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IL-1 enhances expansion, effector function, tissue localization, and memory response of antigen-specific CD8 T cells

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Here, we show that interleukin-1 (IL-1) enhances antigen-driven CD8 T cell responses. When administered to recipients of OT-I T cell receptor transgenic CD8 T cells specific for an ovalbumin (OVA) peptide, IL-1 results in an increase in the numbers of wild-type but not IL1R1$^{-/-}$ OT-I cells, particularly in spleen, liver, and lung, upon immunization with OVA and lipopolysaccharide. IL-1 administration also results in an enhancement in the frequency of antigen-specific cells that are granzyme B^{+}, have cytotoxic activity, and/ or produce interferon γ (IFN-γ). Cells primed in the presence of IL-1 display enhanced expression of granzyme B and increased capacity to produce IFN-γ when rechallenged 2 mo after priming. In three in vivo models, IL-1 enhances the protective value of weak immunogens. Thus, IL-1 has a marked enhancing effect on antigen-specific CD8 T cell expansion, differentiation, migration to the periphery, and memory.

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Abbreviation used: UBC-GFP, C57BL/6 mice that express GFP under the direction of the ubiquitin C promoter.

A major goal in developing protective immune responses is to obtain robust CD8 T cell expansion, effector differentiation, and memory generation using simple protein antigens as immunogens. We have previously reported that IL-1 strikingly enhances CD4 T cell responses when administered to mice during the period immediately after priming (Ben-Sasson et al., 2009), and thus wished to determine whether it would have a comparable effect on CD8 cells.

IL-1's effect on CD4 T cells was observed in vivo, was direct, and largely reflected enhanced survival rather than increased proliferative rate. Furthermore, when wild-type and IL1R1$^{-/-}$ CD4 TCR transgenic T cells specific for an OVA peptide were jointly transferred to IL1R1$^{-/-}$ recipients, only the wild-type cells responded to IL-1 with enhanced antigen-driven expansion (Ben-Sasson et al., 2009). This result indicates that IL-1 acts directly on the antigen-responding CD4 cell. Of a wide range of cytokines, including IL-2, -4, -6, -7, -9, -15, -18, -21, and -33, as well as TNF, only IL-1α and IL-1β showed such profound enhancement activity (Ben-Sasson et al., 2009). The IL-1 effect was observed in both IL-6– and in CD28-deficient recipients. Neutralizing IL-1 diminished responses to protein plus LPS by ∼60%, implying that endogenous IL-1 enhanced antigen-specific CD4 T cells responses.

IL-1 strikingly enhanced antigen-driven expansion in vivo and enhances in vitro expansion of Th17 cells, which express large amounts of IL-1R1 (Guo et al., 2009; Lee et al., 2010), but it had no detectable effect on in vitro expansion of Th1 or Th2 cells. However, administering IL-1 in vivo during CD4 T cell priming, while increasing the proportion of Th17 cells among responders, also causes striking expansion of both IFN-γ and IL-4–producing cells (Ben-Sasson et al., 2009).

S. Ben-Sasson and A. Hogg contributed equally to this paper.

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The role of IL-1 in regulating CD8 T cell responses has not been clear. Some have reported that IL-1 enhances in vitro expansion of CD8 cells responding to polyclonal stimulants (Mizuochi et al., 1988; Hope et al., 2001). Where studied, it appears that the in vitro effects of IL-1 have been limited to cells expressing large amounts of IL-1R1 (Klarnet et al., 1989; Nagoya et al., 1994). In one instance, enhanced capacity to produce IFN-γ was observed (Fischer et al., 1990). However, others have failed to observe IL-1–mediated enhancement of in vitro TCR-driven CD8 T cell expansion (Halvorsen et al., 1987; Panzer et al., 1990; Curtsinger et al., 1999).

IL1R1$^{-/-}$ mice have been reported to have diminished CD8 responses to infection with LCMV (Joeckel et al., 2012), influenza (Ichinohe et al., 2009), *Mycobacterium tuberculosis* (Fremond et al., 2007), vaccinia (Staib et al., 2005), and certain tumors (Elkabets et al., 2009; Ghiringhelli et al., 2009). In addition, Myd88$^{-/-}$ and/or IRAK-4$^{-/-}$ mice, both of which have defective IL-1–mediated signaling, have impaired responses to LCMV (Lye et al., 2008), vaccinia (Zhao et al., 2009), and malaria (Gowda et al., 2012). CD8 T cells specific for LCMV appearing in infected IL1R1$^{-/-}$ mice were reported not to express granzyme B (Joeckel et al., 2012). Furthermore, vaccinia that fail to display a virally encoded soluble IL-1β receptor elicit greater protection and improved CD8 memory responses (Staib et al., 2005) implying that neutralizing endogenous IL-1 normally limits immunity to vaccinia. However, in these infection models, the cell target of IL-1 was not established.

We sought to determine the importance of IL-1 in in vivo priming and differentiation of antigen-specific CD8 T cells. To that end, we transferred WT OT-I cells to WT or IL1R1$^{-/-}$ C57BL/6 recipients that were then immunized with OVA plus LPS. IL-1R1$^{-/-}$ recipients showed increases of WT OT-I T cells comparable to WT recipients in response to IL-1 in lymph nodes and spleen, but not in liver and lung. IL-1 administration also resulted in a striking enhancement in the frequency of granzyme B^{+} cells, in cytotoxic activity, and in cells that produced IFN-γ in response to PMA and ionomycin. Mice primed in the presence of IL-1 developed secondary CD8 T cells responses marked by enhanced expression of granzyme B and augmented capacity to produce IFN-γ when rechallenged 2 mo after priming. In three in vivo models, IL-1 enhanced the protective value of weak immunogens. Thus, IL-1 has a striking effect on enhancing antigen-specific CD8 T cell expansion, differentiation, migration to the periphery, and memory.

RESULTS

IL-1 acts on CD8 T cells to enhance antigen-driven expansion

To test the effect of IL-1 on antigen-driven expansion of CD8 T cells, we transferred 10^4 lymph node cells from B6 OT-I TCR transgenic Rag1$^{-/-}$ donors to C57BL/6 mice that express GFP under the direction of the ubiquitin C promoter (UBC-GFP mice). The recipients were immunized subcutaneously with 1 mg OVA together with 25 μg LPS. They did or did not receive IL-1 for 5 d (2 μg/day) beginning 24 h after immunization. IL-1 administration caused a striking increase in the frequency of transgenic cells at 7 d after immunization (Fig. 1 A). In 9 consecutive experiments, the increase caused by IL-1 in OT-I cell numbers 7 d after immunization was 20.5-fold in the lymph node and 63.6 in the spleen (Fig. 1 B). When CD45.1 OT-I cells were transferred into wild-type or IL-1R1$^{-/-}$ CD45.2 recipients, the degree of IL-1–mediated enhancement of antigen-driven expansion was similar in the two sets of recipients in both lymph nodes and spleens (Fig. 1 C), implying that the bulk of the IL-1–mediated enhancement of antigen-stimulated CD8 T cell priming required the expression of the IL-1 receptor on the antigen-responding CD8 T cells and that IL-1 receptor expression on other cells played only a limited role in enhanced expansion in lymph node and spleen.

IL-1–mediated enhancement of OT-I expansion does not require CD4 T cells

OT-I cells were transferred into Rag1$^{-/-}$ B6 recipients. 9 d later, mice were immunized with OVA plus LPS with or without IL-1. In unimmunized mice, IL-1 alone caused no enhancement in OT-I number. The administration of IL-1 to mice treated with OVA plus LPS caused a substantial increase in frequency of OT-I cells in lymph node and spleen, indicating that in the total absence of CD4 T cells, IL-1 could enhance antigen-driven OT-I expansion (Fig. 2 A). When OT-I cells were transferred to IL-1R1$^{-/-}$ B6 recipients, the IL-1–mediated increase in their response to OVA plus LPS was not enhanced by the co-transfer of a similar number of CD4 OT-II cells (Fig. 2 B). Thus, IL-1 enhancement of antigen-driven expansion of CD8 T cells 1 wk after immunization does not depend upon "help" from CD4 T cells. It should be noted that in both models, the response of OT-I cells to OVA plus LPS, without IL-1, was also not enhanced by the presence of CD4 T cells.

IL-1 causes a massive increase in the frequency of OT-I cells in liver and lung in response to immunization

OT-I cells were transferred into UBC-GFP recipients; the mice were immunized with OVA plus LPS with or without IL-1. At 7 d after immunization (Fig. 3 A), a low frequency of OT-I cells were found in the lymphocyte-enriched fractions of lung (0.7%) and liver (4.7%). The addition of IL-1 caused a massive increase in the frequency of OT-I cells in both organs. Indeed, OT-I cells were now the great majority of total CD8 cells and made up 56% of all cells in the lymphocyte-enriched fractions in liver and 27% in lung.

IL-1 also resulted in an increase in the total number of cells in the liver and lung lymphocyte-enriched Percoll bands (unpublished data). Taking into account the increase in the percentage of OT-I cells and the increase in total cells in the lymphocyte-enriched fraction, the absolute numbers of OT-I cells in the liver increased by 68-fold; in the lung, the increase was 118-fold (Fig. 3 B).

