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Neutropenia Enhances Lung Dendritic Cell Recruitment in Response to Aspergillus via a Cytokine-to-Chemokine Amplification Loop

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Current understanding of specific defense mechanisms in the context of neutropenic infections is limited. It has previously been reported that invasive aspergillosis, a prototypic opportunistic infection in neutropenic hosts, is associated with marked accumulation of inflammatory dendritic cells (DCs) in the lungs. Given recent data indicating that neutrophils can modulate immune responses independent of their direct microbial killing, we hypothesized that neutropenia impacts the host response to Aspergillus by determining the migration and phenotype of lung DCs. Inflammatory DCs, but not other DC subsets, were found to accumulate in the lungs of neutropenic hosts challenged with killed or live-attenuated Aspergillus as compared with non-neutropenic hosts, indicating that the accumulation was independent of neutrophil microbicidal activity. The mechanism of this accumulation in neutropenic hosts was found to be augmented influx of DCs, or their precursors, from the blood to the lungs. This effect was attributable to greatly elevated lung TNF expression in neutropenic as compared with nonneutropenic animals. This resulted in greater lung expression of the chemokine ligands CCL2 and CCL20, which, in turn, mediated enhanced recruitment of TNF-producing inflammatory DCs, resulting in a positive feedback cycle. Finally, in the context of neutropenic invasive aspergillosis, depletion of DCs resulted in impaired fungal clearance, indicating that this mechanism is protective for the host. These observations identify what we believe is a novel defense mechanism in invasive aspergillosis that is the result of alterations in DC traffic and phenotype and is specific to neutropenic hosts. The Journal of Immunology, 2010, 185: 6190–6197.

Neutropenia, defined as reduced concentration of circulating neutrophils in the blood, is a common clinical problem that complicates cytotoxic chemotherapy, transplantation, and hematologic malignancies. Neutropenic hosts are dramatically more susceptible to many infections, but our understanding of specific host defense mechanisms in the context of neutropenic infections is limited (1). Invasive aspergillosis is a severe infection caused by common environmental molds of the Aspergillus species and is a prototypic opportunistic infection of neutropenic hosts. Aspergillus conidia are ubiquitous in air and, when inhaled, can bypass the physical barriers of the respiratory tract and reach beyond the ciliated epithelium, where they become swollen and metabolically active. In normal hosts, swollen conidia are eliminated at this stage, but in immunocompromised patients, they germinate to form hyphae that penetrate the lung epithelium and cause invasive pneumonia. The severity and duration of neutropenia, as well as qualitative defects in neutrophil function, are the best characterized clinical risk factors for the development of this infection (reviewed in Refs. 2 and 3). Thus, host responses to Aspergillus represent a clinically relevant setting to assess mechanisms of host defense in neutropenic hosts.

Dendritic cells (DCs) are APCs critical to shaping T cell responses in many contexts, including in response to Aspergillus fumigatus. DCs recognize Aspergillus cells via pattern-recognition receptors (4–7) and transport them from the lungs to secondary lymphoid tissues to initiate acquired immunity (8–10). The internalization of Aspergillus conidia and hyphae by DCs initiates qualitatively different CD4+ T cell responses: conidia-activated DCs lead to the priming of Th1 response, whereas hyphal phagocytosis by lung DCs results in the generation of IL-4–producing CD4 T cells (8, 11). Inflammatory (CD11bhiCD11c+) DCs are a subset of DCs that accelerate their traffic from the blood to tissues to lymphatic organs during inflammatory responses (12) and have been shown to expand in the lung following a respiratory challenge of Aspergillus (10, 13, 14). We previously reported an unexpectedly large accumulation of these cells in the lungs of neutropenic mice with invasive aspergillosis that was, in part, dependent on the interaction of the chemokine ligand-receptor pair, CCL20-CCR6 (13).

