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Cutting Edge: IL-12 and Type I IFN Differentially Program CD8 T Cells for Programmed Death 1 Re-expression Levels and Tumor Control

Michael Y. Gerner, Lynn M. Heltemes-Harris, Brian T. Fife, and Matthew F. Mescher

Naive CD8 T cells proliferate in response to TCR and CD28 signals, but require IL-12 or type I IFN to survive and develop optimal effector functions. Although murine CTL generated in vitro in response to IL-12 or IFN-α had comparable effector functions, IL-12–stimulated cells were significantly more effective in controlling tumor in an adoptive immunotherapy model. They maintained high numbers and function, whereas IFN-α–stimulated cells declined in number and became exhausted. Consistent with this, IFN-α–stimulated cells in the tumor expressed higher levels of programmed death 1 (PD-1) inhibitory receptor than did IL-12–stimulated cells. When blocking Ab specific for the PD-L1 ligand of PD-1 was administered, the efficacy of IFN-α–stimulated CTL became comparable with that of IL-12–stimulated cells. Thus, IL-12 and IFN-α differentially program CD8 T cells to re-express distinct levels of PD-1 upon re-encountering Ag, resulting in IL-12–stimulated cells being less susceptible to exhaustion in the face of sustained tumor Ag. The Journal of Immunology, 2013, 191: 1011–1015.

Activated CD8 T cells express inhibitory receptors that can limit responses to viruses or tumors, the best characterized being programmed death 1 (PD-1; CD279). PD-1 belongs to the CD28/CTLA-4 family of receptors and binds PD-L1 and PD-L2 ligands that are B7 family members (1–3). Blocking interactions of PD-1 with its ligands can increase CD8 T cell responses to chronic virus infections and tumors (3–5), and PD-1 and PD-L1 Ab therapy has demonstrated significant tumor regression in human trials (6, 7). PD-1 expression is upregulated by TCR binding to Ag and depends on NFATc1 (8), but the factors that regulate PD-1 expression levels and determine whether it mediates tolerance are poorly understood. As we show in this article, the extent to which effector CD8 T cells upregulate PD-1 expression when they re-encounter Ag differs depending on whether they have differentiated in response to IL-12 or type I IFN signals.

Naive CD8 T cells responding to Ag and costimulation develop only weak effector functions unless an inflammatory cytokine(s) is available to signal for differentiation to strong effector status (9). IL-12 and/or type I IFN (IFN-α/β) are the major cytokines that provide this third signal for responses to transplanted tissues, viral and bacterial pathogens, and tumors (9–11). IL-12 and IFN-α stimulate development of comparable effector activities (12), consistent with both cytokines stimulating a common program of regulation of ~350 genes, many of which encode proteins known to be critical for effector functions, including grzB, T-bet, Eomes, FasL, and others (12). However, each cytokine also uniquely regulates expression of 200–300 genes, raising the possibility that in vivo properties of effector cells may differ depending on which signal 3 cytokine drove their differentiation. To begin to examine this, we compared effector cells generated in the presence of IL-12 or IFN-α for their ability to control tumor growth in an adoptive tumor immunotherapy model. This provides an excellent model to examine the differential effects of the cytokines because it allows generation of CTL under well-defined in vitro conditions followed by assessment of the in vivo migration and function of the effector cells. The results described in this study demonstrate that in comparison with IFN-α, programming differentiation with IL-12 results in decreased levels of PD-1 on CD8 T cells in the tumor and increased efficacy of the cells in controlling tumor growth, strongly suggesting that provision of IL-12 during the in vitro generation of cells for adoptive immunotherapy will improve outcomes.

Materials and Methods

Mice, tumor cell line, and reagents

OT-1.PL mice were generated by crossing OT-1 mice with Thy1.1 congenic B6. PL-Thy1a/Cy (Thy1.1) mice (The Jackson Laboratory), and C57BL/6NCr

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Abbreviation used in this article: PD-1, programmed death 1.
and CD45.1-congenic B6 (B6.Ly5.2) mice were from the National Cancer Institute. Experiments were conducted under specific pathogen-free conditions and performed in compliance with relevant laws and guidelines, and with approval of the Institutional Animal Care and Use Committee at the University of Minnesota. B16.OVA (OVA transfect B6.F10) cells were maintained in complete RPMI 1640 medium with 800 μg/ml G418. Abs were purchased from BioLegend, BD Biosciences, eBioscience, or Invitrogen. Anti–PD-L1 mAb for in vivo use (clone M1H6) was generated as previously described (13). Mice received 100 μg (i.p.) anti–PD-L1 or isotype control IgG1 (Jackson Immunoresearch) on the same day as OT-I–CTL cells transferred, and then every 3 d for a total of 4 injections.

