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Research Article

IL-12 has significant antitumor activity in mice that may be mediated by CD8(+) T cells. We show in this report that repeated subcutaneous injections of IL-12 in patients with cancer resulted in the selective expansion of a subset of peripheral blood CD8(+) T cells. This T cell subset expressed high levels of CD18 and upregulated IL-12 receptor expression after IL-12 treatment in vivo. In normal subjects, these CD3(+)CD8(+)CD18(bright) T cells expressed IL-12 and IL-2 receptors and adhesion/costimulatory molecules to a greater degree than other CD8(+) and CD4(+) T cells. They appeared morphologically as large granular lymphocytes, although they did not express NK cell markers such as CD56. In addition, CD8(+)CD18(bright) T cells were almost exclusively T cell receptor (TCR) alphabeta+, and exhibited a TCR Vbeta repertoire that was strikingly oligoclonal, whereas the Vbeta repertoire of CD18(dim) T cells was polyclonal. Although CD8+CD18(bright) T cells demonstrated little functional responsiveness to IL-12 or IL-2 alone in vitro, they responded to the combination of IL-12+IL-2 with strong IFN-gamma production and proliferation and enhanced non-MHC-restricted cytolytic activity. In contrast, CD18(dim) T cells were not activated by IL-12 or IL-2, alone or in combination. These findings demonstrate that CD8+CD18(bright) T cells are a unique population of peripheral blood lymphocytes with features of both memory and effector cells that are capable of TCR-independent activation through combined [...]

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Characterization of a Novel Subset of CD8⁺ T Cells That Expands in Patients Receiving Interleukin-12

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Abstract

IL-12 has significant antitumor activity in mice that may be mediated by CD8⁺ T cells. We show in this report that repeated subcutaneous injections of IL-12 in patients with cancer resulted in the selective expansion of a subset of peripheral blood CD8⁺ T cells. This T cell subset expressed high levels of CD18 and upregulated IL-12 receptor expression after IL-12 treatment in vivo. In normal subjects, these CD3⁺CD8⁺CD18^{bright} T cells expressed IL-12 and IL-2 receptors and adhesion/costimulatory molecules to a greater degree than other CD8⁺ and CD4⁺ T cells. They appeared morphologically as large granular lymphocytes, although they did not express NK cell markers such as CD56. In addition, CD8⁺CD18^{bright} T cells were almost exclusively T cell receptor (TCR) $\alpha\beta^+$, and exhibited a TCR V β repertoire that was strikingly oligoclonal, whereas the V β repertoire of CD18^{dim} T cells was polyclonal. Although CD8⁺CD18^{bright} T cells demonstrated little functional responsiveness to IL-12 or IL-2 alone in vitro, they responded to the combination of IL-12+IL-2 with strong IFN- γ production and proliferation and enhanced non-MHC-restricted cytolytic activity. In contrast, CD18^{dim} T cells were not activated by IL-12 or IL-2, alone or in combination. These findings demonstrate that CD8⁺CD18^{bright} T cells are a unique population of peripheral blood lymphocytes with features of both memory and effector cells that are capable of TCR-independent activation through combined stimulation with IL-12+IL-2. As this activation results in IFN- γ production and enhanced cytolytic activity, these T cells may play a role in innate as well as acquired immunity to tumors and infectious pathogens. Additional studies will be necessary to determine whether CD8⁺CD18^{bright} T cells mediate the antitumor effect of IL-12 or IL-2 administered to cancer patients, and if so, whether maximal activation of these T cells with the combination of IL-12+IL-2 in vivo can augment the clinical effectiveness of these cytokines. (*J. Clin. Invest.* 1998. 102: 561–575.) Key words: lymphocytes • activation • cytokines • immunotherapy • cancer

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Introduction

IL-12 is a cytokine derived from antigen-presenting cells that stimulates NK cells and T cells to proliferate, produce IFN- γ , and lyse tumor cells (1–5). IL-12 promotes the development of cellular immune responses by inducing CD4⁺ T cells to differentiate into T helper type 1 (Th1) cells (6, 7) and by stimulating cytolytic activity and cytokine production among CD8⁺ T cells and NK cells. This effect on cellular immunity appears to underlie the ability of IL-12 to effectively eradicate viral and parasitic infections (8–11) as well as established tumors in mice (12). The antitumor activity of IL-12 in mice has formed the basis for phase I and II clinical trials involving the administration of IL-12 to patients with cancer (13, 14). In mice, some studies have demonstrated that the depletion of CD8⁺ T cells diminishes the antitumor effect of IL-12 (12), whereas another recent report suggested that V α 14 NKT cells are responsible for the antitumor effect (15). However, in murine models of ovarian carcinoma and melanoma, tumor regression in response to IL-12 was associated with the migration of CD8⁺ T cells into tumor sites (16). Furthermore, there is evidence in mice that CD8⁺ T cells mediate the graft-versus-leukemia effect of IL-12 (17). In humans, as in mice, there are data which suggest that CD8⁺ T cells may have an essential role in antitumor immunity. In melanoma patients receiving hapten-modified autologous tumor cell vaccines, lymphocytic infiltrates within regressing metastases are comprised largely of CD8⁺ T cells (18). In patients with AIDS, autologous IL-2-activated CD8⁺ T cells can cause significant regression of Kaposi's sarcoma lesions (19). Taken together, these studies in animal models and the results of clinical trials suggest that CD8⁺ T cells play an important role in antitumor immunity, and that the antitumor activity of IL-12 may be mediated by these cells.

