosphorylation events were evaluated in S100A9-stimulated neutrophils. S100A9 induced a strong phosphorylation of total tyrosine residues after 30 min (Fig. 7A). Phosphorylation was sustained and further increased after 60 min. Among phosphorylated targets, S100A9 induced the phosphorylation of Syk. This phosphorylation was reversed by two Syk inhibitors, namely piceatannol and Syki II (Fig. 7B). Additionally, neutrophils treated with S100A9 displayed increased levels of phosphorylated Erk1/2 (Fig. 7C) and Akt (Fig. 7D). S100A9-induced Erk1/2 phosphorylation was partially reversed by preincubation with the MEK inhibitors PD98059 and U0126, whereas Akt phosphorylation was completely inhibited by wortmannin.

S100A9 enhances human neutrophil phagocytosis by a Syk-, Erk1/2-, and PI3K/Akt-dependent mechanism

To further decipher the mechanisms of action of S100A9, we next examined the involvement of the Syk, MEK/Erk1/2, and PI3K/Akt signaling pathways. Among the various pathways involved, among other things, cytoskeleton reorganization (4) and phosphorylation of different proteins, including the Syk tyrosine kinase (45), PI3K/Akt, and Erk1/2 (46). Consequently, phosphorylation events were evaluated in S100A9-stimulated neutrophils. S100A9 enhanced phosphorylation of total tyrosine residues after 60 min. Among phosphorylated targets, S100A9 induced the phosphorylation of Syk. This phosphorylation was reversed by two Syk inhibitors, namely piceatannol and Syki II (Fig. 7B). Additionally, neutrophils treated with S100A9 displayed increased levels of phosphorylated Erk1/2 (Fig. 7C) and Akt (Fig. 7D). S100A9-induced Erk1/2 phosphorylation was partially reversed by preincubation with the MEK inhibitors PD98059 and U0126, whereas Akt phosphorylation was completely inhibited by wortmannin.
pathways in S100A9-primed phagocytosis. Cells were preincubated in the presence or absence of specific inhibitors of Syk (piceatannol and Syki II), MEK1/2 (PD98059 and U0126), and PI3K/Akt (wortmannin) for 30 min and then stimulated with S100A9. Because we had previously demonstrated that S100A9 also induces the phosphorylation of p38 and JNK in human neutrophils (22), SB203580 and JNK inhibitor II were also tested for their ability to block S100A9-induced phagocytosis as specific inhibitors of p38 and JNK MAPKs, respectively (22). However, both SB203580 (Supplemental Fig. 1) and JNK II had no effect on the ability of S100A9 to enhance phagocytosis. In contrast, the MEK1/2 (PD98059 and U0126) inhibitors partly blocked the effect of S100A9 on phagocytosis without affecting the control (Fig. 8). Interestingly, the Syk inhibitors (piceatannol and Syki II)
blocked the S100A9-enhanced phagocytosis by 90%, whereas phagocytosis in control cells was not significantly affected by the inhibitors. Finally, the PI3K inhibitor (wortmannin) reduced phagocytosis rate by $\sim 25\%$ in both control and S100A9-stimulated neutrophils. Collectively, these results demonstrate that the S100A9-enhanced phagocytic activity in neutrophils is strongly mediated by the activation of Syk and its downstream substrates, and partly by the activation of MEK1/2.

**Discussion**

S100A8, S100A9, and S100A12 form a subgroup of S100 proteins collectively referred to as myeloid-related proteins. They modulate neutrophil functions, including chemotaxis, adhesion, and transmigration via the activation of CD11b/CD18 (18–21). Recently, we demonstrated that S100A9, but neither S100A8 nor S100A12, induces neutrophil degranulation (22). This suggests that these proteins have separate functions, a hypothesis corroborated by the fact that they are secreted separately by neutrophils (P. A. Tessier, unpublished observations). In this study, we further explored the activity of myeloid-related proteins and demonstrated that S100A9, but not S100A8 or S100A12, induces intracellular ROS accumulation over time through NADPH oxidase activation. We also found that S100A9 increases human neutrophil bactericidal activity against *E. coli* at least partly by increasing neutrophil FcR- and CR-mediated phagocytosis. The effect of S100A9 on phagocytosis was independent of the expression of FcγR since it did not upregulate the cell surface expression of CD16, CD32, and CD64.

