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**Gr-1**<sub>high</sub> Polymorphonuclear Leukocytes and NK Cells Act via IL-15 to Clear Intracellular *Haemophilus influenzae* in Experimental Murine Peritonitis and Pneumonia<sup>1</sup>

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Polymorphonuclear leukocytes (PMNs) can be divided into Gr-1<sup>high</sup> and Gr-1<sup>low</sup> subpopulations, but the differences in the functions of these cells in the host are unknown. This study investigated the roles of these two cell populations in the clearance of an intracellular pathogen (*Haemophilus influenzae*) causing murine peritonitis and pneumonia. Microarray analysis and quantitative real-time PCR analysis of proteose peptone-elicited peritoneal murine PMNs showed that *IL-15* mRNA levels were significantly higher in Gr-1<sup>high</sup> PMNs than in Gr-1<sup>low</sup> PMNs. In addition, IL-15 was produced only by Gr-1-positive PMNs, especially Gr-1<sup>high</sup> PMNs. IL-15 was required for efficient clearance of experimental murine *H. influenzae* pneumonia, as 4 days postinfection lungs from IL-15 knockout mice contained 50- to 100-fold more bacteria than did wild-type mouse lungs. Gr-1 PMN-depleted C57BL/6 mice were more susceptible to *H. influenzae* pneumonia than were Gr-1 PMN replete C57BL/6 mice or C57BL/6 nude mice, demonstrating that Gr-1 PMNs are important in the clearance of intracellular bacteria. IL-15-activated NK cells killed *H. influenzae* in PMNs. Flow cytometry confirmed the expression of CD69 on the cell membrane of IL-15-activated NK cells. Our results show that Gr-1<sup>high</sup> PMNs produce more IL-15 than Gr-1<sup>low</sup> PMNs, and that IL-15-activated NK cells protect against early infection by *H. influenzae*. The Journal of Immunology, 2007, 179: 5407–5414.

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<sup>1</sup>Abbreviations used in this paper: PMN, polymorphonuclear leukocyte; MRSA, methicillin-resistant *Staphylococcus aureus*; KO, knockout; PEC, peritoneal exudate cell; PP, proteose peptone; CBO, cell-bound organism.

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<sup>3</sup>Abbreviations used in this paper: PMN, polymorphonuclear leukocyte; MRSA, methicillin-resistant *Staphylococcus aureus*; KO, knockout; PEC, peritoneal exudate cell; PP, proteose peptone; CBO, cell-bound organism.

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extracellular microorganisms. To test our hypothesis, we analyzed the functional roles of Gr-1<sup>high</sup> and Gr-1<sup>low</sup> PMNs in mouse infections and inflammation.

### Materials and Methods

#### Mice

The experimental protocol was approved by the Ethics Review Committee for Animal Experimentation of the Toho University School of Medicine. Four- to 6-wk-old female C57BL/6 mice and C57BL/6 nude mice were obtained from Charles River Laboratories. Four-week-old female IL-15 knockout (KO) mice were purchased from Taconic Farms. Unless otherwise stated, each experimental group consisted of six mice.

#### Preparation of murine PMNs

Murine peritoneal exudate cells (PECs) were harvested on 3 h after injecting mice i.p. with 3% proteose peptone (PP; 3 ml; Difco) under anesthesia, by peritoneal lavage using 3 ml of warm RPMI 1640 medium (Invitrogen Life Technologies) supplemented with 10% heat-inactivated FCS. The cells washed by centrifugation were counted using a hemacytometer, and were also examined microscopically after staining with May-Grünwald-Giemsa stain. Granulocytes were differentiated from mononuclear cells in counts of 200 cells. PMNs comprised >90% of cells in the suspension. The number of PMNs was calculated by multiplying the total number of PECs by the proportion of PMNs. The proportion of Gr-1<sup>high</sup> and Gr-1<sup>low</sup> PMNs was determined by flow cytometry, as described below, and the absolute numbers of these cells in the washed and resuspended PEC was calculated by multiplying the total number of PMNs by the proportion of each PMN fraction.