In vitro stimulation and adoptive transfer of naive OT-I T cells
Naïve OT-I or OT-I.PL T cells were purified from lymph nodes by negative selection (Supplemental Fig. 1A). Cells were stimulated in flat-bottom microtiter wells having DimerX H-2Kb:Ig fusion protein (BD Biosciences) loaded with OVA257–264 peptide (New England Peptide) and rB7-1/Fc chimeric protein (R&D Systems) immobilized on the surface (14). A total of 1–5 × 10^5 cells in 0.2 ml complete RPMI 1640 medium were placed in wells, and 2.5 U/ml IL-2 (R&D Systems) was added. Where indicated, 2 U/ml murine rIL-12 (R&D Systems), 1000 U/ml murine IFN-α (PBL Biomedical Laboratories), or both were added. These cytokine concentrations stimulate optimal development of effector functions (Supplemental Fig. 1). Cells were harvested on day 3 and adoptively transferred (tail vein).

Tumor growth and flow cytometric analysis of T cells
Mice were injected s.c. (flank) with 2 × 10^5 B16.OVA cells, and growth was monitored by determining area as the product of two right-angle measurements with calipers. Tumor-bearing mice received activated OT-I T cells by adoptive transfer on the day indicated (days 6–10 of tumor growth). Mice received 10^5 cells in 0.2 ml complete RPMI 1640 medium with 800 μg/ml G418. Abs were purchased from BioLegend, BD Biosciences, eBioscience, or Invitrogen. Anti–PD-L1 mAb (i.p.) and isotype control IgG1 were injected s.c. (flank) on day 0. Six days later, mice received either no CTL or CTL (i.e., tail vein) that had been stimulated for 3 d in vitro in the presence of IL-12 (IL-12–CTL) or IFN-α (IFN-α–CTL). (A) Tumor growth expressed as area. (B) Numbers of OT-I T cells in tumors. (C) Density of OT-I cells in tumors (number per mm^2 of tumor area). (D) IFN-γ production by OT-I cells isolated from tumors and stimulated ex vivo with Ag for 4 h. (E) IL-2 production by OT-I cells isolated from tumors and stimulated ex vivo with Ag for 4 h. Results in all panels are shown as average ± SD for three to four mice per group.

Results and Discussion

Effectors CTL generated in response to IL-12 control tumor more effectively than CTL generated in response to IFN-α
When naïve CD8 T cells are stimulated in vitro with Ag and B7-1, either IL-12 or IFN-α stimulates development of strong effectors by day 3 (12) and programs the cells to develop a protective memory population if they are then transferred into normal mice (15). To assess the effects of the cytokines on the ability of effector cells to control tumors, purified naïve (CD44^low^) OT-I T cells (Supplemental Fig. 1A) were stimulated for 72 h in microtiter wells having immobilized H-2Kb/OVA257–264 and B7-1/Fc in the presence of either IL-12 (IL-12–CTL) or IFN-α (IFN-α–CTL). The cells were then adoptively transferred (tail vein) into mice having progressing B16.OVA tumors (B16 melanoma expressing full-length OVA) growing s.c. In the experiment shown in Fig. 1, mice received tumor on day 0, and activated OT-I cells were transferred 6 d later. Despite comparable cytolytic activity and IFN-γ production at 72 h (Supplemental Fig. 1B), IL-12–CTL were much more effective in controlling tumor growth over the next 1–2 wk than were IFN-α–CTL (Fig. 1A). This differential control of tumor was reproducibly seen in numerous experiments (see later), and comparing growth after transfer of differing numbers of CTL indicated that the IL-12–CTL are >5-fold more effective than the IFNα–CTL (Fig. 1A and data not shown).