Acute inflammation occurs a few hours following trauma or infection and is characterized by neutrophil adhesion to the endothelial barrier and migration toward affected tissues (47). Polymorphonuclear neutrophils are the first immune cells to arrive at the inflammatory site and they are crucial for the containment of pathogens within the infected site (1). In some cases, the acute response fails to eliminate pathogens and the response is exacerbated, leading to a chronic inflammatory state (47). This attests to the importance of an efficient and fast clearance of pathogens. During the inflammation process, different types of soluble molecules are secreted to regulate the immune response. Among these molecules, S100A8, S100A8/A9, and S100A9 are released in the extracellular milieu after phagocyte activation or cell necrosis. S100A8, S100A9, and S100A12 are potent antimicrobial factors inhibiting microbial growth (24, 48). The importance of these proteins is illustrated by the fact that S100A9-deficient mice had increased abscess lesions and mortality after s.c. challenge with *C. albicans*, probably due to the loss of S100A8/A9 (12). S100A8/A9 is thought to mediate its effect by chelating divalent ions, which are essential for microbial growth. Our results show that S100A9 also enhances neutrophil phagocytosis, corroborating its importance in the control of infection. Thus, in the context of

![Figure 7](http://www.jimmunol.org/DownloadedFrom/3628_ROLE_OF_S100A9_IN_NEUTROPHIL_BACTERICIDAL_ACTIVITY)
an infection, S100A9 secretion would favor clearance of pathogens and restore the normal homeostatic state of the tissue, thereby limiting or preventing excessive tissue injury and chronic inflammation. The results presented in this study demonstrate a new role for S100A9 in pathogen clearance and in the acute immune response.

Phagocytosis plays a crucial role in host defense leading to internalization and destruction of pathogens >0.5 μm. It is also involved in Ag presentation (42), although this latter function for neutrophils remains controversial. Albeit phagocytosis can occur in absence of opsonization, it is greatly enhanced by interactions between the Fc portion of Ig or complement components (iC3b) and FcRs or CRs at the phagocyte surface (3, 49). Interactions between receptors and their ligands trigger the formation of phagopodes and ultimately lead to the complete uptake of the particle. Several soluble mediators are known to enhance phagocytosis in human macrophages or neutrophils, including the cytokines GM-CSF, IL-4, and IL-15 (31, 43, 50), but the mechanisms underlying this biological response remain unclear. However, it has been demonstrated that Src proteins and Syk are essential for signal transduction leading to cytoskeleton remodeling and phagocytosis (51, 52). Additionally, downstream signaling pathways such as PI3K and Erk are the actin regulator protein complex Arp2/3 are also crucial for the uptake of particles (46, 53, 54). Importantly, FcR- and CR-mediated phagocytosis are differentially regulated (4). For instance, FcR-mediated phagocytosis is dependent on Cdc42 and Rac, whereas CR-mediated phagocytosis is regulated by Rho (55). Interestingly, our results demonstrate that Src proteins and Syk are essential for signal transduction leading to cytoskeleton remodeling and phagocytosis (51, 52). Additionally, downstream signaling pathways such as PI3K and ERK or the actin regulator protein complex Arp2/3 are also crucial for the uptake of particles (46, 53, 54).