Because such large numbers of inflammatory DCs are not observed in other models of lung inflammation and given evidence of cross-talk between neutrophils and DCs (15), we posited that the absence of neutrophils from infected tissues alters the local inflammatory environment independent of neutrophil-mediated microbicidal killing and, as a result, modulates the behavior of lung DCs. We therefore tested the hypothesis that neutropenia impacts the host response to Aspergillus by determining the migration and phenotype of lung DCs.
Materials and Methods

Animals and in vivo procedures

Wild-type mice, transgenic mice bearing the simian diphtheria toxin receptor gene under the control of the mouse CD11c promoter (CD11c-DTR mice) (16), or mice heterozygous for targeted replacement of the endogenous CX3CR1 with an enhanced GFP reporter gene (CX3CR1<sup>GFP</sup>/mice) (17), all on C57BL/6 background, were purchased from The Jackson Laboratory (Bar Harbor, ME). Animals were housed and maintained under pathogen-free conditions. Age- and gender-matched 6- to 8-week-old animals were used in all experiments. All animal experiments were approved by the Animal Care and Use Committee of University of Virginia.

Neutrophil depletion was achieved with a single i.p. injection of 80 µg mAb (Gr1, anti-Ly6G/C, clone RB6.8C5) 1 d before an intratracheal challenge with <i>A. fumigatus</i>, as described (18). This resulted in peripheral blood neutrophilia (absolute circulating neutrophil count <50 cells/µl) on days 1 and 3 after injection in both infected and uninfected mice, with a return of peripheral counts to pretreatment levels (>1000 cells/µl) by day 5 (19, 20). Administration of the mAb did not influence the number of nonneutrophil peripheral blood leukocytes, nor lung and spleen lymphocytes or DC subsets (13) (Supplemental Fig. 3A, 3B). In some experiments, neutrophil depletion was achieved by i.p. administration of 200 µg anti-Ly6G/C (clone 1A8; BioXcell). For depletion of DCs, mice heterozygous for the CD11c-DTR transgene were injected with diphtheria toxin (clones LTF2 and 2A3; BioXcell). For depletion of CD4<sup>+</sup> T cells, mice were injected intraperitoneally with 200 µg anti-CD45.1 mAb (clone 16-10A1; BioXcell) 1 d before Aspergillus challenge. For the day 3 time point, an additional i.p. administration of anti-CD45.2 or control Ab was given 48 h later for a total of two doses.

In experiments designed to track the movement of cells to the lungs, we used previously described protocols with minor modifications (22, 23), as follows: circulating blood monocytes were labeled with latex beads by i.v. administration of 100 µl 1:10 dilution of 0.5-µm yellow-green latex microspheres (Polysciences, Warrington, PA) 24 h after administration of Aspergillus hyphae. In adoptive transfer experiments, animals received i.p. administration of 300 µg anti-TNF or isotype control mAbs (clones LTF2 and 2A3 BioXcell). For depletion of DCs, mice heterozygous for the CD11c-DTR transgene were injected with diphtheria toxin (Sigma-Aldrich, St Louis, MO), as described (16). In vivo TNF neutralization experiments, animals received i.p. administration of 300 µg anti-TNF or isotype control mAbs (clones XT3.11 and HRPN, respectively; BioXcell) 1 d before Aspergillus challenge. For the day 3 time point, an additional i.p. administration of anti-TNF or control Ab was given 48 h later for a total of two doses.

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Preparation and administration of <i>A. fumigatus</i>

We used a previously characterized mouse model of neutrophilic invasive aspergillosis (13, 20–23) with some modifications. In these experiments, which animals were challenged with killed fungal elements, <i>A. fumigatus</i> (strain 13073; American Type Culture Collection, Manassas, VA) conidia were isolated from their respiratory samples during that hospital admission and obtained peripheral blood absolute neutrophil counts from the day of surgery. Histologically normal lungs were used as controls. The use of anonymous human samples for this study was reviewed by the University of Virginia Institutional Review Board for Human Subject Research and classified as exempt.