As already noted, the IL-1–mediated increase in numbers of responding OT-I cells in lymph node and spleen was

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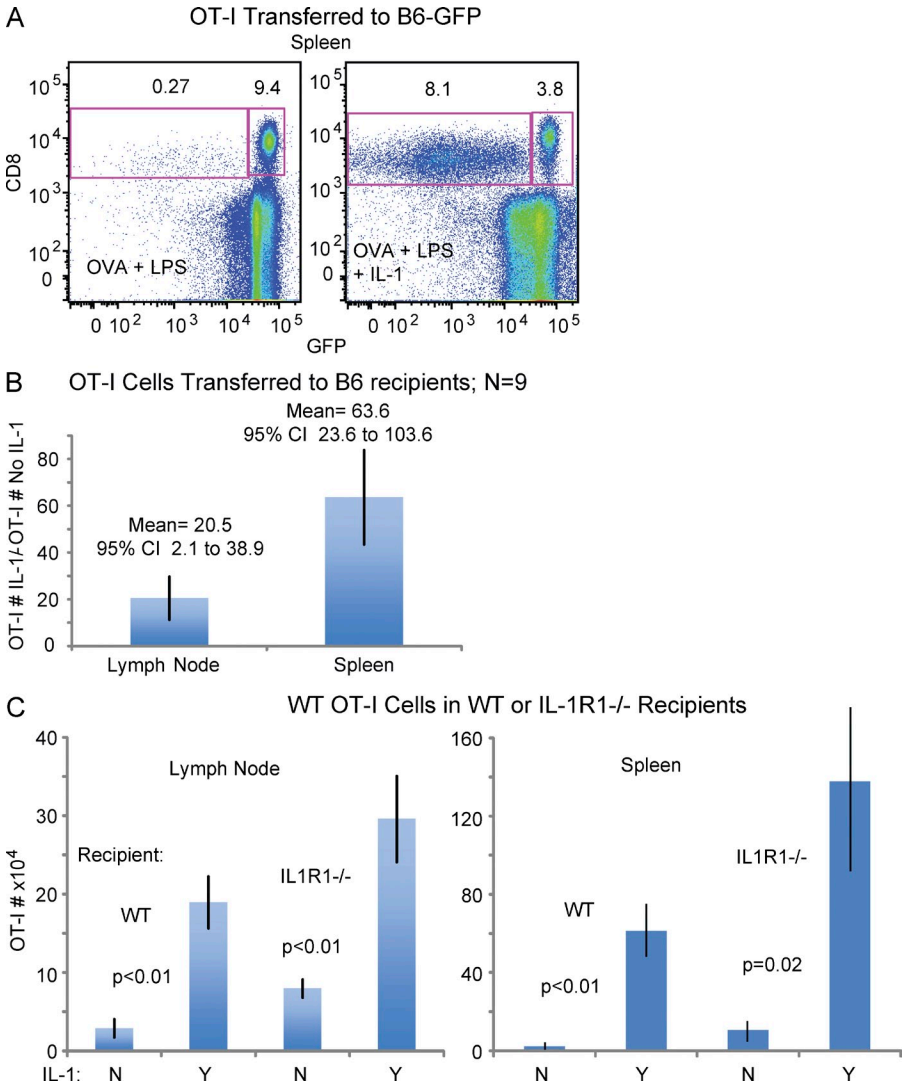

Figure 1. IL-1 enhances antigen-driven CD8 T cell responses. (A) 10^4 OT-I cells were injected into UBC-GFP C57BL/6 mice. Mice were immunized subcutaneously with LPS with or without IL-1β. 7 d after priming, the frequency of splenic GFP^- $CD8^+$ OT-I cells was determined. Results are presented as the percentage of cells in total splenic lymphocytes. (B) 1–3 × 10^4 OT-I cells were injected into UBC-GFP, CD45.1, or CD90.1 C57BL/6 mice. Mice were immunized with OVA plus LPS with or without IL-1. 7 d after priming, the percentage and total number of transferred OT-I cells in the organs was determined. Data are the mean ratios of the number of OT-I cells in mice immunized with OVA plus LPS plus IL-1 compared with that in mice immunized with OVA plus LPS from nine experiments. (C) 10^4 CD45.1 OT-I and 10^4 CD45.1 OT-II cells were injected into CD45.2 IL-$1R1^{-/-}$ and wild-type CD45.2 C57BL/6 mice. Mice were immunized with OVA plus LPS with or without IL-1. 7 d after priming, cells were analyzed for number of OT-I cells. This experiment was performed three times with similar results.

independent of IL-1R1 expression in the non–OT-I cells. In Fig. 3 D, we show that there are actually more OT-I cells in lymph nodes and spleen of immunized IL1$R1^{-/-}$ recipients treated with IL-1 than in WT recipients, although the difference is not statistically significant. In contrast, the number of OT-I cells in liver and lung of immunized IL-$1R1^{-/-}$ recipients treated with IL-1 is far less than in similarly treated WT recipients. In this experiment, recipients received both OT-I and OT-II cells.

Entry into liver and lung was also diminished in IL$1R1^{-/-}$ OT-I–recipient mice that were immunized with OVA plus LPS without exogenous IL-1 (Fig. 3 C). These results indicate that entry or retention in liver and lung requires IL-1R1 expression in cells other than the antigen-specific T cells, presumably at the local site of accumulation, whether IL-1 is administered or not, implying that IL-1, whether endogenous or administered, plays a central role in migration into nonlymphoid organs of recently primed effector or effector/memory CD8 T cells.

IL-1 enhances effector function of CD8 T cells in response to antigen stimulation

Immunization of mice that received OT-I cells alone or OT-I cells plus OT-II cells with OVA plus LPS caused relatively few cells to express granzyme B or to produce IFN-γ when stimulated with PMA plus ionomycin. Addition of IL-1 caused a striking increase in the proportion of granzyme B–expressing cells and in the fraction of OT-I cells that produced IFN-γ in response to stimulation (Fig. 4 A). In spleen, and particularly in liver and lung, the addition of IL-1 strikingly increases the proportion of granzyme B and of IFN-γ–producing cells and the MFI of both granzyme B and IFN-γ staining (Fig. 4, B and C). Strikingly, the increase in both granzyme B expression and in the proportion of IFN-γ–producing cells did not occur if the recipients were IL-$1R1^{-/-}$ mice (Fig. 4 D). Thus, the enhanced "differentiation" of the responding cells was a complex process presumably requiring both a direct interaction of IL-1 with the responding T cells for their expansion and possibly their differentiation and a

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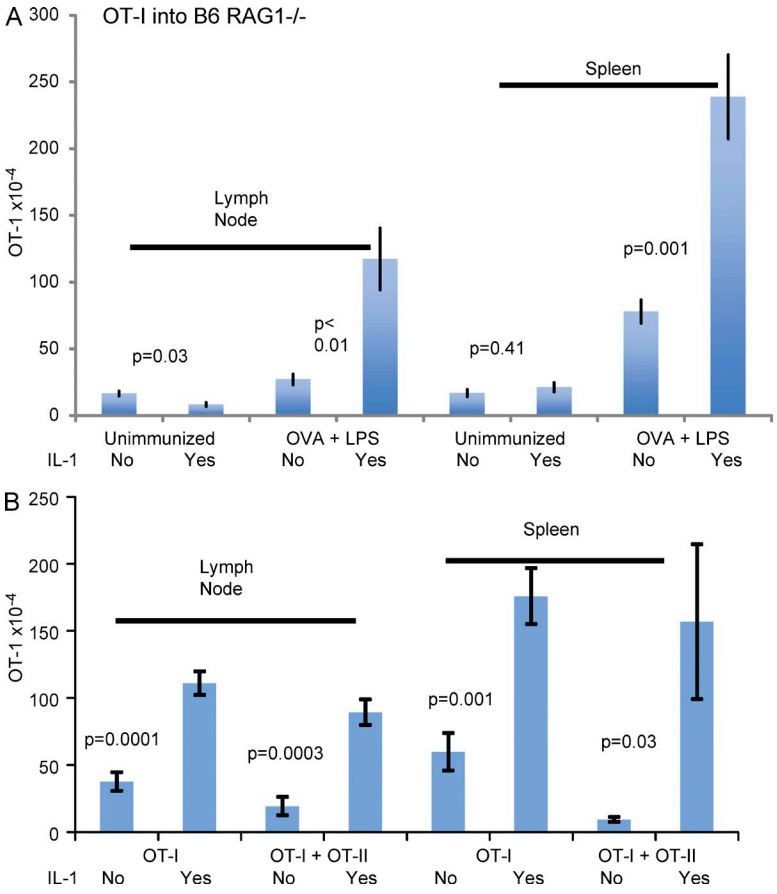

Figure 2. IL-1 enhancement of CD8 responses does not depend on CD4 cells. (A) 4×10^5 OT-I cells were injected into Rag1$^{-/-}$ C57BL/6 mice. Mice were immunized with OVA and LPS with or without IL-1. 7 d after priming, the number of transferred OT-I cells was determined. This experiment was performed twice with similar results. (B) 3×10^4 OT-I cells with or without 3×10^4 OT-II cells were injected into IL-1R1$^{-/-}$ C57BL/6 mice that were immunized with OVA, LPS with or without IL-1. 7 d after priming, the number of OT-I cells was measured. This experiment was performed twice with similar results.

contribution of IL-1–stimulated recipient cell function for expression of granzyme B and production of IFN-γ.

Inclusion of IL-1 in the immunization protocol also increases the cytotoxic activity of primed CD8 T cells. We immunized OT-I transgenic mice with OVA plus LPS with or without IL-1. 9 d after priming, we transferred graded numbers of OT-I cells from the primed donors to naive B6 recipients. We then tested cytotoxic activity of the transferred cells by injecting a mixture of B6 splenocytes labeled with a high concentration of CFSE and loaded with SIINFEKL and of control cells labeled with a low concentration of CFSE. We measured the relative numbers of CFSE^{high} and CFSE^{low} cells 18 h later in lymph node cell suspensions. Transfer of 7.2×10^5 cells from either donor resulted in a striking depletion of SIINFEKL-loaded cells (Fig. 5 A), indicative of cytotoxic activity. In contrast, when 1.2×10^5 OT-I cells were transferred, only those from the donor that had been immunized with IL-1 displayed cytotoxic activity. Transfer of 0.2×10^5 cells from donors primed in the presence of IL-1 resulted in significant but diminished cytotoxic activity, whereas cells from donors immunized with OVA plus LPS showed no cytotoxic activity. In both the 1.2×10^5 and the 0.2×10^5 groups, the differences in the presence and absence of IL-1 were statistically significant. Thus, on a per cell basis, immunization with IL-1 resulted in a greater than sixfold increase in their in vivo cytotoxic activity.

We also immunized normal B6 mice with OVA plus LPS with or without IL-1. The addition of IL-1 increased the frequency of CD8 T cells that bound a SIINFEKL tetramer (Fig. 5 B) in both lymph node and spleen, indicating that IL-1 is active on conventional CD8 T cells as well as on transgenic cells. Although mice immunized with OVA plus LPS displayed very limited cytotoxic activity for SIINFEKL-sensitized cells as determined by injection of mixture of sensitized and nonsensitized target cells into these animals, those that had received IL-1 in the immunization protocol showed striking cytotoxic activity in both lymph nodes and spleen (Fig. 5 C).

