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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.

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 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).

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S100A8 is a proinflammatory protein that 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.
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 Calbiochem (St. Louis, MO). JNK inhibitor II and U0126 were purchased from Calbiochem (San Diego, CA). Wortmannin and Syk inhibitor (Syki) II were obtained from ICN Biomedicals (Aurora, OH). GM-CSF was obtained from PeproTech (H-195) Abs, was obtained from Santa Cruz Biotechnology (Santa Cruz, CA). Antibodies against mouse p47phox (H-195) Abs were purchased from Cell Signaling Technology (Danvers, MA). Anti–phospho-specific Erk1/2 and anti–phospho-specific tyrosine Abs were obtained from Biorad (Hercules, 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 conjugate, and phalloidin-Alexa Fluor 568 were obtained from Invitrogen (Carlsbad, CA). 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 Calbiochem (St. Louis, MO). JNK inhibitor II and U0126 were purchased from Calbiochem (San Diego, CA). Wortmannin and Syk inhibitor (Syki) II were obtained from ICN Biomedicals (Aurora, OH). GM-CSF was obtained from PeproTech (Rocky Hill, NJ). E. coli (O157:H7) was a gift from Prof. Eric Déziel (Institut National de la Recherche Scientifique-Institut Armand-Frappier, Laval, Québec, Canada).

Neutrophil isolation

Neutrophils were isolated from venous blood of healthy volunteers by dextran sedimentation followed by centrifugation over Ficoll-Hypaque cushion (Pharmacia, Uppsala, Ontario, Canada) as described previously (22). Blood donations were obtained from informed, consenting individuals according to institutionally approved procedures. Cell viability was monitored by trypan blue exclusion and found to be consistently >98%. Cell purity (>98%) was monitored by cytometry from cytocentrifuged preparations treated with Wright–Giemsa stain (Fisher Scientific, Ottawa, Ontario, Canada). Cell viability was systematically evaluated before and after each treatment and was always ≥98%. Neutrophils were re-suspended at 1 × 10⁸ cells/ml in HBSS (1×) unless specified.

Phagocytosis of SRBCs

SRBCs were opsonized with a 1:200 dilution of a rabbit IgG anti-SRBC Ab (Sigma-Aldrich) for 45 min at 37°C as described (31). Neutrophils were treated 30 min with the indicated agonists and then incubated in a 1:5 ratio of opsonized SRBCs for 30 min at 37°C. In some experiments, cells were treated with specific inhibitors as indicated. Cells were washed twice after incubation with inhibitors. After incubation with SRBCs, the samples were centrifuged at 200 × g for 10 min at 4°C. Supernatants were discarded and an osmotic shock was performed on the pellets by resuspending the cells with 400 µl H₂O for 15 s, followed by the addition of 4.5 ml PBS. The samples were then washed twice and the final pellets were suspended in 100 µl PBS. Phagocytosis is expressed as the percentage of neutrophils having ingested at least one opsonized SRBC or neutrophils having ingested two or more opsonized SRBCs (phagocytosis index). GM-CSF (65 ng/ml) was used as a positive control (32).

Phagocytosis of latex microspheres or Alexa Fluor 488-labeled E. coli

Phagocytosis was assessed by flow cytometry using FITC-labeled latex microspheres or Alexa Fluor 488 conjugate E. coli. Cells were stimulated with the indicated agonists at 37°C for 30 min before incubation with latex beads or serum-opsonized E. coli. Cells were then centrifuged and supernatant was discarded. Beads or bacteria that were not uptaken by the cells were washed twice with PBS and removed by centrifugation onto a 4.5-ml gradient of RPMI 1640 medium containing 5% BSA. Latex beads or bacteria remaining at the surface were then removed and cells located in the pellet were quenched with trypan blue. After three washes, cells were resuspended in 500 µl PBS for analysis. Cellular phagocytosis was monitored by flow cytometry at 525 nm. A negative control was performed in parallel by incubating cells with latex beads or bacteria at 4°C instead of 37°C. Phagocytosis of latex microspheres and Alexa Fluor 488 conjugate E. coli were expressed as the difference in the mean fluorescence intensity (ΔMFI) measured between 37°C (uptake at 37°C) and 4°C (uptake at 4°C) (33).