Representative 4-µm paraffin-embedded sections were deparaffinized in xylene and rehydrated through graded ethanol to water, subjected to heat-induced target retrieval (for S100 Ag only; Dako Target Retrieval Solution; Dako North America, Carpinteria, CA), had endogenous peroxidase activity quenched (Dual Endogenous Enzyme Block; Dako), and were labeled with Ab against S100 (Dako; code Z0311) or CD1a (Dako; code M3571), followed by incubation with the labeled polymer and 3-3’ dia-minobenidine substrate chromagen. Slides were counterstained with hematoxylin and bluing reagent (Thermo Scientific Anatomic Pathology, Pittsburgh, PA), dehydrated through graded alcohol to xylene, and coverslipped.

Identification of leukocyte subsets

At designated time points, animals were euthanized by CO2 asphyxiation, the pulmonary vasculature was perfused, whole lungs were removed, and lung cell suspensions were prepared, as previously described (13, 19, 24, 25, 27). Peripheral blood was collected from the right ventricle into heparinized tubes. The following Abs were used to label cells for flow cytometry (from BD Biosciences, San Jose, CA; eBiosciences, San Diego, CA; Millenyi Biotec, Auburn, CA; or R&D Systems, Minneapolis, MN): anti-B220 Pacific Blue (clone RA3-6B2); anti-CD3e Pacific Blue (clone 500-A2); anti-CD11b allophycocyanin-Cy7 (clone M1/70); anti-CD11c PE-Cy7 (clone HL3); CD40 PE (clone 23/23); anti-CD45 PerCP (clone 30-F11); CD80 FITC (clone 16-10A1); anti-CD86 PE (clone GL1); anti-CD103 biotin (clone 2E7); anti-CD11D PE (clone AF589); anti-F4/80 PE (clone A31); anti-I-A/II-E FITC, biotin, allophycocyanin, and Pacific Blue (clone M5114.15.2); anti-Ly-6G/CyTC (clone AL-21); anti–Ly-6G PE and FITC (clone 1A8); anti–Ly-6C/GC PE and Pacific Blue (clone RB6-8C5); anti–PDCA1 PE (clone J505-1C2.4.1); and anti–TNF PE (clone MP6-XT22). To determine the lung cells capable of producing TNF, lung suspensions were incubated with brefeldin A (10 ng/ml), PM (10 ng/ml), and ionomycin (100 ng/ml) in RPMI 1640 with 5% FBS for 5 h, and intracellular staining was detected using a commercial kit (Cytofix/Cytoperm; BD Biosciences). Samples were analyzed on a FACS Canto II instrument using Diva software (BD Biosciences). The absolute number of each leukocyte subset was determined as the product of the percentage of the cell type and the total number of cells in the sample, as determined under a hemocytometer or on an automated cell counter (Countess; Invitrogen Life Technologies).

Cytokine and chitin assays

<i>A. fumigatus</i> grows as multicellular branching hyphae and does not form distinct reproductive structures in infected tissues. We therefore used a previously characterized assay for chitin, a carbohydrate component of hyphal wall that is absent from mammalian tissues and conidia, to quantify the burden of hyphae in infected lungs, as detailed previously (29). Organ chitin content in animal models of invasive aspergillosis has been shown by several groups to correlate with histopathological evidence of fungal invasion and mortality from the infection (14, 27, 30–32). TNF, CCL2, and CCL20 protein levels in filtered supernatant of lung homogenates were determined either using commercial ELISA kits (Duoset ELISA Development; R&D Systems) or multiplex bead array kits (Milliplex Map; Millipore, Billerica, MA), according to the manufacturer’s instructions.

Culture and adoptive transfer of DCs

Immune bone marrow–derived conventional DCs were prepared, as described previously (13). In brief, bone marrow cells were cultured in 20 ng/ml murine GM-CSF for 5 d and positively selected by immunomagnetic selection of CD11c<sup>+</sup> cells (Miltenyi Biotec), resulting in >95% purity. Cells were then labeled with the vital fluorochrome CFSE (Invitrogen Life Technologies), according to manufacturers’ instructions, and uniform staining was verified by epifluorescent microscopy. The resulting cells were >95% viable by trypan blue exclusion, and consistent with immature phenotype, had low expression (mean fluorescence intensity) of CD86, CD40, CD80, and MHC class II molecules by flow cytometry. Cells were transferred to animals via lateral tail vein of 4–5 × 10<sup>5</sup> cells/100 µl PBS.