Mice primed with OVA, LPS, and IL-1 show striking secondary responses

Mice that had received OT-I cells were immunized with OVA and LPS with or without IL-1. 8 wk later, these mice were challenged subcutaneously with OVA plus LPS, without IL-1. 3 d after the boost, there was a trend for more OT-I cells in lymph node, spleen, liver, and lung in mice that had been originally primed in the presence of IL-1 (Fig. 6, A and B). The IL-1–primed cells from each organ showed high frequencies of granzyme B$^+$ cells and cells that produced IFN-γ in response to PMA and ionomycin, whereas cells from these organs derived from mice primed without IL-1 showed substantially less granzyme B or IFN-γ (Fig. 6 C). The relatively high proportion of IFN-γ producers in the lung of mice that

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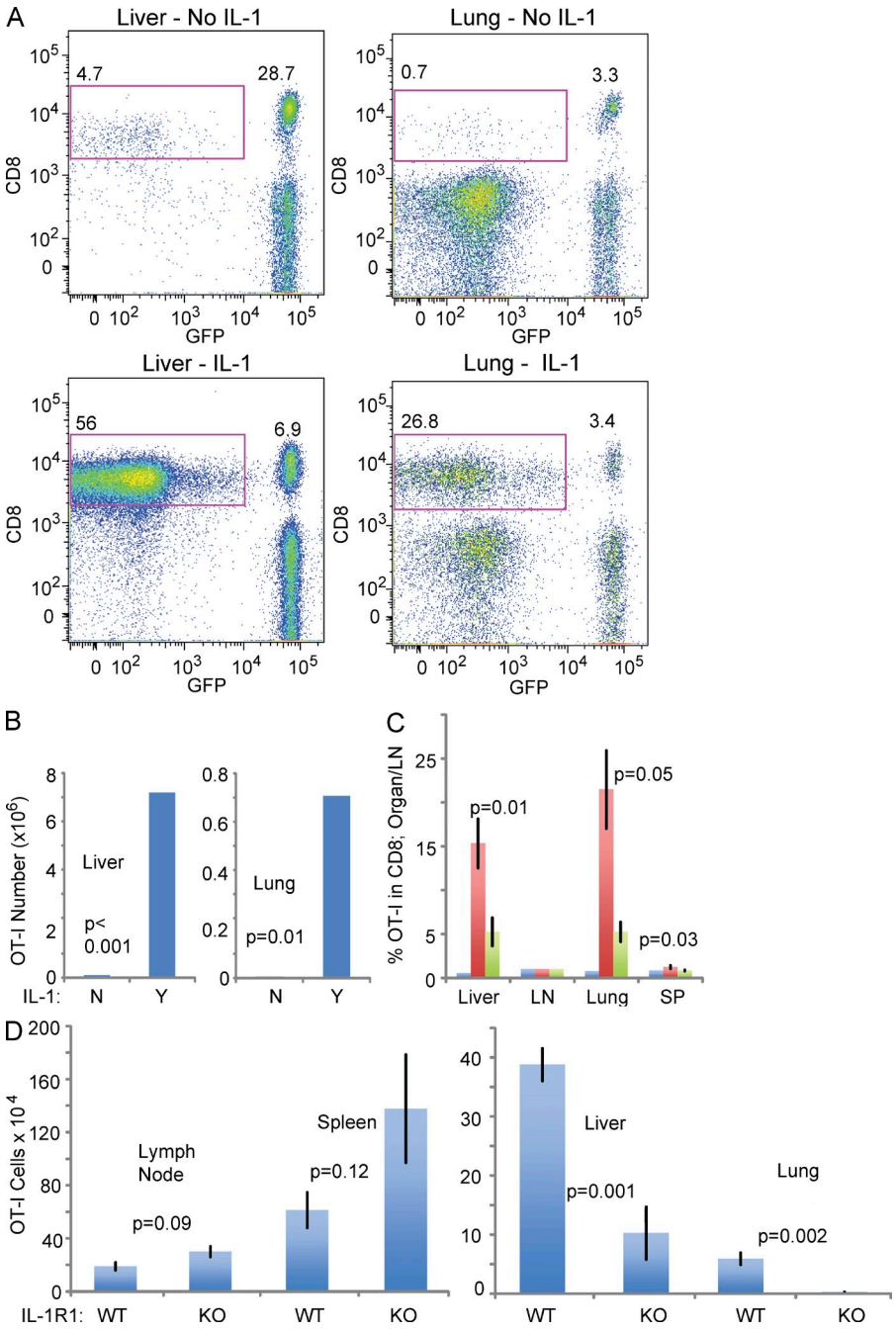

Figure 3. IL-1 increases the frequency of OT-I cells in liver and lung. (A) 10^4 OT-I cells were injected into UBC-GFP C57BL/6 mice. Mice were immunized with OVA and LPS with or without IL-1. 7 d after priming, lymphocyte-enriched fractions were isolated from liver and lung and cells were analyzed for proportion of OT-I cells. This experiment was performed six times with similar results. (B) 10^4 OT-I cells were injected into UBC-GFP C57BL/6 mice that were then immunized with OVA and LPS with or without IL-1. 7 d after priming, lymphocyte-enriched fractions were isolated from liver and lung and number of OT-I cells was measured. This experiment was performed four times with similar results. (C) 1–3 × 10^4 OT-I cells were injected into UBC-GFP CD45.1, CD90.1 C57BL/6, CD45.1 C57BL/6, or IL-1R1$^{-/-}$ C57BL/6 mice. Recipients were immunized with OVA plus LPS. 7 d later, the percentage of transferred OT-I cells among the CD8 population in lymph nodes, spleen, liver, and lung was determined. The mean ratio of the percentage of OT-I in CD8 in liver, lung, and spleen compared with that of the lymph nodes from five experiments in WT mice (red) and from three experiments in IL-1R1$^{-/-}$ recipients (green) were calculated. In addition, in one experiment (blue), 10^6 OT-I cells were transferred without immunization and the ratio of the percentage of OT-I in CD8 in liver, lung, and spleen compared with that of the lymph nodes was determined. (D) 10^4 CD45.1 OT-I and 10^4 CD45.1 OT-II cells were injected into CD45.2 IL-1R1$^{-/-}$ and wild-type C57BL/6 mice. Mice were immunized with OVA and LPS with or without IL-1. 7 d after priming, single-cell suspensions from the lymph nodes, spleen, liver, and lung were analyzed by FACS for the content of OT-I cells. The ratio of the number of OT-I cells in the presence of IL-1 to that in its absence is plotted. This experiment was performed twice with similar results.

had not been immunized with IL-1 may reflect the difficulty in phenotyping the very small number of such cells in the lung. An example of the difference in liver and lung between mice primed with or without IL-1 is shown in Fig. 6 A. In the IL-1–primed groups, the majority of spleen, liver, and lung OT-I cells were granzyme B$^+$, and the frequency of IFN-γ producers in these organs was ∼40% (Fig. 6 C). Thus, the striking phenotypic properties of OT-I cells observed 7 d after priming with IL-1 were also observed when these mice were boosted 8 wk later, even though IL-1 was not administered in the booster immunization.

IL-1 enhances protectivity of weak or ineffective vaccines

We wished to determine whether the striking IL-1–mediated enhancement in both CD4 and CD8 T cell expansion and the accompanying increase in effector phenotype would allow greater efficacy of weak vaccines if IL-1 was included in the vaccination protocol. We chose three model systems for analysis, heat-killed *Listeria monocytogenes* (HKLM) as a vaccine for challenge with live *L. monocytogenes*, an HIV peptide as a vaccine for recombinant vaccinia, a human papilloma virus (HPV)–derived peptide as a therapeutic vaccine for TC1 HPV-transformed lung epithelial cells.

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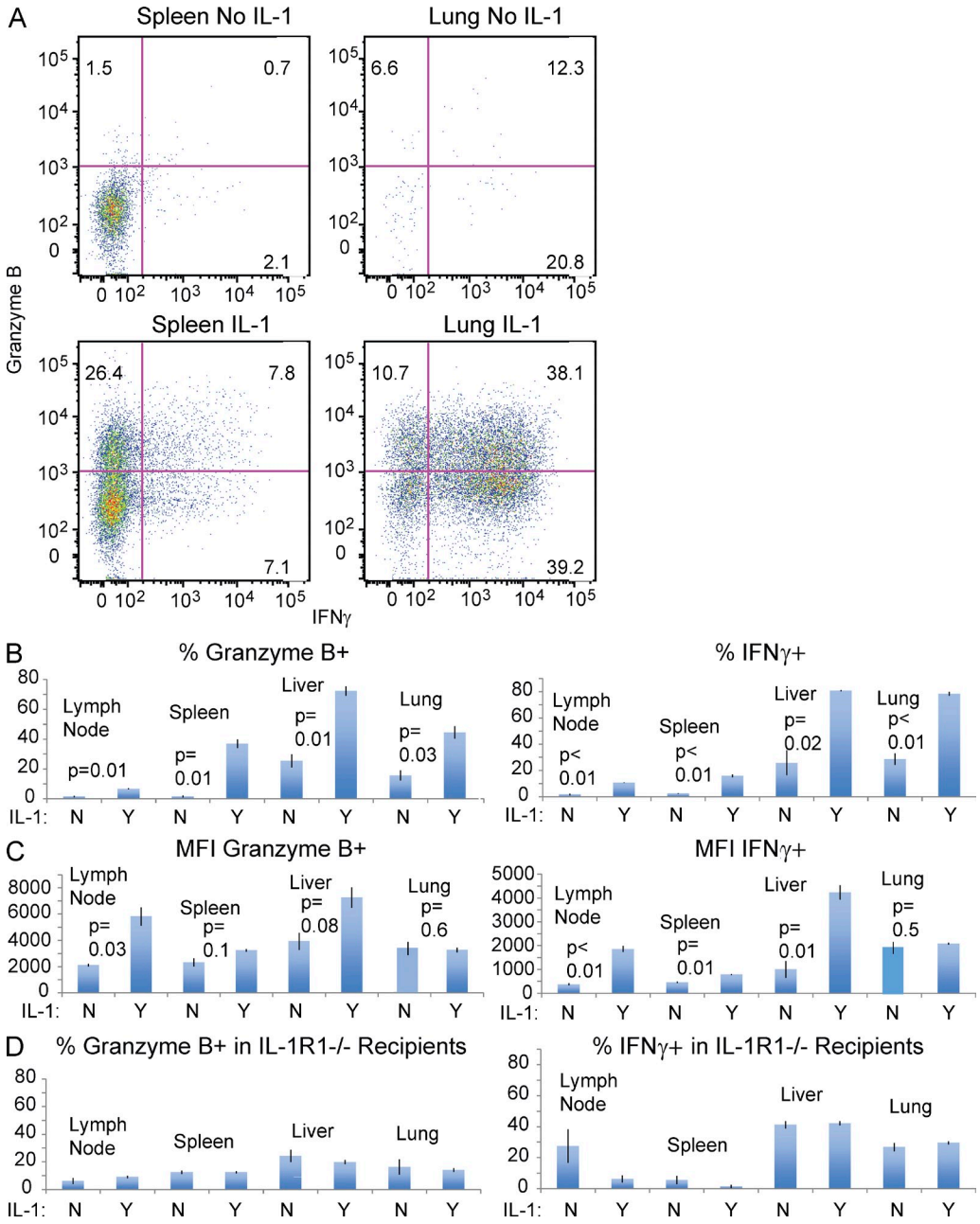