#### Peritoneal infection

Mice were injected with <i>Haemophilus influenzae</i> 770235/Phi (24) to produce peritonitis (i.p., 0.5 ml, 1–2 × 10<sup>6</sup> CFU/ml). In this circumstance, <i>H. influenzae</i> is an intracellular organism (3, 25, 26). Ten minutes postinfection, peritoneal lavage (RPMI 1640, 3 ml) was performed in six mice to determine the baseline bacterial concentrations and cell counts. Thirty minutes, and 1 or 3 h postinfection, the PECs were harvested and enumerated as described for the preparation of PMNs; six mice each were sampled at each time point. The bacterial counts in PEC suspension from each sample were assayed by dilution and plating on chocolate agar plates.

#### Preparation of NK cells

Spleen cells were isolated from C57BL/6 mice. Nonadherent cells were collected on a nylon fiber column, and NK cells were negatively sorted by using a mouse NK cell isolating kit and a protocol supplied by the manufacturer (Miltenyi Biotec). The purity of isolated NK cells was >95%, using anti CD49b mAb (DX5 clone; rat IgM; eBioscience).

#### Flow cytometry

Freshly isolated PMNs from PECs were blocked using 2.4G2 hybridoma cell supernatant for 15 min at 4°C; clone 2.4G2 produces rat anti-mouse FcRII/III (CD32) mAb (27). The PMNs were then stained with FITC-conjugated anti-Gr-1 mAb (clone: RB6-8C5; BD Pharmingen) for 30 min at 4°C (28). The stained cells were analyzed using FACS Calibur (BD Pharmingen) and were sorted according to the content of Gr-1 Ag using a BD FACS Aria Cell Sorter (BD Pharmingen). PMNs were defined as being Gr-1<sup>high</sup> or Gr-1<sup>low</sup> cells based on anti-Gr-1 fluorescence intensity staining, with cells having a fluorescence intensity of >600 intensity units in Gr-1<sup>high</sup> cells having a fluorescence intensity between 20 and 500 intensity units. The purity of PMNs was checked by May-Grünwald-Giemsa stain.

For intracellular IL-15 staining, PECs were separated by Lympholyte-M (Cedarlane Laboratories). The separated granulocytes were treated with LPS (1 µg/ml) and rGM-CSF (100 U/ml; PeproTech) for 20 h at 37°C; then, brefeldin A (5 µg/ml; Sigma-Aldrich) was added for an additional 4 h. Cells were stained with FITC-conjugated anti-Gr-1 mAb, and followed by 4% paraformaldehyde fixation and 0.1% saponin permeabilization. After blocking, the cells were stained with biotin-conjugated anti-IL-15 mAb (PeproTech) at 4°C for 30 min, followed by the addition of streptavidin-allophycocyanin (BD Pharmingen). Cell surface IL-15 expression was also detected using FITC-conjugated anti-IL-15 mAb and a reporter dye and TAMRA as a quencher dye (29). The gene expression levels of cytokine IL-15 of mouse PMNs were quantified using the ABI7300 Real-Time PCR System (Applied Biosystems). cDNAs were amplified with TaqMan probes using Platinum Quantitative PCR SuperMix-UDG with the ROX kit (Invitrogen Life Technologies). The experimental conditions were described previously (29). IL-15 mRNA expression levels of mouse PMNs were normalized relative to β-actin gene expression levels. Fold differences in IL-15 mRNA levels between Gr-1<sup>high</sup> and Gr-1<sup>low</sup> PMNs were determined using Sequence Detection System software (Applied Biosystems).