Although it has been demonstrated that IL-12 has potent immunomodulatory effects on T cells, freshly isolated peripheral blood T cells exhibit little functional responsiveness to IL-12. Instead, T cell IL-12 responsiveness in vitro is dependent on activation via the T cell receptor (TCR)/CD3 complex or with a mitogen such as phytohemagglutinin (2, 3). This activation is required to upregulate the expression of IL-12 receptors (20–22) and render cells responsive to IL-12. In addition, T cell activation is required to induce the expression of signal transducer and activator of transcription (STAT)4 (23), an essential component of IL-12 signaling.

In light of the observations derived from mouse tumor models and from attempts to stimulate cellular immune responses directed against malignancies in humans, the clinical potential of IL-12 in the treatment of human cancer may rest

1. Abbreviations used in this paper: STAT, signal transducer and activator of transcription; TCR, T cell receptor.

in part on its ability to activate in vivo those T cell subsets capable of mediating TCR-dependent and/or TCR-independent killing of tumor cells. However, because human peripheral blood T cells demonstrate little IL-12 responsiveness in the absence of in vitro activation, the mechanism by which CD8⁺ or CD4⁺ T cells would be capable of mediating the antitumor effect of parenterally administered IL-12 is unclear. One possibility is that only a small subset of peripheral blood T cells is capable of responding to IL-12, making it difficult to detect IL-12-induced activation in vitro when intermixed with T cells that are unresponsive to IL-12. Nonetheless, this small T cell subset may be capable of potent antitumor activity. This would be analogous to the IL-12-induced antitumor activity observed in C57BL/6 mice in the small V α 14 NKT lymphocyte subset (15).

The concept that subpopulations of T cells can differ from the majority of T cells in their ability to be activated in vivo has gained credence from observations involving CD8⁺ and CD4⁺ T cells. In humans, T cells with rapid recall responses to antigens such as tetanus toxoid have been termed memory cells. These memory cells, which have been identified among the CD4⁺ and CD8⁺ subsets, are characterized immunophenotypically by the strong expression of CD2, LFA-1, LFA-3, CD45RO, and CD29 relative to other T cells (24). In addition to demonstrating strong recall responses to tetanus, these T cells also produce large amounts of IFN- γ in response to mitogens. Bystander T cell proliferation induced by viruses and type I interferon (25) and LPS-induced T cell stimulation (26) appears to primarily involve a small subpopulation of CD8⁺CD44^{hi} memory T cells.

To determine whether distinct subsets of peripheral blood lymphocytes in humans are capable in vivo of responding to IL-12, we performed an immunophenotypic analysis of T and NK cells in patients with cancer receiving subcutaneous injections of IL-12. Through this approach, we identified a subpopulation of CD8⁺ T cells (CD8⁺CD18^{bright}) that expanded in vivo and strongly upregulated IL-12 receptor expression in response to IL-12. Although in normal subjects, these CD8⁺ T cells constitutively expressed IL-2 and IL-12 receptors, they responded poorly in vitro to either cytokine alone, but, like NK cells, were strongly activated by the combination of IL-12+IL-2. This identifies CD8⁺CD18^{bright} T cells as a unique subset of peripheral blood T cells that can be activated by IL-12+IL-2 in a TCR-independent manner and may play a role in mediating the antitumor effect of these cytokines when administered to patients with cancer.

Methods

Isolation of PBMC and T cell subsets. Heparinized blood samples were obtained from patients and normal volunteers. All patients had solid tumors and were receiving subcutaneous injections of IL-12 on a multicenter phase I dose escalation trial. This protocol was approved by the Human Subjects Protection Committee of the Dana-Farber Cancer Institute (DFCI), and informed consent was obtained from all patients. Blood samples enriched for white blood cells were also obtained from volunteers undergoing platelet pheresis in the DFCI Blood Bank. PBMC were isolated from blood samples through density gradient centrifugation using Ficoll-Hypaque (Pharmacia, Uppsala, Sweden).