Figure 4. IL-1 enhances CD8 T cell differentiation. (A) 10^4 OT-I and 10^4 OT-II cells were injected into UBC-GFP C57BL/6 mice. Mice were immunized with OVA and LPS with or without IL-1. 7 d after priming, cells from the lymph nodes, spleen, liver, and lung were stimulated for 4 h with PMA and ionomycin, and the percentage of granzyme B^+ cells and IFN-γ^+ cells among the OT-I cells was determined. This experiment was performed four times with similar results. (B) 10^4 OT-I and 10^4 OT-II cells were injected into UBC-GFP C57BL/6 mice. 6 d later, the mice were immunized with OVA and LPS with or without IL-1. 7 d after priming, cells from the lymph nodes, spleen, liver, and lung were stimulated for 4 h with PMA and ionomycin. The percentage of granzyme B^+ cells and IFN-γ^+ cells among the $CD8^+$ GFP^- OT-I cells in the various organs was determined. This experiment was performed five times with similar results. (C) The MFI of granzyme B and IFN-γ among positive cells in the various organs was determined by FACS analysis. This experiment was performed four times with similar results. (D) 10^4 CD45.1 OT-I and 10^4 CD45.1 OT-II cells were injected into CD45.2 IL-$1R1^{-/-}$ C57BL/6 mice. Mice were immunized with OVA and LPS with or without IL-1. 7 d after immunization, cells from the lymph nodes, spleen, liver, and lung were stimulated for 4 h with PMA and ionomycin. The percentage of granzyme B^+ cells and IFN-γ^+ cells among the OT-I cells was measured. There were no statistically significant differences in values obtained in mice that did and did not receive IL-1. This experiment was performed twice with similar results.

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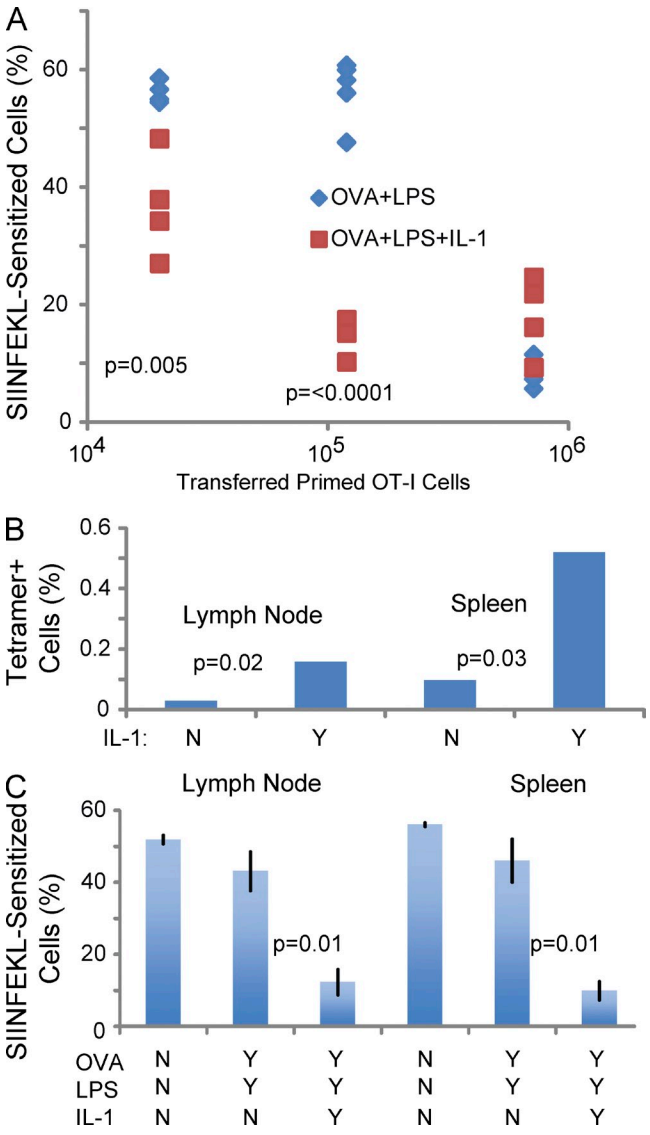

Figure 5. IL-1 increases cytotoxic activity in vivo. (A) OT-I mice were primed in vivo with OVA and LPS with or without IL-1 (3 daily s.c. injections on days 1, 3, and 5 after immunization). 9 d later, 7.6×10^5, 1.2×10^5, or 0.2×10^5 cells from the immunized mice were transferred to C57BL/6 mice. 7 d after the OT-I transfer, recipient mice were injected with 3×10^6 SIINFEKL-loaded $CFSE^{high}$ and 1.4×10^6 control $CFSE^{low}$ syngeneic splenocytes. 18 h later, lymph nodes were removed and the percentage of SIINFEKL-loaded cells among the CFSE-labeled population was determined. This experiment was performed twice with similar results. (B) C57BL/6 mice were immunized with OVA and LPS with or without IL-1. 8 d later, the percentage of SINFEKL tetramer-binding cells among the CD8 population in the lymph nodes and spleen was determined. This experiment was performed three times with similar results. (C) C57BL/6 mice were immunized with OVA and LPS with or without IL-1. 7 d after priming, recipient mice were injected with 4×10^6 SIINFEKL-loaded $CFSE^{high}$ and 2×10^6 control $CFSE^{low}$ syngeneic splenocytes. 18 h later, the percentage of SIINFEKL-loaded cells among the CFSE labeled population of lymph node and spleen was determined. This experiment was performed three times with similar results.

Fig. 7 A shows that unvaccinated mice infected with 4×10^4 live *L. monocytogenes* display 5.85 $\log_{10}$ CFU of bacteria in the liver 3 d after challenge. If they had been immunized with 500 live *L. monocytogenes* 30 d earlier, they had 2.6 $\log_{10}$ fewer CFU. Immunization with 500 HKLM provided no benefit, but the addition of IL-1 to HKLM immunization protocol yielded a 2.0 $\log_{10}$ reduction in liver CFU compared with unimmunized mice. We repeated this experiment using 50,000 HKLM as the immunogen with or without IL-1 and again observed no protection in the HKLM group and significant protection in the group that received HKLM and IL-1 (unpublished data). In a separate experiment, we measured survival of mice infected with live *Listeria*. All mice that were unimmunized, received 50,000 HKLM alone or IL-1 alone had either died by day 4 or had to be euthanized because of excessive weight loss. In contrast, three of five mice that received HKLM plus IL-1 survived as did all the mice that had been immunized with live *Listeria* (data not shown).

Challenging BALB/c mice with 2×10^7 PFU of recombinant vaccinia virus expressing HIV gp160IIIB resulted in 7.3×10^7 PFU in the ovaries 6 d after infection. Immunization with peptide containing the immunodominant CTL epitope of the vaccinia-expressed gp160IIIB HIV protein (Takahashi et al. 1988; Takeshita et al., 1995) 7 d earlier resulted in a modest degree of protection, to 4.0×10^7 PFU. Including TLR ligands (MALP2, poly[I:C], and CpG ODN 1555 and 1466; Zhu et al., 2010) in the immunization protocol resulted in 8.5×10^6 PFU upon challenge. Using IL-1 rather than the TLR ligand mixture provided greater protection, reducing the PFU to 4.0×10^6, a statistically significant improvement over the TLR ligand mixture (Fig. 7 B).

5.0×10^4 HPV-transformed lung epithelial TC1 cells were injected into the right flank of C57BL/6 mice. 14 d later, when the tumor could be palpated, the animals were either not immunized or immunized with 100 µg HPV $E7_{49-57}$ peptide plus 25 µg LPS or LPS + IL-1 (4 doses of 2 µg on day 0, 1, 2, and 4 after immunization). Tumor sizes were measured until day 18 after immunization. The group immunized with IL-1 had statistically significantly smaller tumors from day 4 onward (Fig. 7 C).

DISCUSSION

In this study, we have shown that the expansion of naive TCR transgenic CD8 T cells in response to immunization with their cognate antigen plus LPS is enhanced by >60-fold in the spleen and ~20-fold in lymph nodes by administration of IL-1 over the 5 d after immunization. The effect of IL-1 on CD8 T cell expansion in lymph node and spleen does not require that cells other than the CD8 T cells express IL-1R1. The IL-1 effect does not depend on the presence of CD4 T cells although IL-1 does enhance the antigen-driven response of these cells (Ben-Sasson et al., 2009).