#### Experimental bronchopneumonia caused by <i>H. influenzae</i>

The difference in severity of bronchopneumonia caused by <i>H. influenzae</i> among C57BL/6, C57BL/6 nude, and IL-15 KO mice (12 animals/group) was examined using the partially modified mouse pneumonia model of cell-bound organisms (CBOs) (3). Cell-bound organisms were internalized by the fetal lung cells, but are not killed by them, and are protected from the bactericidal action of serum factors (3). This study differed from the previous report in that C57BL/6, C57BL/6 nude, and IL-15 KO mice were used rather than Slc/ICR mice and the animals were not pretreated with formalin. Briefly, CBOs are instilled intranasally into anesthetized mice and, 4 days later, the mice are euthanized to determine the lung bacterial load (3). The delivered and retained bacterial doses were substantially lower than the retained dose because not all the inoculum enters the lung. Four mice from each group were used to determine the proportion of Gr-1<sup>high</sup> to Gr-1<sup>low</sup> PMNs in the abdominal cavity by flow cytometry as described above. The remaining eight mice from each group were used for counting viable organisms in the infected tissues. The lower limit of detection of <i>H. influenzae</i> in lung was 100 CFU/animal, due to the need to dilute growth-inhibitory tissues before plating.
Gr-1-positive PMNs were depleted in some mice by the administration of rat anti-mouse Gr-1 mAb (R&D Systems) or normal rat IgG (Sigma-Aldrich) to C57BL/6 mice (0.2 mg, i.p.) 1 day before infection; the dose was selected based on a previous report (30). The normal rat IgG possessed no H. influenzae-agglutinating Abs. Immune reconstitution of some IL-15 KO mice was performed by injecting them with PECs (i.p., 2 × 10^5 cells) from C57BL/6 mice or IL-15 KO mice 3 h before infection.

**Bacterial killing activity by NK cells following treatment with IL-15**

To determine the ability of NK cells to kill H. influenzae phagocytosed by PMNs, NK cells were added to the phagocytosed bacteria in quintuplicate and viable bacterial counts were determined at selected times. PECs were obtained from C57BL/6 mice as described above, and then resuspended in RPMI 1640. The PECs were incubated (35°C in 5% CO2 for 1 h) with an equal volume of bacteria. Gentamicin (100 mg/L) was added for 30 min to kill extracellular bacteria, then removed by washing three times with RPMI 1640. The phagocytosed bacteria were dispensed into 12-well tissue-culture trays at a final bacterial concentration of 5 × 10^5 CFU/ml, and a final PEC concentration of 4 × 10^5 cells/ml, in a 1-ml volume. NK cells (5 × 10^5 cells/ml final concentration), IL-15 (20 ng/ml final concentration), both Gr-1high:Gr-1low ratio of PMNs following infection with H. influenzae organisms in C57BL/6 mouse peritoneal lavage fluid decreased to 28 and 7%, 1 and 3 h postinfection, respectively, of the 10-min postinfection count (4.8 × 10^5 ± 2.9 × 10^5 CFU/animal) (Fig. 1A). C57BL/6 nude mice were able to clear i.p. H. influenzae as well as C57 BL/6 mice; 1 and 3 h after infection, the average counts of 2.3 ± 0.5 × 10^5 CFU/animal.

**Results**

**Relationship between viable organism counts and altered Gr-1high:Gr-1low ratio of PMNs following infection with H. influenzae**

To determine the role of Gr-1-positive PMNs in bacterial infection, we examined bacterial clearance, and the number of Gr-1high and Gr-1low PMNs, in the abdominal lavage fluid of mice with experimental bacterial peritonitis. The average number of viable H. influenzae organisms in C57BL/6 mouse peritoneal lavage fluid decreased to 28 and 7%, 1 and 3 h postinfection, respectively, of the 10-min postinfection count (4.8 × 10^5 ± 2.9 × 10^5 CFU/animal) (Fig. 1A). C57BL/6 nude mice were able to clear i.p. H. influenzae as well as C57 BL/6 mice; 1 and 3 h after infection, the average peritoneal lavage fluid bacterial counts were 33 and 2%, respectively, of the 10-min postinfection count (6.5 × 10^5 ± 3.05 × 10^5 CFU/animal).

The total number of peritoneal PMNs increased ~4-fold from 10 min to 3 h following infection with H. influenzae to maximum average counts of 2.3 × 10^6 cells/lavage (p < 0.05, 10 min baseline vs 3 h counts for each of the two different mouse strains) (Fig. 1B). The bulk of the recruited PMNs were Gr-1 high PMNs, with an average of 80% of PMNs being Gr-1 cells 10 min after infection, and 99% being Gr-1 PMN cells 3 h after infection. Over the 3-h observation period, the proportion of PMNs that were Gr-1high cells increased markedly; ~10% of PMNs were Gr-1high cells at baseline, whereas at 3 h, this proportion increased to 59–66% (p < 0.01, Fisher exact test). The numbers of Gr-1low PMNs in
mice infected with *H. influenzae* did not change significantly after inoculation (*p* > 0.05).