Statistical analysis

Data were analyzed on a Macintosh Powerbook G4 computer using Prism statistical package (v.4.0a; GraphPad, San Diego, CA). Values between two groups over multiple times were compared with two-way ANOVA, comparisons between two groups at a single time were performed with unpaired two-tailed Mann-Whitney test (nonparametric test), and comparisons between multiple groups at a single time were compared using the Kruskal-Wallis test with Bonferroni posttest. Probability values were considered statistically significant if they were <0.05.
Results

Absence of neutrophils results in accumulation of DCs in the lungs in response to Aspergillus

Given prior observation of marked accumulation of inflammatory DCs in the lungs of neutropenic mice with invasive aspergillosis (13), we sought to determine whether the absence of neutrophils is the direct cause of increased number of lung DCs. We reasoned that, in the context of a neutropenic host, Aspergillus conidia germinate into hyphae, resulting in invasive infection, whereas, in immunocompetent hosts, they are killed at the conidial stage before forming hyphae (33); as a result, the microbial Ags encountered by neutropenic and immunocompetent hosts after challenge with viable Aspergillus conidia are not comparable and any differences in host response may be related to differences in the antigenic stimulus. We therefore challenged the animals with killed fungal elements to retain a comparable microbial stimulus that is independent of the presence of neutrophils. Increase in the number of lung DCs was observed in both neutropenic and non-neutropenic hosts challenged with killed Aspergillus elements, but was greatly enhanced in neutropenic hosts, resulting in a 4-fold increase in the number of inflammatory DCs in the lungs in neutropenic mice as compared with the nonneutropenic mice 3 d after challenge with hyphae (Fig. 1A, 1B). Moreover, the effect was observed when animals were challenged with killed hyphae as well as swollen conidia (Supplemental Fig. 1A). In contrast, depletion of neutrophils did not influence the number of airway mucosal DCs or lung plasmacytoid DCs after challenge with Aspergillus (Fig. 1C, 1D).

We performed additional studies to ensure that the observed effect was not an epiphenomenon related to the specific experimental conditions. We found a similar increase in lung inflammatory DCs after challenge with killed hyphae when neutropenia was induced using an alternative mAb (Supplemental Fig. 1B). Similar results were found when animals were challenged with live hyphae from an attenuated strain of Aspergillus that is growth impaired at body temperatures (28) (Supplemental Fig. 1C). Lastly, we found that, similar to observations in the animal model, neutropenia was associated with a substantial increase in the number of DCs in the airways and alveolar spaces of patients with invasive aspergillosis compared with the number of DCs found in normal lungs and in nonneutropenic patients with invasive aspergillosis (Supplemental Fig. 2).

Neutropenia results in increased influx and differentiation of inflammatory DCs from the blood to the lungs following challenge with Aspergillus

We next tested the hypothesis that the accumulation of DCs in the lung is the result of enhanced influx or local differentiation. We tested this hypothesis by tracing the fate of peripheral blood monocytes labeled in the circulation with i.v. delivered fluorescent latex beads, as previously described (22, 23). We first confirmed that neutrophil depletion did influence blood monocyte subsets in this system (Supplemental Fig. 3A, 3B) and that, irrespective of neutrophil depletion, bead-labeled peripheral blood leukocytes after i.v. delivery of beads consisted of monocytes (Supplemental Fig. 3C), similar to prior reports (22, 23). We found that few bead-positive cells arrived in the lungs of unchallenged mice after i.v. administration of labeled beads, but that, within hours after i.v. delivery of beads, >2-fold more bead-positive cells arrived in the lungs of neutropenic mice challenged with killed Aspergillus.