For the isolation of CD18^{bright} and CD18^{dim} T cells subsets, PBMC were first depleted of monocytes through passage over a nylon wool column. For the preparation of CD8-enriched T cells, monocyte-

depleted PBMC were depleted of CD4⁺ T cells, B cells, and NK cells using antibodies to lineage-specific markers (anti-CD4, anti-CD20, and anti-CD56) and magnetic beads coated with anti-mouse Ig antibodies (Advanced Magnetics, Cambridge, MA). CD8-enriched T cell preparations were then stained with CD18-FITC and CD8-PE, and PE positive cells were separated on a fluorescence activated cell sorter into CD18^{bright} and CD18^{dim} populations based on CD18-FITC fluorescence intensity (CD18^{bright} cells routinely had a CD18-FITC mean fluorescence intensity five to six times greater than CD18^{dim} cells). CD18^{bright} and CD18^{dim} T cells were 95–98% pure after sorting.

Antibodies and cytokines. The following unconjugated and PE- or FITC-conjugated antibodies were obtained from Coulter (Hialeah, FL): negative control, anti-CD4, anti-CD8, anti-CD56 (NKH1), anti-CD28, anti-CD45RA, anti-CD20 (B1), and anti-CD29. Anti-CD49d was purchased from T Cell Diagnostics (Woburn, MA). The anti-IL-2R β antibody (341, IgG1) was a gift from Stefan Voss (Beth Israel Deaconess Medical Center, Boston, MA). Anti-CD2 (20B6, IgG1), anti-CD2R (T11-3, IgG3), anti-CD18 (8C12, IgM), anti-CD56 (3B8, IgM and N901, IgG1), anti-CD6 (T12, IgM), anti-IL-2R γ (3B5, IgG1) and anti-IL-2R α (IgG2a) have been previously described (27, 28) and were used as dilutions of mouse ascites. MOPC-21 (Sigma Immunochemicals, St. Louis, MO), used as a dilution of ascites, served as a mouse IgG1 negative control antibody. Anti-IL-12R β 1 (12R β .3F12, IgG1) is a non-neutralizing antibody specific for the β 1 subunit of the IL-12 receptor (29). PE- and FITC-conjugated isotype-specific goat anti-mouse antibodies, biotin-conjugated goat anti-mouse IgG1, and streptavidin-PE were purchased from Southern Biotechnology (Birmingham, AL).

Recombinant human IL-12 (specific activity 1.7×10^7 U/mg) was generously provided by Steven Herrmann at Genetics Institute (Cambridge, MA). IL-2 (specific activity 3.9×10^6 U/ml) was generously provided by Amgen (Thousand Oaks, CA).

Proliferation assays and measurement of IFN- γ production. Sorted T cells were incubated in 96-well U-bottom plates at 3×10^4 cells/well with medium alone or the indicated concentration of cytokines at 37°C. Proliferation assays were performed as previously described (28) and consisted of a 96-h incubation, with 1 μ Ci [³H]thymidine (DuPont NEN, Boston, MA) added 8 h before harvesting. For IFN- γ assays, supernatants were harvested after a 72-h incubation and the IFN- γ concentration assayed using an IFN- γ ELISA (Endogen, Cambridge, MA).

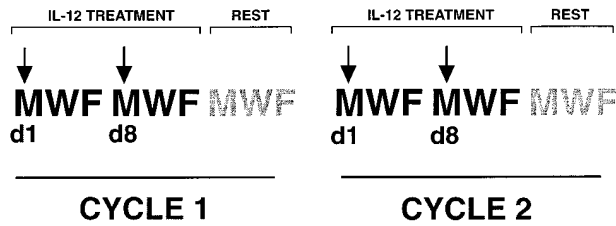
Cytotoxicity assays. Sorted CD8⁺CD18^{bright} or CD8⁺CD18^{dim} T cells were first incubated overnight in U-bottom well plates with either medium alone or the indicated cytokines at 37°C. COLO or OKT3 cells were then labeled with ⁵¹Cr and added to the T cells at a 5:1 effector:target ratio. T cells were incubated with the labeled target cells for 4 h at 37°C, and the supernatants were then harvested. ⁵¹Cr release was assayed using a gamma counter, and percent of specific cytotoxicity calculated as previously described (5).

Immunofluorescence analysis. For direct staining, 2.5×10^5 cells were incubated with the indicated PE- or FITC conjugated antibody for 20 min on ice. For indirect staining, cells were incubated with the primary, unconjugated antibody for 20 min on ice, washed twice, and then incubated with a PE- or FITC-conjugated isotype-specific secondary antibody for 20 min. Cytokine receptor staining was performed with a three-step method using the primary unconjugated antibody, a biotin-conjugated isotype-specific secondary antibody, and streptavidin-PE. Isotype-specific negative controls were used with direct and indirect staining as well as with the three-step staining involving biotin/streptavidin-PE. After staining, cells were fixed with 1% formaldehyde and analyzed by flow cytometry.

Cytospin preparations. Immediately after sorting, CD8⁺CD18^{bright} T cells, CD8⁺CD18^{dim} T cells, or NK cells were spun onto glass slides and stained with Wright-Giemsa. Stained cells were examined using an Olympus BX60 microscope.