Although the mechanism of the IL-1–induced enhancement in lymph node and spleen is not known, it is unlikely to be a result of an "overriding" of a possible inhibitory effect

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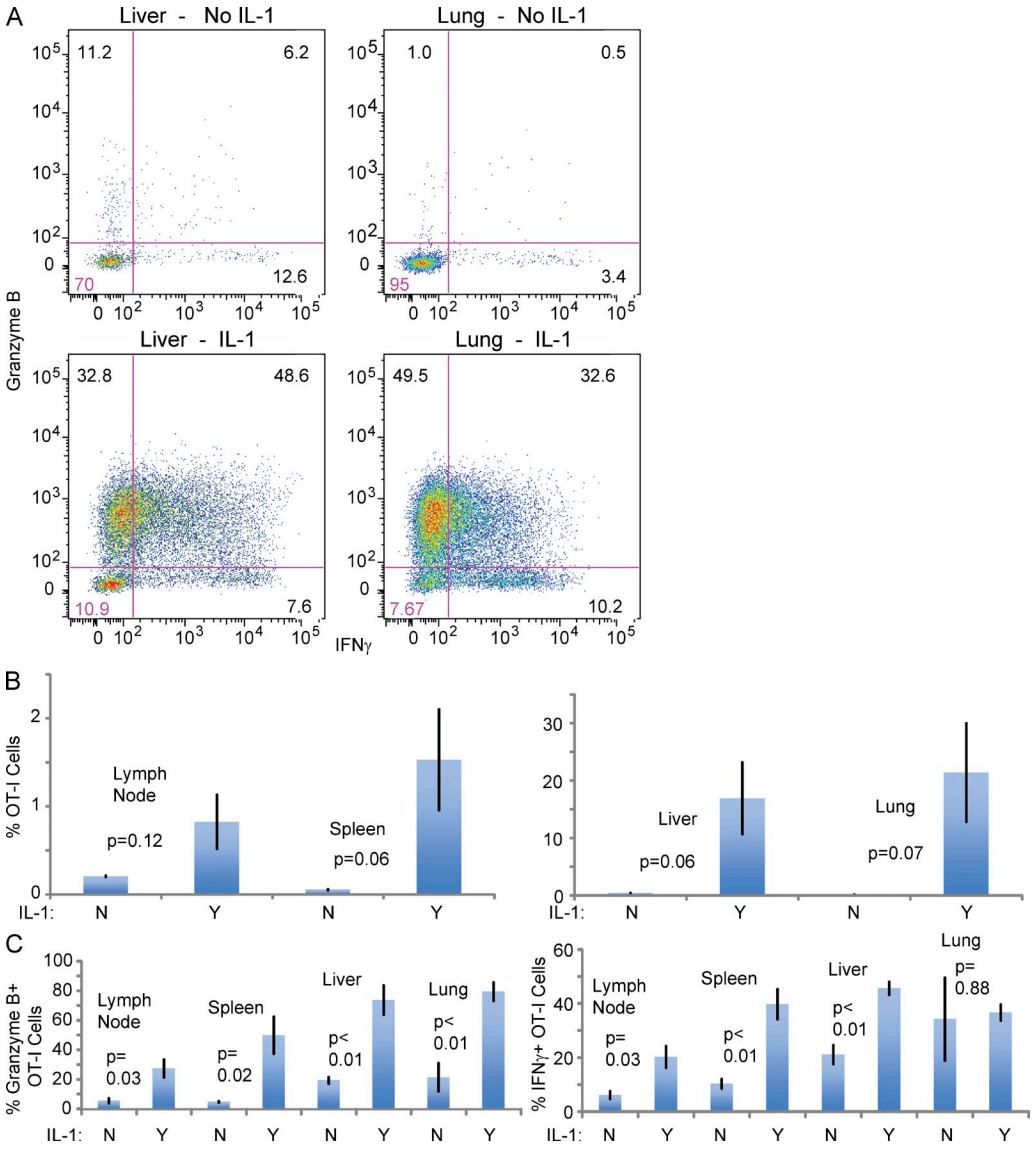

Figure 6. OT-I cells primed in the presence of IL-1 retain their phenotype upon boost 8 wk later. 10^4 OT-I and 10^4 OT-II cells were injected i.p. into UBC-GFP C57BL/6 mice. 6 d later, the mice were immunized with OVA and LPS with or without IL-1. 8 wk after priming, the mice were boosted with OVA and LPS. Three days later, cells from liver and lung were stimulated for 4 h with PMA and ionomycin. The percentage of granzyme B^+ and IFN-γ^+ cells among the OT-I cells in a representative animal is shown in A and summary cell number and percent of granzyme B^+ and IFN-γ^+ cells are shown in B and C. This experiment was performed three times with similar results.

of regulatory T cells because only CD8 cells need to express IL-1R1 for the response to IL-1 to occur. For the same reason, the principal effect is not on accessory cells, including DCs. A possible explanation for the IL-1–induced enhancement in cell number is IL-1–mediated suppression of apoptosis in the antigen-stimulated CD8 cells (McConkey et al., 1990; McAleer et al., 2007; von Rossum et al., 2011), which appears to be the major mechanism for IL-1 enhancement of CD4 responses (Ben-Sasson et al., 2009).

The enhanced expansion of OT-I cells is particularly dramatic in the liver and lung where, even with transfer of 10,000 cells, the responding OT-I cells constitute the great majority of all the CD8 T cells in the organ. Interestingly, although the IL-1 effect on expansion in spleen and lymph node does not require IL-1R1 expression on cells other than the OT-I cells, this is not the case for cells trafficking to liver or lung. If the recipient is an IL-1R1–deficient mouse, OT-I cells fail to accumulate in liver or lung, implying that entry into, or retention in, these tissues is enhanced by the action of IL-1 on a tissue cell. Indeed, even the accumulation of OT-I cells in liver and lung in mice immunized with OVA plus LPS without exogenous IL-1 is diminished in IL1R1$^{-/-}$ recipients. This implies that IL-1 action, possibly on vascular endothelial cells, is important to the robust entry of memory/effector or

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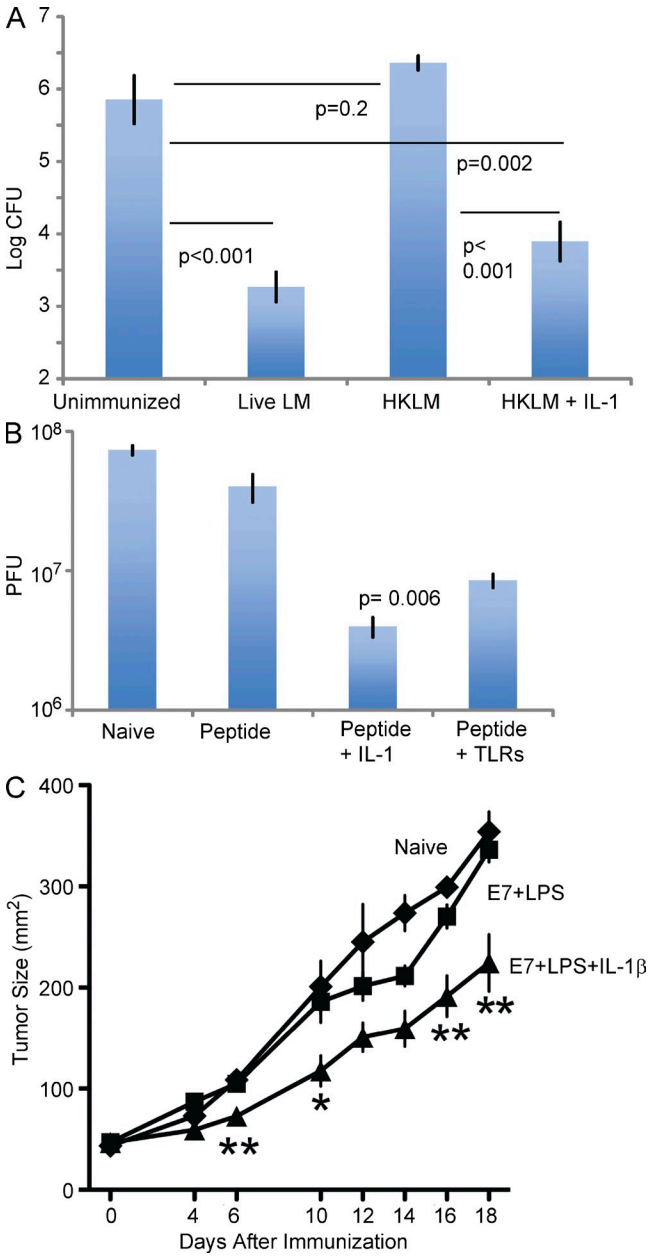

Figure 7. IL-1 effect on protective responses to *L. monocytogenes*, recombinant vaccinia, and a tumor line. (A) C57BL/6 mice were either untreated, inoculated with 500 live *L. monocytogenes* (Lm), the equivalent of heat-killed *L. monocytogenes* (HKLM), or HKLM and IL-1 (10 µg delivered over 7 d in a mini-osmotic pump). 29 d later, the mice were challenged with 5×10^4 CFU of live Lm. Bacterial CFU in liver were enumerated 3 d later. This experiment was performed three times with similar results. (B) BALB/c mice were immunized twice with 100 µg of the HIV-1 peptide RGPGRAFVTI, 10 d apart, alone, with IL-1, or with a cocktail of TLR ligands, and then infected i.p. with 2×10^7 recombinant vaccinia virus (vPE16) 1 wk after the last immunization. 6 d after infection, viral load in the ovaries was determined by a plaque assay using BSC-1 cells. This experiment was repeated five times with similar results. (C) TC1 cells were injected s.c. into the flank of C57BL/6 mice. 14 d later, when the tumor was measurable, mice were immunized with a vaccine containing the HPV16 $E7_{49-57}$ peptide with 20 µg DOTAP and 25 µg LPS with or without IL-1 (2 µg on days 0, 1, 2, and 4). Each group contained 3–5 mice. P-values were calculated using the Mann-Whitney test. This experiment was repeated twice with similar results. **, P = 0.02; *, P = 0.03.

effector cells into liver and lung, and possibly other tissues, or to retention in these tissues. Indeed, IL-1 has been reported to regulate adhesion and/or transmigration of CD8 effector lymphocytes into various tissues by controlling chemokine production and possibly adhesion molecule expression (Pietschmann et al., 1992; Sikorski et al., 1993; Wang et al., 1993; Kanda et al., 1995; Freedman et al., 1996; Muehlhoefer et al., 2000; Stocker et al., 2000; Mohamadzadeh et al., 1998; Ding et al., 2000; McCandless et al., 2009).