FIGURE 1. Effect of neutrophil depletion on the number of lung DCs in response to Aspergillus. Number of lung neutrophil (A), inflammatory DCs (B), mucosal DCs (C), and plasmacytoid DCs (D) are shown at various times after challenge with killed Aspergillus hyphae in animals with Ab-mediated neutrophil depletion and mice treated with isotype control Ab. Data shown represent mean ± SEM; n = 20 mice per group per time point pooled from four independent experiments for A and B and n = 8 mice per group per time point pooled from two independent experiments for C and D. Time 0 represents unchallenged animals. *p < 0.05 comparing trend between the two groups over time.
hyphae as compared with nonneutropenic mice (Fig. 2). In addition, the bead-positive cells arriving in the lungs of neutropenic mice consisted mostly of CD11bhighCD11c+ inflammatory DCs as early as 1 h after administration of beads, with smaller numbers of CD11bhighCD11c- inflammatory monocytic cells; in contrast, bead-positive cells arriving in the lungs of nonneutropenic mice consisted almost entirely of inflammatory monocytic cells (Fig. 2C, 2D).

The rapidity of appearance of bead-positive DCs in the lungs of neutropenic mice suggested the possibility of selection of small numbers of circulating DCs from the blood in addition to in situ differentiation from recruited DC precursors in the lungs. To assess whether the recruitment of circulating cells was influenced by neutropenia, we i.v. delivered cultured and fluorochrome-labeled immature conventional DCs and tracked their arrival in the lungs after intrapulmonary challenge with killed Aspergillus hyphae. We found ~2-fold higher numbers of transferred DCs in the lungs of neutropenic as compared with nonneutropenic animals (Fig. 2E). Taken together, these results suggest that in the context of host response to Aspergillus, neutropenia results in enhanced influx of DCs, DC precursors, or both, to the lungs.

Absence of neutrophils results in increased local production of inflammatory cytokines in response to Aspergillus

Because neutropenia appeared to cause a much greater influx of DCs and/or their precursors to the lungs after challenge with...
Aspergillus, we next sought to determine the mechanism for this effect. TNF is a key proximal cytokine in innate defenses against many infections (34) and has been shown to be critical to host defense against Aspergillus both in humans (35) and in animal models, where it induces the expression of multiple chemokines in the lungs (36, 37). We noted a rapid and marked induction of TNF in the lungs of neutropenic, but not in nonneutropenic mice that were challenged with killed Aspergillus hyphae (Fig. 3), supporting the hypothesis that TNF may be a proximal signal responsible for recruitment of DCs or their precursors to the lungs in neutropenic hosts. To address this possibility, we also measured lung levels of CCL2 and CCL20, chemokines known to be strongly induced by TNF and previously shown to be critical to recruitment of DCs and monocytes (10, 13, 36), and noted a similar marked induction of CCL2 and CCL20 in the lungs of neutropenic mice in response to Aspergillus hyphae as compared with nonneutropenic animals (Fig. 3A–C). Similar inductions were observed when neutrophil depletion was achieved with an alternative mAb (Fig. 3D).

We next sought to establish the cellular sources of the elevated lung TNF in neutropenic mice. As expected, we found ∼2-fold greater number of TNF-producing cells in the lungs of neutropenic, as compared with nonneutropenic, mice challenged with Aspergillus hyphae (Fig. 4). Interestingly, the TNF-producing cells consisted of approximately equal numbers of CD11b<sup>high</sup>CD11c<sup>+</sup> inflammatory DCs and CD11b<sup>high</sup>CD11c<sup>−</sup> inflammatory monocytic cells early after challenge with Aspergillus in both groups, but mostly of CD11b<sup>high</sup>CD11c<sup>+</sup> inflammatory DCs in neutropic mice late after challenge (Fig. 4B). Resident lung macrophages (identified as CD11b<sup>low</sup>CD11c<sup>+</sup> cells) were found to be a minor population of TNF-producing cells in both groups (Fig. 4B).