**Gene expression profiling with cDNA microarray hybridization and quantitative real-time PCR**

To investigate the mechanism of action of Gr-1^high^ PMNs against intracellular organisms, microarray analysis was used to determine the gene expression of various cytokines in PP-elicited peritoneal Gr-1^high^ and Gr-1^low^ PMNs. Using May-Grünwald-Giemsa staining, 99% of the flow-cytometry purified Gr-1^high^ PMNs were PMNs, while the Gr-1^low^ PMN cell fraction was composed of 90% PMNs and 10% monocytes. The ratios of Gr-1^high^:Gr-1^low^ PMN mRNA levels for various cytokines is shown in Table I. IL-15 mRNA levels were 14.73 (95% confidence interval 8.2 to 21.2) times greater in Gr-1^high^ PMNs than in Gr-1^low^ PMNs. IL-1^β^ was the only other measured cytokine that was expressed significantly more in Gr-1^high^ PMNs than in Gr-1^low^ PMNs, with a 3.05-fold (95% confidence interval 2.3 to 3.8) mRNA level difference detected. Thus, we were interested in the IL-15 gene expression ratio between Gr-1^high^ and Gr-1^low^ PMNs. Quantitative real-time PCR showed that the mRNA expression level of IL-15 in Gr-1^high^ PMNs was ~28-fold higher than that of Gr-1^low^ PMNs, which were expressed at basal levels, thus confirming the results of microarray analysis.

**Detection of intracellular production of IL-15 and cell surface-bound IL-15**

We next investigated whether and which Gr-1 PMNs produce IL-15, using flow cytometry and staining of PP-elicited PECs for the cellular presence of IL-15 and Gr-1 Ags. Gr-1 PMNs cultured without LPS produced little IL-15, with only 0.26% of Gr-1 cells

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**Table I. Cytokine and cytokine receptor gene expression in Gr-1^high^ and Gr-1^low^ PMNs**

<table>
<thead>
<tr>
<th>Cytokine</th>
<th>Gr-1^high^-Gr-1^low^ PMN expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL-1α</td>
<td>0.80 ± 0.22</td>
</tr>
<tr>
<td>IL-1β</td>
<td>3.05 ± 0.47</td>
</tr>
<tr>
<td>IL-2</td>
<td>1.87 ± 0.27</td>
</tr>
<tr>
<td>IL-4</td>
<td>0.85 ± 1.49</td>
</tr>
<tr>
<td>IL-5</td>
<td>0.88 ± 0.33</td>
</tr>
<tr>
<td>IL-6</td>
<td>0.82 ± 0.74</td>
</tr>
<tr>
<td>IL-7</td>
<td>0.38 ± 0.28</td>
</tr>
<tr>
<td>IL-9</td>
<td>0.98 ± 0.75</td>
</tr>
<tr>
<td>IL-10</td>
<td>0.47 ± 0.21</td>
</tr>
<tr>
<td>IL-11</td>
<td>0.34 ± 0.42</td>
</tr>
<tr>
<td>IL-12</td>
<td>0.55 ± 0.06</td>
</tr>
<tr>
<td>IL-15</td>
<td>14.73 ± 4.09</td>
</tr>
<tr>
<td>IL-16</td>
<td>0.25 ± 0.09</td>
</tr>
<tr>
<td>IL-17</td>
<td>0.39 ± 0.25</td>
</tr>
<tr>
<td>IL-18</td>
<td>1.34 ± 1.40</td>
</tr>
<tr>
<td>CCL2</td>
<td>0.20 ± 0.04</td>
</tr>
<tr>
<td>CCL3</td>
<td>1.23 ± 0.32</td>
</tr>
<tr>
<td>IL-2 receptor</td>
<td>0.83 ± 0.39</td>
</tr>
<tr>
<td>IL-15α receptor</td>
<td>0.30 ± 0.25</td>
</tr>
</tbody>
</table>