RNA extraction, reverse transcription and PCR. RNA was extracted from sorted CD8⁺CD18^{bright} and CD8⁺CD18^{dim} T cells using the RNASat-60 kit (Tel-test Inc., Friendswood, TX) according to the

A



B

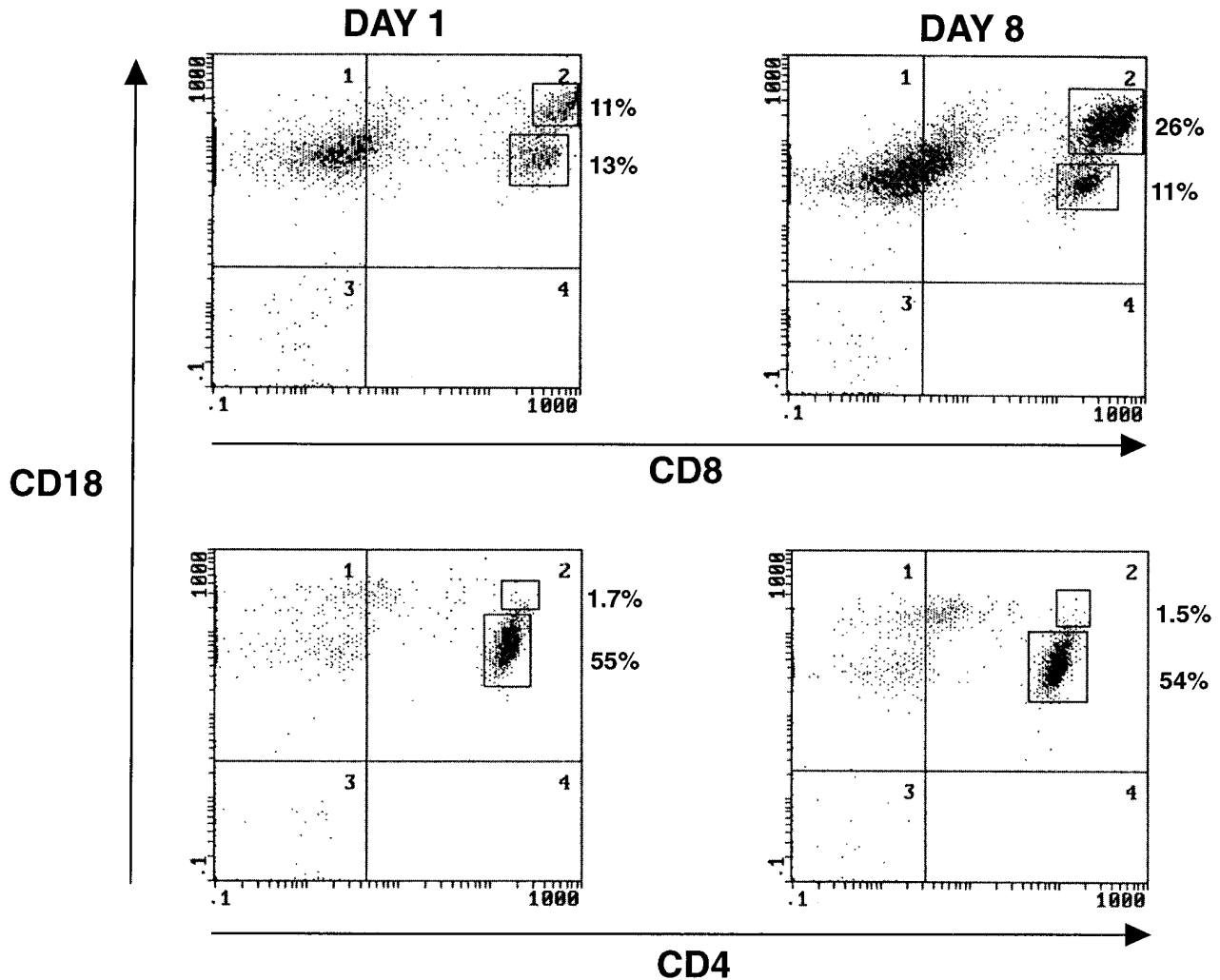


Figure 1. A subset of human CD8⁺ T cells expands in vivo in response to subcutaneously administered IL-12. (A) Subcutaneous injections of IL-12 were administered to cancer patients as part of a phase I dose escalation study. Treatment cycles were begun 14 d after receiving a single test dose of IL-12. A cycle of treatment consisted of single injections of IL-12 on Monday, Wednesday, and Friday for two consecutive weeks, followed by a week of rest. Arrows point to the days (days 1 and 8) within each cycle when blood samples were obtained for immunophenotypic analysis. Blood samples were drawn just before receiving the IL-12 injection. (B) PBMC were isolated from patient blood samples drawn before the administration of IL-12 on days 1 and 8 of each treatment cycle. PBMC were two-color stained with CD18-FITC (*y-axis*) and either CD4-PE or CD8-PE (*x-axis*) and subjected to FACS analysis, gating on the lymphocyte population. Results shown are from one patient at the 500 ng/kg dose level during cycle 1, and are representative of the results obtained with two other patients (one at the 500 ng/kg dose level and one at 700 ng/kg). (C) PBMC were isolated from three patients at the 500 ng/kg and 700 ng/kg dose levels on days 1 and 8 of cycle 1 and stained with either CD56-PE/CD18-FITC, CD4-PE/CD18-FITC, or CD8-PE/CD18-FITC. Cell number was obtained by multiplying the lymphocyte subset percentage (calculated by FACSTM analysis) by the absolute number of lymphocytes (calculated by performing a complete blood count on the blood sample).