Our data show that the absence of neutrophils results in increased expression of lung TNF, CCL2, and CCL20 in response to Aspergillus and that, in this setting, TNF is also a product of recruited DCs. We therefore hypothesized a causal series of events, as follows: in the lungs of neutropenic hosts infected with Aspergillus, DC-derived TNF results in induction of CCL2 and CCL20 recruiting DCs to the lungs, which, in turn, act as a source of TNF, thereby setting up a positive feedback loop. To test this hypothesis, we examined the effect of Ab-mediated neutralization of TNF on lung expression of CCL2 and CCL20, and accumulation of inflammatory DCs in the lungs after challenge with killed Aspergillus hyphae. Immune neutralization of TNF in neutropenic mice led to a marked reduction in both lung CCL2 and CCL20 levels, indicating that TNF is necessary for optimal expression of CCL2 and CCL20 in this setting (Fig. 5A, 5B). In addition, TNF...
neutralization resulted in reduction of the number of lung inflammatory DCs to levels observed in nonneutropenic animals (Fig. 5C). Together with previous data supporting the role of CCL20 and its receptor, CCR6, in recruitment of inflammatory DCs to the lungs (13), these data provide evidence for an amplification loop in the lungs of neutropenic hosts challenged with *Aspergillus*, which results in accumulation of large numbers of TNF-producing inflammatory DCs.

Accumulation of inflammatory DCs in the lungs of neutropenic mice is beneficial during the early phase of invasive aspergillosis

Lastly, we sought to determine the contribution of the accumulated lung DCs to host defense in mice with neutropenic invasive aspergillosis. We used transgenic mice expressing the simian diphtheria toxin receptor driven by the mouse CD11c promoter (16) to achieve conditional depletion of DCs in neutropenic mice with invasive aspergillosis. We confirmed that diphtheria toxin administration in neutrophil-depleted transgenic mice challenged with live *Aspergillus* conidia resulted in depletion of lung conventional DCs, but did not affect other lung DCs or macrophage subsets (Fig. 6A, 6B). Using this system, ablation of lung inflammatory DCs in neutropenic invasive aspergillosis resulted in >7-fold increase in lung fungal burden on day 3 of infection as compared with neutropenic wild-type mice (Fig. 6C), thus providing evidence for a protective role for the inflammatory DCs that accumulate in the lung in neutropenic hosts with invasive aspergillosis.

Discussion

In this study, we demonstrate that neutropenia fundamentally alters the inflammatory environment of the lung in response to the opportunist mold, *Aspergillus*, resulting in dramatic changes in the traffic and phenotype of lung inflammatory DCs. As a mechanism for the observed accumulation of inflammatory DCs in the lungs, we found greatly accelerated recruitment of DCs to the lungs in neutropenic mice, which contrasts with prior reports of neutrophils mediating the recruitment of DCs in other experimental systems (38–40). This enhanced recruitment was dependent on a positive feedback cycle involving lung DC-derived TNF, driving

**FIGURE 5.** Effect of TNF neutralization on lung chemokine levels and lung inflammatory DC number in response to *Aspergillus*. Mice with Ab-mediated neutrophil depletion and mice treated with isotype control Ab were challenged with killed *Aspergillus* hyphae. *A* and *B*, Protein levels of CCL2 and CCL20 in whole-lung homogenates were measured 1 d after hyphal challenge. *C*, Number of lung inflammatory DCs in whole-lung single-cell suspensions on day 3 after hyphal challenge. *p* < 0.05 compared with unchallenged animals; ***p* < 0.05 compared with animals receiving control IgG and challenged mice not receiving any treatment. Data shown represent mean ± SEM; n = 5–6 for each group at each time point, representative data from two experiments.

**FIGURE 6.** Effect of DC depletion in neutropenic mice with invasive aspergillosis. Mice with Ab-mediated neutrophil depletion were inoculated intratracheally with live *Aspergillus* conidia. *A*, Lung conventional DCs in CD11c-DTR and wild-type mice treated with diphtheria toxin on the day before the measurements were obtained. *B*, Other lung DC and macrophage subsets in CD11c-DTR and wild-type mice treated with diphtheria toxin, measured on day 1 of infection. DC subsets as defined in Fig. 1; macrophage subsets as defined in Fig. 2 and (13). *C*, Lung chitin content in neutropenic wild-type and CD11c-DTR mice treated with diphtheria toxin, measured on day 3 of infection. Neutropenia was induced with mAbs indicated on the graph; data represent mean ± SEM; n = 4–10 for each group. *p* < 0.05 compared with respective neutropenic wild-type mice.
the local production of the chemokine ligands CCL2 and CCL20, and resulting in further recruitment of TNF-producing DCs to the lungs. This observation provides an explanation for prior observations of very high expression of these mediators in the lungs of neutropenic mice with invasive aspergillosis (25, 36). In addition, this paradoxical finding—enhanced inflammatory cytokine milieu in the absence of neutrophils, which are the cellular hallmarks of acute inflammation—is consistent with the recently described role of neutrophils in dampening immune responses (41).