Priming in the presence of IL-1 markedly induces granzyme B expression, antigen-specific cytotoxic T cell activity, and IFN-γ–producing capacity of the antigen-specific responding CD8 T cells. What was quite interesting and somewhat perplexing was that the increased expression of granzyme B and the enhanced capacity to produce IFN-γ required expression of IL-1R1 by cells other than the responding CD8 T cells. This implies that factors other than IL-1, possibly produced by dendritic cells that have received an IL-1 signal, are required to cooperate with those generated by IL-1 in the responding T cells to yield robust differentiation in the expanding cells (Wesa and Galy, 2002; Sheng et al., 2008; Thompson et al., 2012).

Not only did recently primed cells display a greater degree of differentiation when IL-1 was part of the immunization regimen, CD8 cells from these mice showed greater granzyme B expression and IFN-γ–producing capacity when challenged 8 wk after priming without readministration of IL-1. Whether this secondary response reflects the expansion of highly differentiated cells in the tissues upon rechallenge or, more likely, the response of cells in spleen and/or lymph node followed by traffic to tissues immediately after the boost is still uncertain. In challenge with live influenza, the process of expansion of CD8 memory cells has been reported to occur largely in the secondary lymphoid organs, with the activated cells then migrating to the tissues (Kohlmeier et al., 2010).

The capacity of IL-1 to enhance both the expansion and differentiation of responding cells and the retention of the enhanced effector capacity of the differentiated cells upon boosting 8 wk late implies that IL-1 as an "adjuvant" could increase the "competence" of weak vaccines to provide protective activity. Indeed, we observed that IL-1 given together with HKLM resulted in a reduction by ~2-$\log_{10}$ of the CFU titer in liver compared with immunization with HKLM alone even when the number of HKLM was very low. When IL-1 was used with an HIV peptide, ~1 $\log_{10}$ of increased protection was obtained against a recombinant vaccinia expressing the gp160IIIB HIV protein. IL-1 also enhanced the efficacy of a peptide vaccine against an established tumor. In unpublished work, we have observed that IL-1 enhances the role of both subunit and attenuated *Herpes simplex* vaccines to offer protection (unpublished data) and increases the protection

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obtained in priming with heat killed *Blastomyces dermatitidis* (unpublished data).

The molecular mechanisms underlying IL-1 actions are still unresolved. IL-1 signals through the Myd88 pathway and has been reported to activate both NF-κB and MAP kinases (Weber et al., 2010). This would allow both the expansion and differentiation processes that have been observed. Recently, it has been reported that IL-1–driven cytokine production by CD4 T cells is largely mediated through the activation of PI-3 kinase and mTOR (Gulen et al., 2010; Chi, 2012). In addition, it has been shown that IL-33 signaling in CD8 T cells augments both the proliferative and the cytolytic activity of cells responding to vaccinia virus (Bonilla et al., 2012). Because IL-1 and IL-33 share IL-1RAcP as a co-receptor for signaling and activate similar, if not identical, pathways (Weber et al., 2010; Palmer and Gabay, 2011), it may well be that both molecules perform the same function in antigen-stimulated CD8 cells, depending on expression of the appropriate cytokine receptor. Interestingly, the in vivo generalized expansion of antigen-stimulated CD4 cells is augmented by IL-1 but not by IL-33 (Ben-Sasson et al., 2009), possibly because of little or no expression of the IL-33 binding chain (T1-ST2) on naive CD4 T cells.

IL-1 displays properties that would seem to be of great value in enhancing primary responses and readiness to deal with reintroduction of pathogens. Thus, it strikingly enhances the magnitude of primary expansion, increases the degree of differentiation, allows the cells to enter tissues, and induces the capacity to develop an enhanced secondary response marked by increased responder cell expression of granzyme B and increased capacity to produce IFN-γ. The principal barrier to exploiting these extremely desirable properties is the potent proinflammatory effects of the cytokine. If a method could be found to tame IL-1 by limiting its range of action only to CD4 and/or CD8 cells or if a cell type–specific small molecule analogue could be identified, the possibility of exploiting the IL-1 adjuvant effect could be considered.

MATERIALS AND METHODS

Mice. Female mice of the following strains were obtained from Taconic Farms: TCR Tg OT-I/RAG1$^{-/-}$ C57BL/6; TCR Tg OT-I/RAG1$^{-/-}$ CD45.1 C57BL/6; TCR Tg OT-I/RAG1$^{-/-}$ IL-1R1$^{-/-}$ C57BL/6; TCR Tg OT-II/RAG1$^{-/-}$ C57BL/6; TCR Tg OT-II/RAG1$^{-/-}$ CD45.1 C57BL/6; CD45.1 C57BL/6; RAG1$^{-/-}$ C57BL/6; IL-1R1$^{-/-}$ C57BL/6; and CD90.1 C57BL/6. UBC-GFP C57BL/6 and the appropriate C57BL/6 control female mice were obtained from The Jackson Laboratory. WT BALB/c and C57BL/6 mice for the vaccinia and tumor experiments were obtained from Charles River. Mice were maintained under pathogen-free conditions and were used at 6–8 wk of age. Mice was cared for under protocols approved by the NIAID Animal Care and Use Committee.

Cytokines, peptides, and antibodies. Recombinant mouse IL-1β was prepared as preciously described (Wingfield et al., 1986). Fluorochrome-conjugated anti-Vα2 (B20.1) and anti-Vβ5 (MR9–4) antibodies were purchased from BD. Anti-CD45.1 (A20), anti-CD45.2 (104), anti-CD90.1 (HIS51), anti-CD90.2 (53–2.1), anti-CD4 (L3T4), anti-CD8 (53–6.7), anti–IFN-γ (XMG1.2), anti–granzyme B (16G.6) fluorochrome-conjugated antibodies were purchased from eBioscience. SIINFEKL peptide was purchased from American Peptide Co. APC-H-2K^b restricted SIINFEKL tetramer was obtained from the National Institutes of Health Tetramer Core Facility. HIV envelope peptide RGPGRAFVTI and HPV E7 peptide RAHYNIVTF were obtained from the Polypeptide Group.

Tetramer staining. Lymph node or spleen cells (2–5 × 10^6) were incubated for 30 min at 37°C in 0.2 ml of RPMI 1640 + 2% FCS containing 50 μg/ml anti-FcγR II (2.4G2) antibody with 2 μg/ml APC-conjugated H-2K^b SIINFEKL tetramer, followed by staining at 4°C for 30 min with PE Cy7 anti-CD8. Cells were washed in PBS with 0.1%BSA and analyzed with a BD LSRII, using FlowJo software (Tree Star).

Intracellular cytokine staining. Single-cell suspensions (1–5 × 10^6 cells/ml) from lymph nodes, spleen, liver, or lung were stimulated with ionomycin and phorbol 12-myristate 13-acetate (PMA), fixed, permeabilized, and stained as previously described (Ben-Sasson et al., 2009). For cytokine staining, cells were blocked with anti-FcγR II (2.4G2; 50 μg/ml) for 5 min and stained for 30 min at room temperature with anti-PerCP Cy5-5 anti-CD8 and eFluor 450 anti–IFN-γ, PE anti–granzyme B. The stained cells were analyzed with a BD LSRII, using FlowJo software (Tree Star).

In vivo priming of adoptively transferred transgenic cells. Unless otherwise specified, cells (0.1–3 × 10^5) from lymph nodes of donor mice were injected i.p. or retroorbitally (RO) into normal recipients (3–5 mice for each experimental group). Mice were immunized s.c. by injection of 1 mg of OVA (Sigma–Aldrich) with 25 μg of LPS (*Escherichia coli* 0111:B4; InvivoGen). IL-1β was injected daily (2 μg/injection) s.c. for 5 d starting at 24 h after immunization, unless otherwise stated.

Preparation of single-cell suspensions from lymph nodes and spleen. Single-cell suspensions were prepared from the lymph nodes and spleens by mechanical dispersion of the organs with a syringe top over a 40-μm sieve on a 50-ml tube in RPMI 1640 containing 5% FCS.

Preparation of lymphocyte-enriched populations from liver and lung. The lymphocyte-enriched fraction was isolated from the liver by mechanical dispersion of the organ, followed by Percoll gradient centrifugation. In brief, the liver was cut into small pieces that were transferred to a 70-μm sieve on a 50-ml tube and pushed through the sieve with a syringe top. The cells were washed with RPMI 1640 containing 1% FCS, and the pellet was resuspended in 40% isotonic Percoll solution that was underlayed by 60% isotonic Percoll and spun at 2,000 RPM for 20 min at room temperature. Cells at the 40–60% Percoll interface were collected and washed with RPMI 1640 containing 5% FCS. The pellet was resuspended in the same medium.

The lymphocyte-enriched fraction was isolated from the lung after digestion with collagenase/DNase and further purification by Percoll gradient centrifugation. In brief, washed, perfused lung tissue was cut into small pieces and digested by incubation in Petri dishes for 30 min at 37°C in humidified CO_2 incubator with collagenase/DNase (50 μg/ml collagenase-Liberase; Roche) and 8 U/ml DNase type I (Roche) in RPMI. The lung digest was then treated in the same manner as the liver fragments.

Monitoring donor CD8 transgenic cells. The percentage of donor cells among the single-cell suspensions of the lymph nodes, spleen, liver, and lung of the recipient mice was determined by staining for 30 min at 4°C with a cocktail of fluorochrome-conjugated anti-cell surface antibodies in the presence of 50 μg/ml of blocking anti-FcγRII/III Abs (2.4G2), followed by flow cytometric analysis with a BD LSRII, using FlowJo software (Tree Star) for the identification of the OT-I–transferred cells. In C57BL/6 recipients, FITC-anti-Vβ5, PE-anti-Vα2, and APC-anti-CD8 antibodies were used for the identification of the CD8$^+$/Vα2$^+$/Vβ5$^+$ OT-I cells. In GFP C57BL/6 mice, the FITC conjugated antibody was omitted for the identification of the CD8$^+$/Vα2$^+$/GFP$^-$ OT-I cells.