* Data are mean ± SD; *n* = 4–5 in each group.
positive for IL-15, with a geometric mean value of 705 fluorescence intensity units in those PMNs (Fig. 2B). In contrast, LPS stimulation of PMNs increased the proportion of IL-15-positive Gr-1-positive PMNs to 26.8% with a geometric mean value of 738 fluorescence intensity units (Fig. 2C). In the stimulated and non-stimulated PMNs, 89 and 92% of IL-15-positive Gr-1 PMNs were Gr-1<sup>high</sup> cells, respectively, and the level of IL-15 production correlated with the number of Gr-1<sup>high</sup> PMNs. Furthermore, flow cytometry with staining for cell surface IL-15 showed that resting PMNs did not secrete IL-15. In contrast, LPS-activated PMNs were strongly positive for surface-expressed IL-15 (Fig. 2D).

Role of IL-15 and Gr-1 PMNs in experimental H. influenzae murine pneumonia

To determine the role of IL-15 and Gr-1 PMNs in host defenses against H. influenzae, we determined the pulmonary clearance of H. influenzae 4 days after experimental induction of H. influenzae pneumonia in mice with and without functional IL-15 or Gr-1 PMNs (Fig. 3A).

C57BL/6 mice and C57BL/6 nude mice were resistant to H. influenzae infection, based on the lack of detectable infective organisms in the lungs of all eight mice. H. influenzae infection of C57BL/6 mice that were not pretreated with normal rat IgG gave results identical with the IgG-pretreated mice (data not shown). In contrast, seven of eight C57BL/6 mice depleted of circulating Gr-1 PMNs failed to clear lung H. influenzae, with average bacterial counts of 157 CFU/lung, demonstrating that Gr-1 PMNs play a role in clearance of the bacterium from the lungs (p < 0.01, χ<sup>2</sup> test, for comparison of Gr-1-depleted vs non-Gr-1-depleted C57BL/6, or C57BL/6 nude, mice).

IL-15 KO mice had a severe immune defect and were unable to clear H. influenzae from the lungs; mean bacterial counts were 8 × 10<sup>3</sup> CFU/lung (Fig. 3A). This immune defect was rescued by the i.p. administration of PP-elicited PECs obtained from C57BL/6 mice; mean lung bacterial counts were 197 CFU/lung (p < 0.05 vs one-way ANOVA, Tukey comparison test, vs IL-15 KO mice). IL-15 KO mice injected with homologous PECs failed to clear lung bacteria.

Flow cytometric analysis of PP-elicited PECs obtained from C57BL/6 mice 1 day after administration of anti-mouse Gr-1 mAb confirmed the absence of Gr-1 PMNs in the PECs (Fig. 3B). The relative ratios of Gr-1<sup>high</sup> to Gr-1<sup>low</sup> in PP-elicited PECs of IL-15 KO mice were similar to those found in C57BL/6 mice. The ratios of Gr-1<sup>high</sup>:Gr-1<sup>low</sup> PMNs in C57BL/6 and IL-15KO mice were 1.18 and 1.40, respectively. As expected, administration of i.p. PECs to IL-15 KO mice increased the numbers of i.p. Gr-1 cells of both types. The ratio of Gr-1<sup>high</sup>:Gr-1<sup>low</sup> PMNs in the PEC-recipient IL-15 KO mice was 0.97. The relative populations of Gr-1<sup>high</sup> and Gr-1<sup>low</sup> PECs in C57BL/6 nude mice were similar to those in the wild-type background C57BL/6 mice strain (data not shown).

Effect of exogenous IL-15 on NK cell killing of phagocytosed H. influenzae

To determine whether exogenous IL-15 promotes NK cell-mediated killing of phagocytosed H. influenzae in excess of the IL-15 produced by the phagocytic cells, the effect of exogenous IL-15 on bacterial killing was determined. Also, to determine whether the NK cell bactericidal effect was IFN-γ dependent, the effect of IFN-γ Ab addition on the NK bactericidal effect was examined. Incubation of the phagocytosed bacteria with RPMI 1640 alone, or the culture medium with IL-15, had no significant effect on bacterial concentrations (Fig. 4). In contrast, addition of NK cells to the phagocytosed bacteria resulted in a 1–3 log<sub>10</sub> decrease in bacterial concentration over 2–5 h (p < 0.001). Addition of IL-15 to the NK cells reduced the bacterial concentration by half.