C

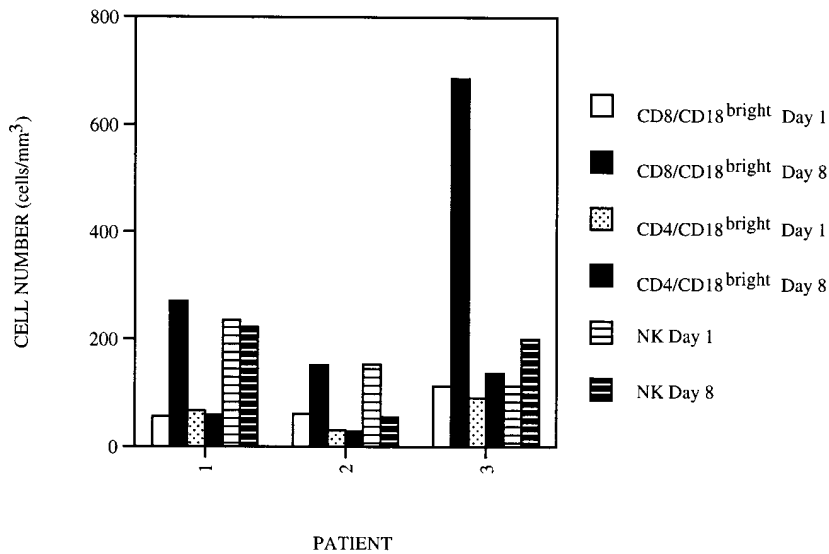


Figure 1 (Continued)

manufacturer's protocol. First strand cDNA was generated from 2 μ g of total RNA using random hexanucleotides (Pharmacia Biotech Inc., Piscataway, NJ) and reverse transcriptase (Superscript, Gaithersburg, MD). Each V β segment was amplified with one of the 26 V β subfamily specific primers and a C β primer recognizing both C β 1 and C β 2 regions. PCR amplification of V β 5 and V β 13 each required the use of two primers to identify the entire V β subfamily. The sequences of primers used in these experiments were described by Choi et al. (30) except for the C β and V β 3, V β 19, V β 21, V β 22, V β 23, and V β 24 primers that were described by Puisieux et al. (31). The C β primer was conjugated to fluorescent dye 6-FAM (Applied Bioethicists, Foster City, CA) for CDR3 size analysis. The amplification was performed over 30 cycles in a final volume of 100 μ l on a DNA thermal cycler (Perkin-Elmer Corp., Norwalk, CT). The PCR cycle profile was as follows: denaturation at 94°C for 1 min, annealing at 55°C for 1 min, extension at 72°C for 1 min, and a final polymerization step of 10 min at 72°C. Experiments in which template DNA was titrated and in which the number of cycles was varied were carried out to ensure that the PCR reactions were linear under the conditions used, as demonstrated by a dose-response relationship between initial amounts of cDNA and quantity of the final products.

Quantitation of TCR V β subfamily representation in peripheral blood T cells. 25 μ l (1/4) of each PCR reaction was electrophoresed on a 2% agarose gel and blotted to nylon membranes (Boehringer Mannheim, Mannheim, Germany). The membrane was hybridized at 42°C overnight with a [³²P] γ -ATP-labeled C β internal probe (5'-GAGGACCTGAACAAGGTGTTCCACCCGAG-3') and washed twice at 4°C for 30 min in 6 \times SSC and twice at 65°C for 20 min in TMAC. The membrane was exposed to a Phosphor screen and radioactive intensity of each specific band was quantified on a Phosphor-Imager using ImageQuant software (Molecular Dynamics, Sunnyvale, CA). Representation of each V β subfamily was calculated as a percentage of the sum of all V β signals detected on the autoradiogram.

TCR β chain CDR3 fragment size analysis. The size distribution of each fluorescent PCR product was determined by electrophoresis on an automated 373 DNA sequencer (Applied Biosystems) using a 5.5% polyacrylamide gel and data analyzed by GeneScan software

(Perkin Elmer, Foster City, CA). Because the positions of the 5' and 3' primers are fixed, fragment size differences within each V β subfamily are due entirely to different CDR3 region lengths, reflecting junctional diversity and *N*-random nucleotide insertions in the V-D-J region. Peaks corresponding to in-frame transcripts are detected at three nucleotide intervals. As described previously (32), a normal transcript size distribution, reflecting polyclonal cDNA, contains 8 to 10 peaks for each V β subfamily with a Gaussian size distribution. The appearance of dominant peaks indicates the presence of excess cDNA of identical size, suggesting the presence of an oligoclonal or clonal T cell population.