S100A9 also activates in human neutrophils (19, 21, 22). It is well known that phagocytosis mediated by FcγRIIa and/or FcγRIII depends on Syk, PI3K, and ERK1/2 (22). We have already

FIGURE 8. S100A9 increases human neutrophil phagocytosis by Syk-PI3K/Akt-Erk1/2-dependent mechanisms. The percentage of phagocytosis was assessed by counting the uptake of SRBCs as described in Materials and Methods. Cells (1 × 10⁷ cells/ml) were pretreated with specific inhibitors (30 μM piceatannol, 1 μM Syk II, 5 μM PD98059, 5 μM U0126, 5 μM SB203580, 10 μM JNKII, or 10 nM wortmannin) and then incubated with 40 μg/ml S100A9 or the equivalent volume of buffer (Ctrl) for 30 min. SRBCs were then added at a 5:1 ratio for 30 min and phagocytosis was assayed. Data represent the mean ± SEM of four experiments performed on cells from different donors.

FIGURE 9. Proposed model of signalization involved in S100A9-induced degranulation and phagocytosis in human neutrophils. 1) S100A9 (A9) binds to its as yet unidentified receptor (possibly the receptor for advanced glycation end products and/or TLR-4) and induces early events (2) that are still unknown (represented here as a black box), ultimately leading to the activation of MAPKs (3). More specifically, S100A9 activates p38 (3) and JNK (6), which are both involved in its ability to induce degranulation. Unlike these two MAPKs, the activation of Erk-1/2 by S100A9 (8) leads to enhanced phagocytosis (8a). In addition to MAPKs, S100A9 activates Syk (9) and Akt (10), which are both involved in phagocytosis. The use of specific inhibitors of p38 (SB203580), JNK (JNKII), MEK1/2 (PD98059 and U0126), Syk (piceatannol [Pic] and SykiII), and Akt (wortmannin [Wort]) leads to inhibition of S100A9-induced degranulation and phagocytosis (see boxed Xs). The dotted arrow indicates a probable association between Syk and Akt.
demonstrated that the MAPKs p38, JNK, and ERK1/2 are activated in neutrophils in response to S100A9 and that only p38 and JNK participate in the induction of degranulation (22). Therefore, we first tested the involvement of these kinases in S100A9-enhanced phagocytic activity. Unexpectedly, p38 and JNK inhibitors had no effects on the enhanced phagocytic activity of S100A9–primed neutrophils. However, abolishment of ERK1/2 activation, through the inhibition of MEK1/2, slightly diminished the priming effect of S100A9 on phagocytosis. Therefore, this pathway seems not to be largely implicated in S100A9-mediated signals rendering neutrophils more efficient to phagocyte pathogens.

Interestingly, using Syk-deficient neutrophils, it was recently demonstrated that specific deletion of Syk results in reduced host defense against bacterial infection, including E. coli (59). Corroborating the importance of Syk in neutrophil phagocytosis, we recently demonstrated that depletion of Syk by an antisense strategy dramatically diminished the ability of IL-4 to enhance phagocytosis of opsonized SRBCs (31). In this study, we demonstrate that S100A9 induces phosphorylation of Syk in neutrophils. Indeed, phosphorylation occurs between 15 and 30 min postexposure to S100A9. According to our data and considering the role of Syk in the phosphorylation of downstream cytoskeletal substrates and in F-actin remodeling (reviewed in Ref. 60), we think that S100A9–exposed neutrophils start reorganization of actin cytoskeleton before the addition of the phagocytic stimuli. This phenomenon might facilitate upstream events and augment the efficacy of the engulfment. Because membrane 3'-phosphoinositides, products derived from the activation of the PI3K, play also a relevant role in the recruitment of cytoskeletal substrates, pseudopodes extension, and phagocytosis (46), experiments using the PI3K inhibitor wortmannin have been performed to investigate whether exposure to S100A9 can activate this kinase. We demonstrate signaling cascades induced by S100A9 promote phosphorylation of Akt in neutrophils, which is a substrate of the activated PI3K. However, based on our results we cannot discriminate between the S100A9– and SRBCs-mediated PI3K activation in the initiation of phagocytosis since wortmannin inhibits similarly phagocytosis in control and in S100A9–treated neutrophils. Overall, these observations suggest specific roles for p38, ERK1/2, Syk, PI3K/Akt, and JNK in neutrophil functions, as well as a new mechanism of action for S100A9, which is summarized in Fig. 9.