IFN-α–CTL, but not IL-12–CTL, become “exhausted” during tumor growth
OT-I effector cells increased in number in the tumor over the first 3 d posttransfer, and numbers were similar for IL-12 and IFN-α effectors up to ~7 d posttransfer (day 13; Fig. 1B). Thus, differing efficacy does not result from differential ability of the effector cells to traffic to the tumor. Beyond day 13, the number of IFN-α–CTL in the tumor declined, whereas the number of IL-12–CTL remained high. In fact, when expressed as total OT-I per tumor volume (i.e., density of OT-I in the tumor mass), the IL-12–CTL remained constant for at least 14 d posttransfer, whereas IFN-α–CTL declined >100-fold as the total number of CTLs declined and the tumors continued to grow (Fig. 1C).

When the functional capacities of the OT-I cells in the tumors were assessed by their ability to produce IFN-γ upon ex vivo restimulation, IL-12–CTL and IFN-α–CTL were comparable on days 8 and 10 (days 2 and 4 posttransfer). However, by day 13, most of the IFN-α–CTL were not. Thus, the IFN-α–CTL not only decline in number in comparison with the IL-12–CTL, they undergo increased functional impairment over time in the tumor environment.

Intratumoral IL-12–CTL and IFN-α–CTL differentially express PD-1
The declining numbers and loss of functional capacities of the IFN-α–CTL resembled the exhaustion that CD8 effector CTLs undergo in the face of chronic virus infections and tumors. In virus and tumor models, considerable evidence has accumulated to implicate the inhibitory receptor PD-1 (CD279)
in development of exhaustion (1, 3). Furthermore, the B16 melanoma tumor expresses PD-L1 (B7-H1; CD274), a ligand for PD-1 (16). We therefore examined the expression levels of PD-1 on IL-12–CTL and IFN-α–CTL.

Naive CD8 T cells do not express PD-1, but they are upregulated within 72 h of in vitro stimulation with Ag/B7 alone, and levels do not differ when either IL-12 or IFN-α are present (Fig. 2A). This is consistent with oligonucleotide microarray analysis that showed mRNA levels for PD-1 to be strongly upregulated by just Ag and B7-1 signals, and not changed when the cytokines are present (12). Thus, PD-1 expression is comparably high on IL-12–CTL and IFN-α–CTL at the time of transfer into tumor-bearing mice. Within 4 d of transfer, the OT-1 CTL in the spleens of the mice have downregulated PD-1 expression (Fig. 2B, 2D), as expected for cells no longer exposed to Ag. In contrast, PD-1 expression is high on intratumoral OT-1 cells and is at a significantly higher level on IFN-α–CTL than on IL-12–CTL (Fig. 2C, 2D). By 14 d posttransfer (day 20), the number of IFN-α–CTL had declined substantially in comparison with the IL-12–CTL (Fig. 2E). In additional experiments, we found that PD-1 expression was also higher on IFN-α–CTL when 5-fold higher concentrations of the cytokines were used for the in vitro stimulation (Supplemental Fig. 2).

Differential expression of PD-1 might result from the cytokines mediating differential programming for receptor upregulation upon Ag re-encounter. Alternatively, other functional differences between the IL-12– and IFN-α–stimulated cells might account for differing control of tumor growth, with PD-1 expression being secondarily affected. To address this, IL-12–CTL and IFN-α–CTL having differing congenic markers were transferred in equal numbers into B16.OVA-bearing mice. Six days later, the tumors were smaller in mice that received 5 × 10^6 IL-12–CTL than in mice that received 5 × 10^6 IFN-α–CTL, and tumors were of intermediate size when 2.5 × 10^6 of each type of CTL (Mix[IFN-α–CTL + IL-12–CTL]) was transferred into the same mouse (Fig. 3A). As expected, intratumoral OT-1 cells in mice that received just IL-12–CTL had lower PD-1 expression than those in mice that received just IFN-α–CTL (Fig. 3B). For mice that received both types of CTL, congenic markers were used to distinguish IL-12–CTL (Mix IL-12 CTL) from IFN-α–CTL (Mix IFN-α CTL) in the tumors, and the IL-12–CTL still exhibited significantly lower PD-1 expression than did IFN-α–CTL (Fig. 3B). Thus, OT-1 effector cells in the same tumor express lower or higher levels of PD-1 depending on whether they initially responded to IL-12 or IFN-α.