Results

IL-12 administration induces in vivo the selective expansion of a subpopulation of CD8⁺ T cells and the upregulation of lymphocyte IL-12 receptor expression. Patients with solid tumors received subcutaneous injections of IL-12 given as part of a multi-center phase I dose escalation study. A single injection of IL-12 was given 2 wk before the first cycle of therapy, as this has been shown to diminish the toxicity of subsequent repetitive IL-12 dosing. A cycle of therapy consisted of a single injection of IL-12 administered three times a week for two consecutive weeks followed by a week of rest (Fig. 1A). To determine whether subcutaneous injections of IL-12 had any effect on populations of circulating lymphocytes, we obtained blood samples from three patients enrolled at the two highest dose levels (two patients at the 500 ng/kg dose level and one patient at the 700 ng/kg dose level) at the Dana-Farber Cancer Institute. Blood was drawn from patients before IL-12 injections on days 1 and 8 of each cycle. PBMC were isolated from blood samples and subjected to immunophenotypic analysis using antibodies against lineage-specific markers on T, NK, and B cells, an antibody against the CD18 adhesion molecule (part of the CD11a/CD18 complex, referred to also as LFA-1), and an

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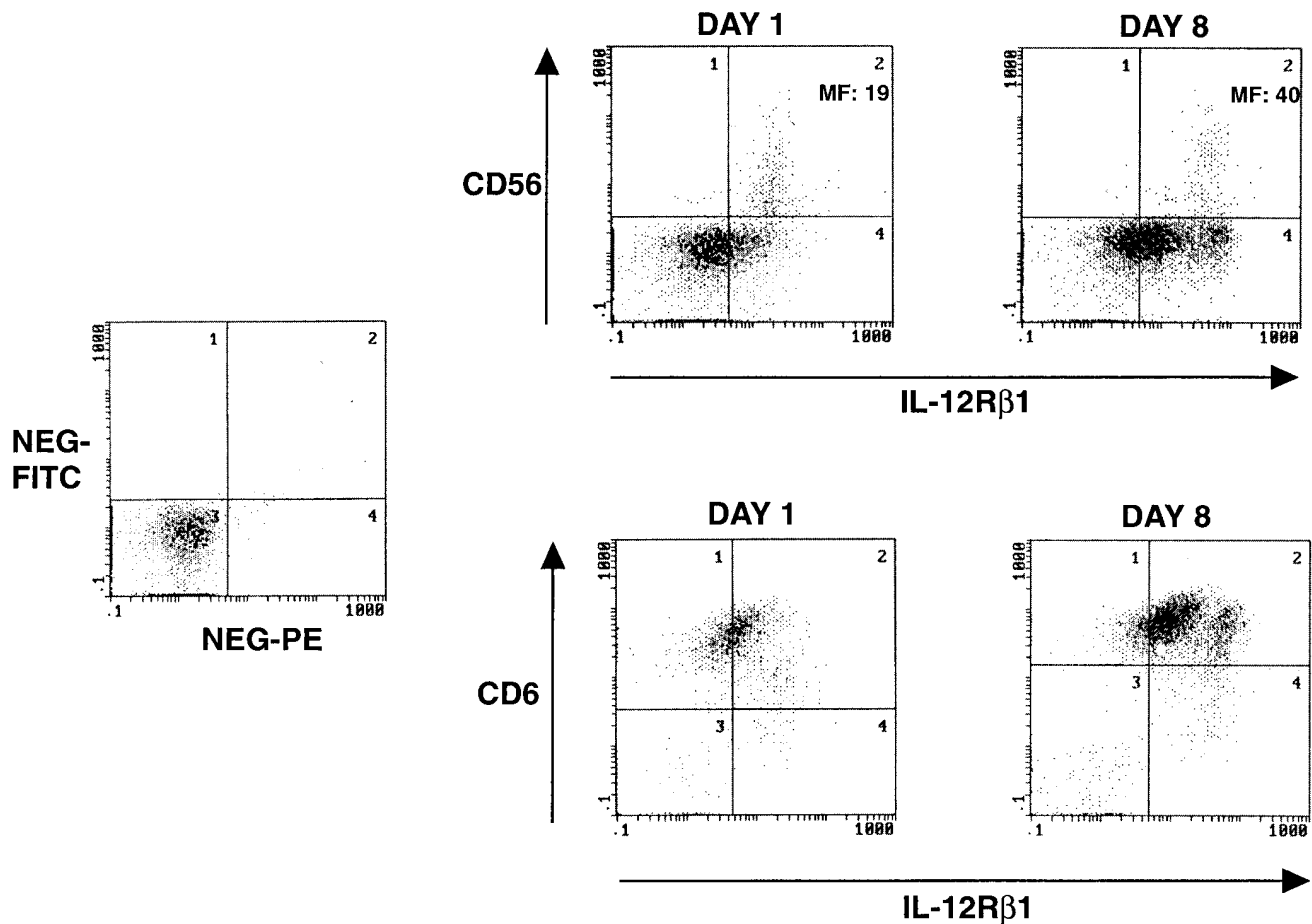