FIGURE 4. NK cell killing of phagocytosed H. influenzae. NK cells were added to H. influenzae phagocytosed by PECs in the presence of IL-15, IFN-γ Ab, or no additives, for 2 or 5 h. Controls included phagocytosed bacteria incubated with just IL-15 or tissue-culture medium alone; n = 5 for each point. The group mean and value for each data point is shown. The table shows the results of one-way ANOVA analysis of the data, with Tukey post-hoc comparisons.

FIGURE 5. Expression of CD69 on the membrane of NK cells cocultured with Gr-1<sup>high</sup> or Gr-1<sup>low</sup> PMNs. NK cells were stained with FITC-conjugated anti-CD69 mAb (eBioscience), and allophycocyanin-conjugated anti-CD49b (eBioscience). A, Isotype control containing Gr-1<sup>high</sup> and Gr-1<sup>low</sup> PMNs. B, NK cells cocultured with Gr-1<sup>high</sup> and Gr-1<sup>low</sup> PMNs, without stimulation of the PMNs with LPS. C, NK cells cocultured with Gr-1<sup>low</sup> PMNs stimulated with LPS. D, NK cells cocultured with Gr-1<sup>high</sup> PMNs stimulated with LPS.
of that observed for the NK cells alone at 2 h ($p < 0.05$), but after a 5-h incubation no added benefit of IL-15 was apparent. Further addition of anti-IFN-γ to the IL-15 and NK cells resulted in decreased bacterial killing over that seen with combined IL-15 and NK cells ($p < 0.05$ at 2 and 5 h). These results suggest that the phagocytic cells provide sufficient IL-15 to mediate NK cell killing of *H. influenzae*, and that this process is to some degree IFN-γ dependent.

**Day 69 expression on NK cells by stimulation of PMNs**

To confirm that NK cells are activated by Gr-1$^{\text{high}}$ cells, NK cells were cocultured with Gr-1$^{\text{positive}}$ PMNs purified to subtype fractions by flow cytometry. NK cell activation was detected by flow cytometric analysis of CD69 expression. As shown in Fig. 5D, the percentage of CD69-expressing NK cells cocultured with LPS-stimulated Gr-1$^{\text{high}}$ PMNs was 22.8%, but only 0.2% when the NK cells were cocultured with LPS-stimulated Gr-1$^{\text{low}}$ PMNs (Fig. 5C). The latter value was the same for NK cells that were cocultured with non-LPS-stimulated Gr-1$^{\text{high}}$ and Gr-1$^{\text{low}}$ cells (Fig. 5B). These results confirm that stimulated Gr-1$^{\text{high}}$, but not Gr-1$^{\text{low}}$, PMNs activate NK cells.

**Discussion**

We conducted a series of experiments using PMNs harvested from the peritoneum of mice inoculated i.p. with bacteria, as a model of PMN migration to sites of infection. Using this model, we classified PMNs into two groups (Gr-1$^{\text{high}}$ and Gr-1$^{\text{low}}$ PMNs) based on the quantity of Gr-1 translated (23). It is well-known that anti-Gr-1 mAb strongly reacts with Ly-6G, and this mAb also reacts with another Ly-6 family molecule, Ly-6C (31). Ly-6G is expressed on PMNs while Ly-6C is expressed on PMNs, monocytes, and other cells (23, 32). In the present study, the purity of Gr-1$^{\text{high}}$ PMNs was very high while that of Gr-1$^{\text{low}}$ PMNs was lower than Gr-1$^{\text{high}}$ PMNs. Combined together, these data indicate that the Gr-1$^{\text{high}}$ PMN preparation contained no other cells, while Gr-1$^{\text{low}}$ PMN preparations contained monocytes. Under these conditions, we investigated the functional differences between Gr-1$^{\text{high}}$ and Gr-1$^{\text{low}}$ PMNs.