We also examined effector cells generated in the presence of both IL-12 and IFN-α (IFN-α/IL-12–CTL). Upon adoptive transfer, these cells controlled tumor growth comparably with cells stimulated with Ag/B7 and IL-12, and more effectively than cells stimulated with Ag/B7 and IFN-α (Fig. 3A). Expression of PD-1 on IFN-α/IL-12–CTL in the tumors was low, comparable with levels on IL-12–CTL and lower than on IFN-α–CTL (Fig. 3B). Thus, the IL-12–dependent PD-1low phenotype predominates when both IL-12 and IFN-α are present to drive differentiation in response to Ag/B7.

**Figure 2.** PD-1 is expressed at higher levels on IFN-α–differentiated CTLs when they re-encounter Ag in the tumor. (A) Naive OT-1 cells were stimulated for 3 d in vitro in the presence of IL-12 (IL-12–CTL) or IFN-α (IFN-α–CTL), and PD-1 expression was determined. (B and C) Cells stimulated as in (A) were transferred into mice that had 6-d-old B16.OVA tumors. Four days later, PD-1 expression on OT-1 cells from spleens and tumors was determined. Representative histograms (2–3 mice/group) are shown. (D) Cells were stimulated in vitro as in (A) and transferred at 5 × 10^6 cells/mouse into mice that had received B16.OVA tumor 6 d earlier. PD-1 expression was determined 10 d later on OT-1 cells in the spleens and tumors, and results are shown as mean fluorescence intensity (MFI; geometric mean) ± SD (2–3 mice/group). Significantly higher PD-1 expression on IFN-α–CTL versus IL-12–CTL in tumors was seen in five independent experiments when examined at varying times posttransfer. (E) Numbers of OT-1 cells in tumors of mice from (D), shown as average ± SD (2–3 mice/group) on days 10 and 20.
PD-1 is upregulated when T cell activation results in translocation of NF-ATc1 (NFAT2) to the nucleus where it interacts with the pdcld promoter (8). Upon transition of naive to effector cells, the Pdcd1 locus is demethylated to facilitate transcription and is remethylated as Ag is cleared, but remains demethylated in exhausted CD8 T cells in chronic virus infections (17). Thus, a potential mechanism for differential regulation of PD-1 re-expression might be differences in the level of demethylation/remethylation of the pdcld locus by IL-12 versus IFN-α. In our experiments, IFN-α does not increase expression of PD-1 on primary effector cells, but it does program the cells to subsequently re-express higher levels of PD-1 upon re-encountering Ag. Schurich et al. (18) also reported that IFN-α does not increase PD-1 levels during initial priming of T cells, but showed that when it is provided beyond the peak of the primary response, it has the effect of maintaining PD-1 expression at a higher level. A postprogramming effect of IL-12 on PD-1 expression has also been observed. Schurich et al. (19) showed that treatment of exhausted human HBV-specific T cells with IL-12 results in downregulation of PD-1 expression and recovery of effector functions, suggesting that PD-1 re-expression levels programmed during priming can be altered by an IL-12 signal at later times in the response. Whether these late effects of signal 3 cytokines involve similar mechanisms to those of the differential programming that occurs during priming, as shown in this study, remains to be determined.

Adoptive cell therapy for treatment of cancers holds considerable promise (20), and numerous studies have evaluated...
methods for activating and expanding tumor-specific CD8 T cells in vitro for adoptive transfer, including the use of various cytokines. Differentiation of naive CD8 T cells to acquire optimal effector functions and develop memory requires a signal from an inflammatory cytokine, and either IL-12 or type I IFN provides this signal (9–11), suggesting that CTLs generated using either might be equally effective in controlling tumor. The results described in this study demonstrate that this is not the case. CTLs generated in response to IL-12 are much more effective as a result of the fact that they do not upregulate PD-1 expression to as high a level upon re-encountering Ag as do CTLs generated in response to IFN-α. Thus, including IL-12 during activation of CD8 T cells for adoptive immunotherapy is likely to yield cells with greater efficacy. Furthermore, the IL-12–driven PD-1low phenotype dominates when both cytokines are present, obviating any need to eliminate type I IFN signaling during generation of the effectors.

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Disclosures

The authors have no financial conflicts of interest.

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