S100A8, S100A9, and S100A12 have both intracellular and extracellular activities. Via its interaction with arachidonic acid, p67phox, and Rac-2, intracellular S100A8/A9 activates NADPH oxidase (60). However, a recent study reported that exogenous administration of S100A8, S100A8/A9, and S100A9 inhibit neutrophil oxidative metabolism (61). This is in contrast with our results indicating that S100A9 (but not S100A8 or S100A12) induces neutrophil ROS production. These different outcomes might be explained by the sensitivity of T100 proteins to their environment, as the functions of these proteins are regulated by various modifications, including oxidation and glutathionylation (62–64), thereby providing a possible explanation for this discrepancy. Compared to PMN, which induces a strong and rapid oxidative burst, S100A9 rather induced ROS accumulation over a longer period of time. No superoxide anions were detected in the extracellular medium following S100A9 stimulation. Although ROS were detected in the intracellular compartment, we did not observe any significant difference in the neutrophil K5. This suggests that ROS are dispensable in S100A9–induced bacterial killing. Of note, as ROS can also transmit signals, these results suggest that S100A9–induced ROS accumulation could act as a danger signal for the organism, as ROS regulate neutrophil functions, including gene expression, cytokine production, and, more importantly, phagocytosis (65). Additionally, potentiation of neutrophil responses by ROS production was previously associated with tyrosine phosphorylation (66, 67). However, ROS can also act as second messengers by inducing tyrosine phosphorylation events, which can in turn modulate ROS accumulation (68). The evidence that reactive oxygen species act as signaling molecules suggests that S100A9 could transduce its effects, at least in part, via a ROS-dependent mechanism that needs to be further investigated. ROS production could occur via multiple routes in neutrophils. For example, the production of PGs and leukotrienes is a process known to generate ROS. Whether S100A9 induces the production of these proinflammatory mediators remains to be confirmed.

In conclusion, this study leads us to propose a novel role for S100A9 relevant to the control of infections. Early on during infections, S100A8, S100A9, and S100A12 are released upon phagocyte activation, for example, in tissue abscesses and infected mucosae (23–27). As they are highly expressed in the cytoplasm of neutrophils, the secretion of S100A9 even by a few neutrophils could easily lead to high concentrations of S100 proteins at the infection site. Upon their release, S100A8, S100A9, and S100A12 act as danger signals for the organism, inducing the recruitment of neutrophils from the blood to the inflammatory site. This activity is triggered by the stimulation of Mac-1 and the degranulation of neutrophils (20, 22, 30). Additionally, S100A8/A9 and S100A12 would inhibit the growth of bacteria at the infection site, allowing time for the migration of large numbers of neutrophils to occur. Finally, as neutrophils reach the infection site, they become activated by S100A9, leading to the enhancement of their phagocytic activity and the rapid clearance of the pathogens.

**Disclosures**

The authors have no financial conflicts of interest.

**References**


Supplementary FIGURE S1 Legend: p38 is not involved in S100A9-induced bactericidal activity of human neutrophil. Killing of E. coli was evaluated by a one-step assay, as described in "Materials and Methods". Cells were pretreated with the p38 inhibitor (SB203580 5μM) for 30 min, then incubated in the presence of buffer (ctrl) or 40 μg/mL S100A9 for 30 min before being incubated with E. coli for increasing periods of time. Results are from one experiment representative of three others.
Fig. S1

A graph showing the percentage survival over time for different conditions:
- Ctrl
- Ctrl + SB203580
- S100A9
- S100A9 + SB203580

The x-axis represents time in minutes, ranging from 0 to 30, and the y-axis represents percentage survival, ranging from 0 to 100.