In response to i.p. infection, Gr-1$^{\text{high}}$ cells rapidly became the predominant type of PMNs in the peritoneal exudate, as has been previously shown for the response to i.p. LPS injection (23). These cells, and presumably other immune effectors, were able to control *H. influenzae* peritonitis. The rate of fall of *H. influenzae* bacterial counts in C57BL/6 nude mice was the same as in C57BL/6 mice, and in addition the migrating numbers of total PMNs, Gr-1$^{\text{high}}$ and Gr-1$^{\text{low}}$ PMNs were not apparently different between the two strains of mice. Combined together, these results suggest that Gr-1$^{\text{high}}$ cells might have other role(s) apart from the phagocytosis of intracellular bacteria.

As this killing of intracellular bacteria may involve IL-15, we determined whether Gr-1 subtype PMNs make IL-15, and whether the IL-15 is surface expressed. First, we compared mRNA content in Gr-1$^{\text{high}}$ and Gr-1$^{\text{low}}$ PMNs by microarray analysis. The results showed that *IL-15* gene expression in Gr-1$^{\text{high}}$ PMNs was significantly greater than in Gr-1$^{\text{low}}$ PMNs. Moreover, quantitative real-time PCR confirmed that mRNA content in Gr-1$^{\text{high}}$ PMNS was significantly higher than in Gr-1$^{\text{low}}$ PMNs. Furthermore, both intracellular and surface IL-15 protein was detected mainly in Gr-1$^{\text{high}}$ PMN by flow cytometry. Taken together, the results indicate that Gr-1$^{\text{high}}$ PMNs produce IL-15, and that such production is higher than in Gr-1$^{\text{low}}$ PMNs.

The contribution of Gr-1 PMNs to bacterial killing was determined in a murine pneumonia model. These studies showed that Gr-1 cells played an important role in bacterial killing, based on the decreased lung clearance of the bacteria in mice depleted of Gr-1 PMNs. Furthermore, these studies showed that IL-15 plays a dominant role in the control of this pneumonia, based on the high bacterial load in the lungs of IL-15 KO mice, and the clearance of these bacteria when the IL-15 deficit was rescued by C57BL/6 PECs. Because IL-15 is made by activated Gr-1$^{\text{high}}$ cells, it is likely that Gr-1$^{\text{high}}$ cells modulate intracellular bacterial killing via the production of IL-15, and perhaps other cytokines. A previous report described that IL-15 KO mice are susceptible to vaccinia virus (33). Taken together, these data indicate that PMNs among the PECs transplanted from C57BL/6 mice can produce IL-15, which enhances NK-induced killing activity in IL-15 KO mice and thereby host defenses against *H. influenzae*. These observations provide good evidence that PMNs, which produce IL-15, play an important role against intracellular pathogen by activating NK cells to enhance their killing activity.

We did not determine whether the C57BL/6 PECs used to rescue the *H. influenzae*-infected IL-15 KO mice acted by migration from the peritoneum to the lung. We do know that after i.p. administration of LPS, peritoneal Gr-1 PMNs migrate from the peritoneum to the mesenteric lymph nodes (23), which establishes the possibility of further migration of these cells to the inflamed lung via the lymphatic system. Until this question is studied directly, the mechanism by which peritoneal PMNs rescued the infected IL-15 KO mice is uncertain.

NK cells are essential players in host defenses against intracellular pathogens (8, 34), and were required for the in vitro killing of intracellular *H. influenzae* in our experiments. We believe that it is highly likely that NK cells play a similar role in vivo, in both the lung and peritoneum, but only experiments with *H. influenzae*-infected NK cell-deficient mice would answer this question definitively.