Figure 2. IL-12Rβ1 expression is upregulated on NK cells and T cells in response to subcutaneously administered IL-12. (A) PBMC were isolated from patients on days 1 and 8 of a cycle of IL-12 therapy and stained with IL-12Rβ1-PE (*x-axis*) and either CD56-FITC (NK cells) or CD6-FITC (T cells) (*y-axis*). Quadrants were set using isotype-matched negative control antibodies. MF = mean fluorescence intensity. (B) PBMC were isolated from patients on days 1 and 8 and stained with IL-12Rβ1-PE (*x-axis*) and CD18-FITC (*y-axis*). Results shown for A and B are for one patient at the 500 ng/kg dose level during cycle 1 and are similar to the results obtained with two other patients at the 500 ng/kg and 700 ng/kg dose levels.

antibody against the β1 subunit of the IL-12 receptor (IL-12Rβ1). Among peripheral blood T cells, two populations of CD8⁺ cells could be discerned based on the intensity of staining with a CD18 antibody (Fig. 1 B). CD18^{bright} and CD18^{dim} CD8⁺ T cells differed four- to fivefold in their CD18 mean fluorescence intensity, and the ratio of dim/bright CD8⁺ cells was usually 1–2:1. CD4⁺ T cells were more homogeneous in their CD18 staining, with the majority (> 95%) of CD4⁺ T cells staining dimly for CD18.

In patients receiving IL-12 at the highest dose levels (500–700 ng/kg/d), CD8⁺CD18^{bright} T cells were the only lymphocyte subset consistently observed to expand (by percentage and absolute number) by the second week of each cycle (Fig. 1, B and C). During the week of rest within each cycle, the number of circulating CD8⁺CD18^{bright} T cells partially diminished, only to expand again during the second week of the subsequent cycle (data not shown). As seen during cycle 1 (Fig. 1 C), the N-fold change in the CD8⁺CD18^{bright} T cell number between

days 1 and 8 (ranging from 2.6- to 6-fold for the three patients studied) was significantly increased over the N-fold change in the CD4⁺CD18^{bright} T cell (range: 0.9- to 1.4-fold) and NK cell (range: 0.34- to 1.3-fold) numbers. This was assessed by examining the ratio of the N-fold change in CD8⁺CD18^{bright} number divided by the N-fold change in either the CD4⁺CD18^{bright} or NK cell number for each patient. Testing was performed using a one-sided Student's *t* test, against a null hypothesis of equal increases (ratio = 1). The *P* value for assessing the CD8⁺CD18^{bright} T cell change relative to the CD4⁺CD18^{bright} T cell change was 0.05; the *P* value assessing the CD8⁺CD18^{bright} T cell change relative to the NK cell change was 0.02.

Changes in IL-12 receptor expression were also analyzed during each cycle of IL-12 therapy. Whereas all NK cells were uniformly positive for IL-12Rβ1 before starting IL-12 therapy, most T cells were only weakly positive, with a small subset expressing IL-12Rβ1 at a level more comparable to NK cell expression (Fig. 2 A, Day 1). By the second week of IL-12 injection,

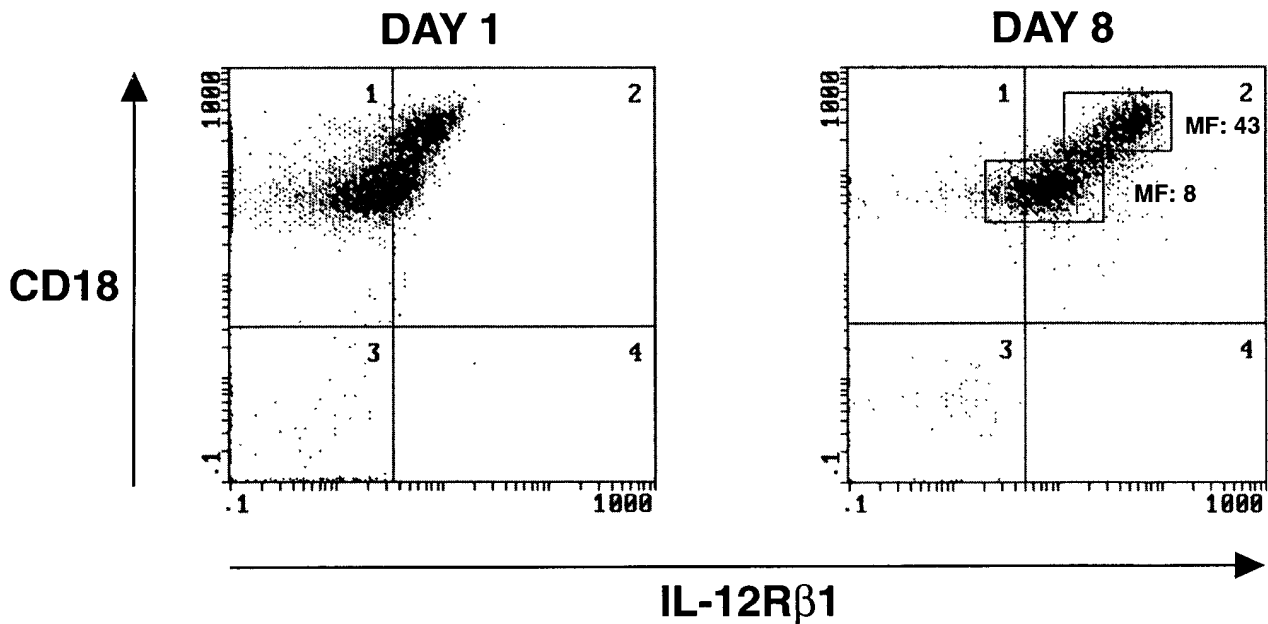
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Figure 2 (Continued)