In CD45.1 C57BL/6 recipients, FITC-anti-CD45.1, PE-anti-Vα2, APC-anti-CD45.2, and PE-Cy7 anti-CD8 antibodies were used for the

identification of the $CD8^+/V\alpha2^+/CD45.1^+/CD45.2^-$ OT-I cells. In CD90.1 C57BL/6 recipients, PE-anti-CD8, APC-anti-Vα2, FITC anti-CD45.1, PerCP Cy5-5-anti-CD45.2, eFluor 450-anti-CD90.1, and PE Cy7-anti-CD90.2 were used to identify the $CD8^+/V\alpha2^+/CD90.1^-/CD90.2^+/CD45.1^+/CD45.2^-$ OT-I cells or the $CD8^+/V\alpha2^+/CD90.1^-/CD90.2^+/CD45.1^-/CD45.2^+$ OT-I cells. The number of OT-I cells in the examined organs was determined by multiplying the cell number in the organ by the percentage of OT-I Tg cells in that organ.

In vivo cytotoxicity assay. Target cell populations were prepared from naive B6 mice using RBC-lysed splenocytes. The residual white cells (2×10^7 cells/ml PBS) were labeled with either 2.5 or 0.25 μM carboxyfluorescein succinimidyl ester (CFSE), (Molecular Probes) for 8 min at RT followed by quenching with 50% FCS for 2 min at RT. The $CFSE^{high}$ and $CFSE^{low}$ labeled cells were washed 3x with RPMI 1640 containing 10% FCS. The $CFSE^{high}$ target cells were pulsed with SIINFEKL peptide for 90 min at 37°C and the $CFSE^{low}$ cells were incubated under the same conditions as an internal control. The cells were mixed at a ratio of 2:1 $CFSE^{high}/CFSE^{low}$ and injected retroorbitally into mice. Lymph nodes and spleens were removed 18 h later and single-cell suspensions were analyzed for the percentage of $CFSE^{high}$ among total CFSE-labeled cells. A reduction to less than the starting percentage of 67% implies cytotoxicity of peptide-pulsed target cells.

Preparation of heat killed *L. monocytogenes*. *L. monocytogenes* (Lm) 10403S was grown at 30°C overnight in BHI broth. Before infection, bacteria were washed in Ringer's lactate solution twice. Heat-killed *L. monocytogenes* (HKLM) were generated by heating the *Listeria* in Ringer's lactate solution at 65°C for 30 min. All HKLM preparations were tested for residual bacterial viability by plating 100 μl of HKLM on BHI agar.

***L. monocytogenes* vaccination.** Mice were inoculated via tail vein with either no bacteria (PBS), with 500 CFU of live *L. monocytogenes*, or equivalent of HKLM or with HKLM and IL-1 (10 μg which was delivered by 7-d mini-osmotic pump as previously described [Ben-Sasson et al., 2009]). 29 d after priming, mice were challenged with 5×10^4 CFU of live *L. monocytogenes*, and then sacrificed 3 d after the challenge. Bacteria in liver were enumerated using serial dilution and colony counts on either BHI or TSA 5% blood agar plates. At least 5 mice were used in each experimental group.

Immunization with virus-expressed peptide and challenge with virus. BALB/c mice were immunized subcutaneously with 100 μg of the P18-I10 (RGPGRAFVTI) peptide from the V3 loop of the IIIB strain of HIV-1 (Takahashi et al., 1988) complexed in DOTAP liposomal transfection reagent (20 μg; Roche). Some mice were also given IL-1 (2 μg on days 0, 1, 2, and 4) or a single dose of 0.1 μg MALP2, 25 μg poly (I:C), and 2 μg CpG ODN 1555 and 1466 on the day of the immunization (Zhu et al., 2010).

BALB/c mice were challenged i.p. with 2×10^7 pfu of recombinant vaccinia virus expressing gp160IIIB (vPE16; Earl et al., 1991). Mice were sacrificed 6 d after challenge; both ovaries were removed, homogenized in PBS, sonicated, and assayed for viral titers by culturing 10-fold serial dilutions with BS-C-1 cells. After 48 h of culture, crystal violet (0.1% in 20% Ethanol) was added to the cells and the number of plaques were counted and multiplied by the dilution factor.

TC1 tumor. The TC1 tumor cell line was derived from primary lung epithelial cells of C57BL/6 mice that had been transfected with HPV 16 E6 and E7 genes (Feltkamp et al., 1993). 50,000 TC1 cells were injected subcutaneously into the right flank of 8-wk-old C57BL/6 mice. 14 d after tumor injection, some mice were immunized s.c. with 100 μg HPV $E7_{49-57}$ peptide (RAHYNIVTF; Feltkamp et al., 1993) with DOTAP alone or in combination with IL-1β (4 doses of 2 μg on day 0, 1, 2, and 4 after immunization). Tumor growth was measured every 2–3 d.

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REFERENCES

Ben-Sasson, S.Z., J. Hu-Li, J. Quiel, S. Cauchetaux, M. Ratner, I. Shapira, C.A. Dinarello, and W.E. Paul. 2009. IL-1 acts directly on CD4 T cells to enhance their antigen-driven expansion and differentiation. *Proc. Natl. Acad. Sci. USA.* 106:7119–7124. http://dx.doi.org/10.1073/pnas.0902745106

Bonilla, W.V., A. Fröhlich, K. Senn, S. Kallert, M. Fernandez, S. Johnson, M. Kreutzfeldt, A.N. Hegazy, C. Schrick, P.G. Fallon, et al. 2012. The alarmin interleukin-33 drives protective antiviral $CD8^+$ T cell responses. *Science.* 335:984–989. http://dx.doi.org/10.1126/science.1215418

Chi, H. 2012. Regulation and function of mTOR signalling in T cell fate decisions. *Nat. Rev. Immunol.* 12:325–338.

Curtsinger, J.M., C.S. Schmidt, A. Mondino, D.C. Lins, R.M. Kedl, M.K. Jenkins, and M.F. Mescher. 1999. Inflammatory cytokines provide a third signal for activation of naive CD4+ and CD8+ T cells. *J. Immunol.* 162:3256–3262.

Ding, Z., K. Xiong, and T.B. Issekutz. 2000. Regulation of chemokine-induced transendothelial migration of T lymphocytes by endothelial activation: differential effects on naive and memory T cells. *J. Leukoc. Biol.* 67:825–833.

Earl, P.L., S. Koenig, and B. Moss. 1991. Biological and immunological properties of human immunodeficiency virus type 1 envelope glycoprotein: analysis of proteins with truncations and deletions expressed by recombinant vaccinia viruses. *J. Virol.* 65:31–41.

Elkabets, M., Y. Krelin, S. Dotan, A. Cerwenka, A. Porgador, R.G. Lichtenstein, M.R. White, M. Zoller, Y. Iwakura, C.A. Dinarello, et al. 2009. Host-derived interleukin-1alpha is important in determining the immunogenicity of 3-methylcholantrene tumor cells. *J. Immunol.* 182:4874–4881. http://dx.doi.org/10.4049/jimmunol.0803916

Feltkamp, M.C., H.L. Smits, M.P. Vierboom, R.P. Minnaar, B.M. de Jongh, J.W. Drijfhout, J. ter Schegget, C.J. Melief, and W.M. Kast. 1993. Vaccination with cytotoxic T lymphocyte epitope-containing peptide protects against a tumor induced by human papillomavirus type 16-transformed cells. *Eur. J. Immunol.* 23:2242–2249. http://dx.doi.org/10.1002/eji.1830230929

Fischer, H., G. Hedlund, T. Kalland, H.O. Sjögren, and M. Dohlsten. 1990. Independent regulation of IFN-gamma and tumor necrosis factor by IL-1 in human T helper cells. *J. Immunol.* 145:3767–3772.

Freedman, D.O., S. Parker-Cook, M.C. Maia e Silva, C. Braga, and A. Maciel. 1996. Very late antigen-4/vascular cell adhesion molecule-1 (VLA-4/VCAM-1) pathway is involved in the transendothelial migration of lymphocytes in bancroftian filariasis. *J. Immunol.* 156:2901–2908.

Fremond, C.M., D. Togbe, E. Doz, S. Rose, V. Vasseur, I. Maillet, M. Jacobs, B. Ryffel, and V.F. Quesniaux. 2007. IL-1 receptor-mediated signal is an essential component of MyD88-dependent innate response to Mycobacterium tuberculosis infection. *J. Immunol.* 179:1178–1189.

Ghiringhelli, F., L. Apetoh, A. Tesniere, L. Aymeric, Y. Ma, C. Ortiz, K. Vermaelen, T. Panaretakis, G. Mignot, E. Ullrich, et al. 2009. Activation of the NLRP3 inflammasome in dendritic cells induces IL-1beta-dependent adaptive immunity against tumors. *Nat. Med.* 15:1170–1178. http://dx.doi.org/10.1038/nm.2028

Gowda, N.M., X. Wu, and D.C. Gowda. 2012. TLR9 and MyD88 are crucial for the development of protective immunity to malaria. *J. Immunol.* 188:5073–5085. http://dx.doi.org/10.4049/jimmunol.1102143

Gulen, M.F., Z. Kang, K. Bulek, W. Youzhong, T.W. Kim, Y. Chen, C.Z. Altuntas, K. Sass Bak-Jensen, M.J. McGeachy, J.S. Do, et al. 2010. The receptor SIGIRR suppresses Th17 cell proliferation via inhibition of the interleukin-1 receptor pathway and mTOR kinase activation. *Immunity.* 32:54–66. http://dx.doi.org/10.1016/j.immuni.2009.12.003

Guo, L., G. Wei, J. Zhu, W. Liao, W.J. Leonard, K. Zhao, and W. Paul. 2009. IL-1 family members and STAT activators induce cytokine production by Th2, Th17, and Th1 cells. *Proc. Natl. Acad. Sci. USA.* 106:13463–13468. http://dx.doi.org/10.1073/pnas.0906988106

Halvorsen, R., G. Gaudernack, T. Leivestad, F. Vartdal, and E. Thorsby. 1987. Activation of resting, pure CD4+, and CD8+ cells via CD3. Requirements for second signals. *Scand. J. Immunol.* 26:197–205. http://dx.doi.org/10.1111/j.1365-3083.1987.tb02252.x

Hope, J.C., P. Sopp, R.A. Collins, and C.J. Howard. 2001. Differences in the induction of CD8+ T cell responses by subpopulations of dendritic cells from afferent lymph are related to IL-1 alpha secretion. *J. Leukoc. Biol.* 69:271–279.