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/ml) were treated with the indicated agonists for the indicated period of time at 37°C, centrifuged, and lysed in nonnudendruling 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 p47(phox) at 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 an 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 µM penicillin, and 100 µg/ml streptomycin) were stimulated with PMA (10⁻⁹ 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, 4% 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 p47(phox), p47(phox) immunoprecipitates were electroblotted onto 15% SDS-PAGE gels and transferred to polyvinylidene fluoride 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 Ab was added to remove Sepharose of 1.750. A dilution of 1:1000 in 3% BSA was used for total 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, or antibody followed by several washes with PBS. Protein expression was revealed using an ECL Western blot analysis 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 × 10^7 cells) were stimulated with 40 μg/ml S100A8, S100A9, S100A12, or the equivalent volume of the diluent (HBSS) for 30 min at 37°C. Plates were incubated 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. For some experiments, cells were pretreated with the p38 pharmacological inhibitor (5 μM SB203580) for 30 min at 37°C. In a separate assay (control), the cells were replaced with the equivalent volume of HBSS, thus allowing the direct measurement of the starting number of bacteria, their growth over the time course, any negative impact of opsonization and dilution in water, and all the possible effects of S100 proteins on bacterial growth. The reaction was started by adding 3 × 10^9 opsonized bacteria (1 × 10^7 bacteria/ml) and incubated for various periods of time at 37°C. Fifty-microliter aliquots were removed at 10, 20, and 30 min and diluted into 2.45 ml H2O with one drop of 1 mM sodium hydroxide (NaOH) (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 an initial concentration of 500–1500 CFU per plate in duplicate. Plate counts were converted to original bacterial densities by multiplying with the appropriate dilution factor. Growth adjustment, phagocytosis rate constant (Kp), and killing rate constant (Kk) 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 × 10^7 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 FACSScan. 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 × 10^8 cells/ml) were suspended in HBSS (supplemented with 1.6 mM CaCl2) 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 (O2^-) 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 O2^- 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 O2^- has been detected in S100A9-stimulated neutrophils compared with PMA-treated cells (Fig. 1C). We next investigated whether the observed ROS production in S100A9-primed neutrophils was from the activation of NADPH oxidase. For this purpose, we measured the phosphorylation of p47phox, 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 p47phox, 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-primed neutrophils can further produce ROS in response to phagocytic stimuli. Interestingly, S100A9-primed 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 intracellu-
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 μg/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 μg/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.

S100A9 increases human neutrophil bactericidal activity. Killing of 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 μg/ml S100A9, S100A8, or S100A12 for 10–30 min before incubation with E. coli. Data represent the mean ± SEM of 4 experiments performed on cells from different donors.
FIGURE 3. S100A9 increases intracellular bactericidal activity and $K_p$. Killing of *E. coli* was evaluated by a two-step assay (A), as described in Materials and Methods. $K_p$ and $K_r$ were evaluated using bacterial concentrations from the two-step assay (B). Cells were treated with buffer (Ctrl) or 40 μg/ml S100A9 for 30 min before incubation with *E. coli*. Data represent the mean ± SEM of three experiments performed with cells from different donors.

4) 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 (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 pathways in the S100A9-mediated increase in phagocytosis. To this end, we used the following reagents: Wortmannin (PI3K/Akt and Syk pathway inhibitor), U0126 (MEK inhibitor), and piceatannol (Syk inhibitor).

FIGURE 4. S100A9 increases human neutrophil phagocytosis dependent of FcγR in a concentration-dependent manner. Percentage of phagocytosis was assessed by counting the uptake of opsonized SRBCs, as described in Materials and Methods. Cells were stimulated with 40 μg/ml S100A8, S100A9, or S100A12 or 65 ng/ml GM-CSF (A, B) or 0.1–100 μg/ml S100A9 (C) for 30 min. SRBCs were then added at a 5:1 ratio for 30 min and the phagocytosis rate (A, C) and index (B) were determined. Data represent the mean ± SEM of four experiments performed on cells from different donors. Arrows point to ingested SRBCs. Images were obtained by cytology from cytocentrifuged preparations colored by Wright-Giemsa staining (original magnification ×400).
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 ∼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 or 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 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 microorganismal 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. S100A9 induces phosphorylation events in human neutrophils. Phosphorylation of (A) total tyrosyl residues, (B) Syk, (C) Erk1/2, and (D) Akt were assessed by immunoblotting using specific Abs as described in Materials and Methods. Cells (4 × 10^7 cells/ml) were incubated with 40 μg/ml S100A9 (A9) or the equivalent volume of buffer (Ctrl) for 1–60 min (A), or 10 min with 65 ng/ml GM-CSF. For some samples, a 30-min pretreatment with specific inhibitors of the Syk, MEK1/2, or PI3K/Akt pathways (30 μM piceatannol, 1 μM Syki II, 5 μM PD98059, 5 μM U0126, or 10 nM wortmannin) was performed. Shown here is one experiment representative of at least three others.](http://www.jimmunol.org/)

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 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](http://www.jimmunol.org/)

**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 x 10^7 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](http://www.jimmunol.org/)

**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.
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