The relative role of NK cells and IL-15 in killing intracellular *H. influenzae* was determined by in vitro experiments (Fig. 4). Addition of IL-15 to PECs containing the bacteria had no effect on bacterial killing, whereas the addition of NK cells to the PECs resulted in substantial bacterial killing. Addition of IL-15 to the NK cells had a minor effect on the bacterial killing produced by the NK cells alone, significant only at 2 h postincubation, but not at the 5-h time point. These paradoxical findings are best explained by sufficient IL-15 production by the Gr-1$^{\text{high}}$ cells present in the PECs used to ingest the bacteria. Previous studies reported the up-regulation of *IL-15* mRNA in mouse cells at 3 h postinfection (35, 36). Taken together, these findings indicate that PMNs have already started producing IL-15 when PMNs and native NK cells were mixed. In this regard, there are two isoforms of IL-15; one is the secretable isoform and the other is the nonsecretable one (36). The former isoform exists on the cell surface and exhibits various biological effects. The latter IL-15 is expressed in the nucleus and regulates IL-15 production by posttranscriptional control (37). Another report also described IL-15 binding to IL-15Rα on the cell surface (38). In our study, IL-15Rα mRNA was expressed in both Gr-1$^{\text{high}}$ and Gr-1$^{\text{low}}$ PMNs by microarray analysis. With regard to the receptor, we cannot exclude the possible involvement of the IL-2R in this process because IL-2R mRNA was detected by microarray analysis and previous reports described IL-15 binding to not only IL-15Rα but also IL-2R (39). Moreover, the present study could not detect any secreted IL-15 by LPS-stimulated PECs by ELISA. The instructions provided by the manufacturer stipulated that the detection limit of this method is 100 pg/ml. It seems that most of the secreted IL-15 binds to IL-15Rα (or IL-2Rα) on the surface of PMNs that phagocyte *H. influenzae* organisms, resulting in activation of native NK cells.
The in vitro bacterial killing experiments did not directly determine whether isolated Gr-1<sup>high</sup> cells were the sole contributors to <i>H. influenzae</i> killing by NK cells, or whether both Gr-1<sup>high</sup> and Gr-1<sup>low</sup> PMNs are important for this effect. Unfortunately, we were unable to purify sufficient numbers of functional Gr-1 PMN subfractions to determine this directly, as the cells purified by flow cytometry were poorly functional. However, indirect evidence exists that NK-directed killing of intracellular <i>H. influenzae</i> is dependent on Gr-1<sup>high</sup>, but not Gr-1<sup>low</sup>, PMNs. This indirect evidence includes the fact that IL-15 is expressed almost exclusively by Gr-1<sup>high</sup>, but not Gr-1<sup>low</sup>, PMNs. The results of our in vitro and in vivo studies thus allow us to propose the following schema on the killing mechanism of Gr-1<sup>high</sup> PMNs in the innate immune response against intracellular bacteria.

Our results demonstrate that intracellular <i>H. influenzae</i> is killed by interaction of IL-15-activated NK cells and PMNs (3, 25, 26). With regard to the mechanism involved in killing of intracellular <i>H. influenzae</i>, anti-IFN-γ mAb only partially protected the organisms from the bactericidal activity of IFN-γ, although IFN-γ plays a significant role against intracellular pathogen infection. Previous work demonstrated that human PMNs stimulated by a combination of LPS, IL-12, and TNF-α secrete IFN-γ (40). These results suggest that it is possible that IFN-γ had already been produced and/or expressed before addition of anti-IFN-γ mAb. It has been reported that the production of this cytokine from NK cells is enhanced by synergistic actions of IL-15 and IL-12 (39). The killing action of NK cells against intracellular pathogens is not mediated through only IFN-γ but also other cytokines like TNF-α (41, 42). These results suggest that a cytokine(s) other than IFN-γ is also intimately associated with killing of intracellular <i>H. influenzae</i> in PMNs.

The results of our in vitro and in vivo studies thus allow us to propose the following schema on the killing mechanism of Gr-1<sup>high</sup> PMNs (Fig. 6). IL-15 KO mice are susceptible to <i>H. influenzae</i> infection, although the wild-type C57BL/6 mice are resistant. Thus, IL-15 enhances PMN activity via the autocrine system and activates NK cells by binding to IL-15Rα and/or IL-2R on the surface of NK cells and Gr-1<sup>high</sup> PMNs. As discussed above, IL-15 plays a pivotal role in the activation and survival of NK cells via the sandwich system because most IL-15 was sandwiched between Gr-1<sup>high</sup> PMNs and NK cells. Secretion of IL-15 by Gr-1<sup>high</sup> PMNs results in further activation of NK cells. Activated NK cells also produce IFN-γ, and other cytokines like TNF-α are also involved in killing intracellular pathogens. We propose the term “positive feedback loop” for this overall bactericidal system. Finally, PMNs, which form the first line of defense in the inflammatory response against invading pathogens, play the most important role in innate immunity against infections of both extracellular and intracellular pathogens.

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References