An interesting finding of the current work pertains to the specific role of the accumulated lung DCs in defense against neutropenic invasive aspergillosis. In prior studies, interruption of the CCL20–CCR6 axis resulted in reduced lung DC numbers and worsened outcome of infection (13); given the well-documented role of DCs in initiating T cell-mediated protective immunity, this observation may have been attributable to failure to mount acquired immunity. Absence of CCR7, which resulted in failure of efflux of lung DCs, however, was found to result in an unexpected improvement of the outcome of the infection (14), suggesting one of two possibilities, as follows: either that DC migration to mediastinal lymph nodes was detrimental [for example by initiating T regulatory responses (42)] or that retaining activated DCs in the lung was beneficial. As an additional consideration, observations in CCR6- and CCR7-deficient mice could conceivably be attributable to lack of expression of these receptors on cells other than DCs. In the context of this literature, we found that the depletion of conventional DCs in neutropenic hosts resulted in substantial worsening of pathogen clearance at a very early phase of the infection, suggesting that the accumulation of inflammatory DCs in the lungs of neutropenic hosts, rather than their maturation and efflux to mediastinal lymph nodes, is the key protective mechanism.

The phenotype of lung DCs observed in neutropenic mice with invasive aspergillosis as inflammatory TNF-producing cells that are important in antimicrobial defense is reminiscent of TNF- and inducible NO synthase (iNOS)-producing DCs (Tip-DCs). Tip-DCs were first described as monocyte-derived inflammatory DCs in the spleens of mice early after i.p. Listeria infection (43) and have subsequently been described in several bacterial and protozoal infections (reviewed in Ref. 12). Tip-DCs contribute to host defense in some (43, 44), but not other (45, 46) models of infection. The present work relates to this literature in several ways, as follows: first, the inflammatory DCs that accumulate in the lungs of mice with neutropenic invasive aspergillosis differ from the description of Tip-DCs in that they do not express iNOS—specifically, the iNOS-producing cells in this system consisted of inflammatory monocytes/macrophages (data not shown). Interestingly, in the context of the lung, cells with a Tip-DC–like phenotype were identified in the lungs in experimental influenza pneumonia and were found to contribute to lung injury, but not to viral clearance (47). Our findings also contrast with prior reports in that the absolute number of accumulated inflammatory DCs in lungs of neutropenic mice with aspergillosis is an order of magnitude greater than in other models.

In humans, neutropenia is typically the result of treatment with cytotoxic drugs that influence both the number and function of multiple, often incompletely defined, lineages of cells in addition to neutrophils. In experimental models that seek to examine the consequences of neutropenia, the means of depleting neutrophils is an important methodological consideration. There are currently no genetic approaches to achieve neutropenia in experimental models, and inherent to Ab-mediated approaches are concerns over specificity of neutrophil depletion and potential off-target immune complex-mediated effects (48). Specifically, RB6-8C5, the most commonly used mAb, reacts with two cell surface markers, as follows: Ly-6G, an Ag expressed by neutrophils and inflammatory monocytes (49), and 10- to 100-fold lower affinity, Ly-6C, an Ag expressed by multiple leukocyte subsets (50) (B. Mehrad, unpublished observations). Whereas administration of large quantities of RB6-8C5 depletes Ly-6C–expressing cells (including subsets of DCs and monocytes), the administration of titrated doses results in neutropenia without detectable effect on the number of other leukocyte subsets in naive animals and the administration of isotype control Ab does not appear to influence leukocyte numbers (this study; Refs. 13, 19, 20). Finally, depletion of neutrophils using an alternative mAb against Ly-6G (clone 1A8), previously shown to deplete neutrophils without affecting monocytes (21), resulted in comparable accumulation of lung DCs to that seen with RB6-8C5. Finally, treatment with the alkylating agent cyclophosphamide, which results in depletion of multiple cell lines including neutrophils, was recently reported to result in expansion of CD11b+ CD11c+ DCs (51).