Ichinohe, T., H.K. Lee, Y. Ogura, R. Flavell, and A. Iwasaki. 2009. Inflammasome recognition of influenza virus is essential for adaptive immune responses. *J. Exp. Med.* 206:79–87. http://dx.doi.org/10.1084/jem.20081667

Joeckel, L.T., R. Wallich, S.S. Metkar, C.J. Froelich, M.M. Simon, and C. Borner. 2012. Interleukin-1R signaling is essential for induction of proapoptotic CD8 T cells, viral clearance, and pathology during lymphocytic choriomeningitis virus infection in mice. *J. Virol.* 86:8713–8719. http://dx.doi.org/10.1128/JVI.00682-12

Kanda, T., M. Yamawaki, T. Ariga, and R.K. Yu. 1995. Interleukin 1 beta up-regulates the expression of sulfoglucuronosyl paragloboside, a ligand for L-selectin, in brain microvascular endothelial cells. *Proc. Natl. Acad. Sci. USA.* 92:7897–7901. http://dx.doi.org/10.1073/pnas.92.17.7897

Klarnet, J.P., D.E. Kern, S.K. Dower, L.A. Matis, M.A. Cheever, and P.D. Greenberg. 1989. Helper-independent CD8+ cytotoxic T lymphocytes express IL-1 receptors and require IL-1 for secretion of IL-2. *J. Immunol.* 142:2187–2191.

Kohlmeier, J.E., T. Cookenham, A.D. Roberts, S.C. Miller, and D.L. Woodland. 2010. Type I interferons regulate cytolytic activity of memory CD8(+) T cells in the lung airways during respiratory virus challenge. *Immunity.* 33:96–105. http://dx.doi.org/10.1016/j.immuni.2010.06.016

Lee, W.W., S.W. Kang, J. Choi, S.H. Lee, K. Shah, E.E. Eynon, R.A. Flavell, and I. Kang. 2010. Regulating human Th17 cells via differential expression of IL-1 receptor. *Blood.* 115:530–540. http://dx.doi.org/10.1182/blood-2009-08-236521

Lye, E., S. Dhanji, T. Calzascia, A.R. Elford, and P.S. Ohashi. 2008. IRAK-4 kinase activity is required for IRAK-4-dependent innate and adaptive immune responses. *Eur. J. Immunol.* 38:870–876. http://dx.doi.org/10.1002/eji.200737429

McAleer, J.P., D.J. Zammit, L. Lefrançois, R.J. Rossi, and A.T. Vella. 2007. The lipopolysaccharide adjuvant effect on T cells relies on nonoverlapping contributions from the MyD88 pathway and CD11c+ cells. *J. Immunol.* 179:6524–6535.

McCandless, E.E., M. Budde, J.R. Lees, D. Dorsey, E. Lyng, and R.S. Klein. 2009. IL-1R signaling within the central nervous system regulates CXCL12 expression at the blood-brain barrier and disease severity during experimental autoimmune encephalomyelitis. *J. Immunol.* 183:613–620. http://dx.doi.org/10.4049/jimmunol.0802258

McConkey, D.J., P. Hartzell, S.C. Chow, S. Orrenius, and M. Jondal. 1990. Interleukin 1 inhibits T cell receptor-mediated apoptosis in immature thymocytes. *J. Biol. Chem.* 265:3009–3011.

Mizuochi, T., D.J. McKean, and A. Singer. 1988. IL-1 as a co-factor for lymphokine-secreting CD8+ murine T cells. *J. Immunol.* 141:1571–1575.

Mohamadzadeh, M., H. DeGrendele, H. Arizpe, P. Estess, and M. Siegelman. 1998. Proinflammatory stimuli regulate endothelial hyaluronan expression and CD44/HA-dependent primary adhesion. *J. Clin. Invest.* 101:97–108. http://dx.doi.org/10.1172/JCI1604

Muehlhoefer, A., L.J. Saubermann, X. Gu, K. Luedtke-Heckenkamp, R. Xavier, R.S. Blumberg, D.K. Podolsky, R.P. MacDermott, and H.C. Reinecker. 2000. Fractalkine is an epithelial and endothelial cell-derived chemoattractant for intraepithelial lymphocytes in the small intestinal mucosa. *J. Immunol.* 164:3368–3376.

Nagoya, S., P.D. Greenberg, C. Yee, K.E. Weisser, H. Sugawara, M.B. Widmer, J. Slack, S.K. Dower, S.D. Lupton, and R.W. Overell. 1994. Helper T cell-independent proliferation of CD8+ cytotoxic T lymphocytes transduced with an IL-1 receptor retrovirus. *J. Immunol.* 153:1527–1535.

Palmer, G., and C. Gabay. 2011. Interleukin-33 biology with potential insights into human diseases. *Nat Rev Rheumatol.* 7:321–329. http://dx.doi.org/10.1038/nrrheum.2011.53

Panzer, S., R.L. Geller, and F.H. Bach. 1990. Purified human T cells stimulated with cross-linked anti-CD3 monoclonal antibody OKT3: rIL-1 is a co-stimulatory factor for CD4+CD29+CD45RA- T cells. *Scand. J. Immunol.* 32:359–371. http://dx.doi.org/10.1111/j.1365-3083.1990.tb02930.x

Pietschmann, P., J.J. Cush, P.E. Lipsky, and N. Oppenheimer-Marks. 1992. Identification of subsets of human T cells capable of enhanced transendothelial migration. *J. Immunol.* 149:1170–1178.

Sheng, K.C., M. Kalkanidis, D.S. Pouniotis, M.D. Wright, G.A. Pietersz, and V. Apostolopoulos. 2008. The adjuvanticity of a mannosylated antigen reveals TLR4 functionality essential for subset specialization and functional maturation of mouse dendritic cells. *J. Immunol.* 181:2455–2464.

Sikorski, E.E., R. Hallmann, E.L. Berg, and E.C. Butcher. 1993. The Peyer's patch high endothelial receptor for lymphocytes, the mucosal vascular addressin, is induced on a murine endothelial cell line by tumor necrosis factor-alpha and IL-1. *J. Immunol.* 151:5239–5250.

Staib, C., S. Kisling, V. Erfle, and G. Sutter. 2005. Inactivation of the viral interleukin 1beta receptor improves CD8+ T-cell memory responses elicited upon immunization with modified vaccinia virus Ankara. *J. Gen. Virol.* 86:1997–2006. http://dx.doi.org/10.1099/vir.0.80646-0

Stocker, C.J., K.L. Sugars, O.A. Harari, R.C. Landis, B.J. Morley, and D.O. Haskard. 2000. TNF-alpha, IL-4, and IFN-gamma regulate differential expression of P- and E-selectin expression by porcine aortic endothelial cells. *J. Immunol.* 164:3309–3315.

Takahashi, H., J. Cohen, A. Hosmalin, K.B. Cease, R. Houghten, J.L. Cornette, C. DeLisi, B. Moss, R.N. Germain, and J.A. Berzofsky. 1988. An immunodominant epitope of the human immunodeficiency virus envelope glycoprotein gp160 recognized by class I major histocompatibility complex molecule-restricted murine cytotoxic T lymphocytes. *Proc. Natl. Acad. Sci. USA.* 85:3105–3109. http://dx.doi.org/10.1073/pnas.85.9.3105

Takeshita, T., H. Takahashi, S. Kozlowski, J.D. Ahlers, C.D. Pendleton, R.L. Moore, Y. Nakagawa, K. Yokomuro, B.S. Fox, D.H. Margulies, and J.A. Berzofsky. 1995. Molecular analysis of the same HIV peptide functionally binding to both a class I and a class II MHC molecule. *J. Immunol.* 154:1973–1986.

Thompson, A.L., B.T. Johnson, G.D. Sempowski, M.D. Gunn, B. Hou, A.L. DeFranco, and H.F. Staats. 2012. Maximal adjuvant activity of nasally delivered IL-1α requires adjuvant-responsive CD11c(+) cells and does not correlate with adjuvant-induced in vivo cytokine production. *J. Immunol.* 188:2834–2846. http://dx.doi.org/10.4049/jimmunol.1100254

von Rossum, A., R. Krall, N.K. Escalante, and J.C. Choy. 2011. Inflammatory cytokines determine the susceptibility of human CD8 T cells to Fas-mediated activation-induced cell death through modulation of FasL and c-FLIP(S) expression. *J. Biol. Chem.* 286:21137–21144. http://dx.doi.org/10.1074/jbc.M110.197657

Wang, Y.F., V.L. Calder, J. Greenwood, and S.L. Lightman. 1993. Lymphocyte adhesion to cultured endothelial cells of the blood-retinal barrier. *J.Neuroimmunol.* 48:161–168.http://dx.doi.org/10.1016/0165-5728(93)90188-5

Weber, A., P. Wasiliew, and M. Kracht. 2010. Interleukin-1 (IL-1) pathway. *Sci. Signal.* 3:cm1. http://dx.doi.org/10.1126/scisignal.3105cm1

Wesa, A., and A. Galy. 2002. Increased production of pro-inflammatory cytokines and enhanced T cell responses after activation of human dendritic cells with IL-1 and CD40 ligand. *BMC Immunol.* 3:14. http://dx.doi.org/10.1186/1471-2172-3-14

Wingfield, P., M. Payton, J. Tavernier, M. Barnes, A. Shaw, K. Rose, M.G. Simona, S. Demczuk, K. Williamson, and J.M. Dayer. 1986. Purification and characterization of human interleukin-1 beta expressed in recombinant Escherichia coli. *Eur. J. Biochem.* 160:491–497. http://dx.doi.org/10.1111/j.1432-1033.1986.tb10066.x

Zhao, Y., C. De Trez, R. Flynn, C.F. Ware, M. Croft, and S. Salek-Ardakani. 2009. The adaptor molecule MyD88 directly promotes CD8 T cell responses to vaccinia virus. *J. Immunol.* 182:6278–6286. http://dx.doi.org/10.4049/jimmunol.0803682

Zhu, Q., C. Egelston, S. Gagnon, Y. Sui, I.M. Belyakov, D.M. Klinman, and J.A. Berzofsky. 2010. Using 3 TLR ligands as a combination adjuvant induces qualitative changes in T cell responses needed for antiviral protection in mice. *J. Clin. Invest.* 120:607–616. http://dx.doi.org/10.1172/JCI39293