In summary, we report that neutropenia causes enhanced lung inflammatory response to the common environmental mold, Aspergillus, and is associated with augmented influx of TNF-producing inflammatory DCs to the lungs, resulting in an accumulation of these cells in the lungs to the benefit of the host. These findings have several ramifications for future investigations, as follows: first, whereas we have demonstrated influx and local differentiation as major factors contributing to lung DC accumulation, neutrophils may also have a role in DC efflux from the lungs to draining lymph nodes. Indeed, in vitro studies with human neutrophils and DCs (52–54) have shown neutrophils to be involved in mediating maturation of DCs (which may, in turn, result in their efflux). Second, given recent evidence for the existence of phenotypically and functionally distinct subpopulations of neutrophils (55, 56) and an immunoregulatory role for neutrophils (41), determining the mechanism of neutrophil-mediated downregulation of lung inflammatory responses is of interest. Finally, we provide data in support of the paradigm that inflammatory DCs, like other myeloid cells, can act as effector cells in the early phase of infection, suggesting a function that is independent of their Ag presentation properties.

Disclosures

The authors have no financial conflicts of interest.

References

Supplemental figure 1. Effect of neutrophil depletion on the number of lung DCs in response to *Aspergillus*. (A) Number of lung inflammatory DC in mice with Ab-mediated neutrophil depletion (Gr-1, anti-Ly-6C/G, clone RB6-8C5) and mice treated with isotype control Ab were challenged with killed swollen conidia. (B) Number of lung neutrophils (top panel) and inflammatory DC (bottom panel) in neutropenic and non-neutropenic mice after challenge with killed *Aspergillus* hyphae, using an alternative neutrophil-depleting mAb (anti-Ly-6G, clone 1A8) as compared to animals treated with isotype control mAb. (C) Number of lung inflammatory DC after challenge with live hyphae from an attenuated mutant strain of *Aspergillus* strain of *A. fumigatus* in mice with Ab-mediated neutrophil depletion and mice treated with isotype control Ab. In all panels, data shown represent mean ± SEM; n = 4 for each group, representative data from 2 experiments. *, p < 0.05 comparing trend between the two groups over time.
**Supplemental figure 2:** Accumulation of lung DCs in neutropenic patients with invasive aspergillosis. Representative photomicrographs of the immunolocalization of DCs using CD1a and S100 in normal lung tissue (top panels), neutropenic invasive aspergillosis (middle panels) and non-neutropenic invasive aspergillosis (bottom panels). Insets show control thymic tissue labeled with Cd1a or S100 (left) or respective control Ab (right). Neutrophils are identifiable in lower panels based on their nuclear morphology. All scale bars are 20 μm; original magnifications were 400X for all the panels.
Supplemental figure 3. Blood monocyte analysis in neutropenic and non-neutropenic mice. (A) Representative flow cytometry plots in mice with or without administration of the Gr-1 mAb (anti-Ly-6G/C; clone RB6-8C5) on day 3 following challenge with killed *Aspergillus* hyphae, representative data from 2 experiments, *n* = 4 mice per group. (B) Representative flow cytometry plot and quantitative data in CX3CR1<sup>GFP/+</sup> mice. Monocytes subsets and neutrophils were enumerated following administration of Gr-1 mAb on day -1 in uninfected mice. Data shown represent mean +/- SEM of *n* = 4 mice per group. (C) Representative flow cytometry plots and (D) quantitative data after labeling of circulating monocytes with FITC<sup>+</sup> beads in mice with Ab-mediated neutrophil depletion and mice treated with isotype control Ab on day 3 following challenge with killed *Aspergillus* hyphae. Top panel shows total monocytes based on CD115 and CD11b expression. Bottom panels show the same population gated on FITC<sup>+</sup> beads. Representative data from 2 experiments, *n* = 4 mice per group.