tions, there was upregulation of IL-12R β 1 expression on NK cells, with a twofold increase in the mean fluorescence intensity (Fig. 2 A, Day 8). IL-12R β 1 expression was also upregulated on all T cells, but this upregulation was strongest on a small subpopulation of T cells (IL-12R β 1^{bright}) that now expressed IL-12R β 1 with a mean fluorescence intensity that was five to six times greater than that which was observed on the majority of T cells (Fig. 2 A, Day 8). The mean fluorescence intensity of these IL-12R β 1^{bright} T cells during the second week of IL-12 injections paralleled NK cell IL-12R β 1 staining.

Because IL-12 responsiveness is determined in part by IL-12 receptor expression, we hypothesized that the CD18^{bright} T cells observed to expand *in vivo* in response to IL-12 might be the same T cells that stained the brightest for IL-12R β 1 during the second week of IL-12 therapy. As shown in Fig. 2 B, CD18^{bright} lymphocytes stained brightly for IL-12R β 1 relative to CD18^{dim} lymphocytes before IL-12 therapy and upregulated IL-12R β 1 expression to the greatest extent during IL-12 therapy. As CD18^{bright} lymphocytes consisted of NK cells and predominantly CD8⁺ T cells (Fig. 3 A), it was clear that the differential expansion of CD8⁺CD18^{bright} T cells relative to other T cells was associated with the differential expression of IL-12R β 1.

CD18^{bright} T cells and NK cells express higher levels of adhesion molecules and receptors for IL-12 and IL-2 than CD18^{dim} T cells. Having observed the selective expansion of CD8⁺CD18^{bright} T cells in patients receiving subcutaneous injections of IL-12, we further characterized this subpopulation of T cells in normal subjects. As shown in Fig. 3 A, CD18 expression on NK cells and T cell subsets in normal individuals

was similar to the pattern observed in patients with solid tumors. Specifically, CD18^{bright} lymphocytes were comprised primarily of NK cells and CD8⁺ T cells, along with a smaller number of CD4⁺ T cells (Fig. 3 A). CD18^{bright} lymphocytes stained brightly relative to CD18^{dim} lymphocytes for adhesion molecules other than CD18, such as CD2R and CD49d (Fig. 3 B) as well as CD29 (data not shown). However, CD18^{bright} lymphocytes exhibited more variable expression of CD2 and CD28. Three-color staining demonstrated that the CD18^{bright} lymphocytes strongly expressing CD2 were T cells, whereas those with weaker expression of CD2 were NK cells. In addition, whereas CD18^{bright} and CD18^{dim} T cells expressed CD28 to a similar degree (Fig. 3 B), three-color staining showed that the CD18^{bright} lymphocytes with weak CD28 expression were NK cells (data not shown).

As was observed for patients receiving IL-12, IL-12R β 1 expression was stronger on CD18^{bright} T and NK cells compared to CD18^{dim} T cells in normal subjects (Fig. 3 C). Because IL-2 can augment the functional response of T and NK cells to IL-12, we also examined IL-2 receptor expression on peripheral blood lymphocytes. As shown in Fig. 3 C, both the β and γ chains of the IL-2 receptor were expressed to a greater extent on CD18^{bright} T and NK cells compared to CD18^{dim} T cells, whereas IL-2R α was only weakly expressed to a similar extent on CD18^{bright} and CD18^{dim} lymphocytes.

CD8⁺CD18^{bright} T cells morphologically resemble NK cells. To obtain pure populations of CD8⁺CD18^{bright} and CD8⁺CD18^{dim} T cells, preparations of CD8-enriched lymphocytes from normal subjects were stained with CD8 and CD18 antibodies and sorted into two populations using fluorescence acti-

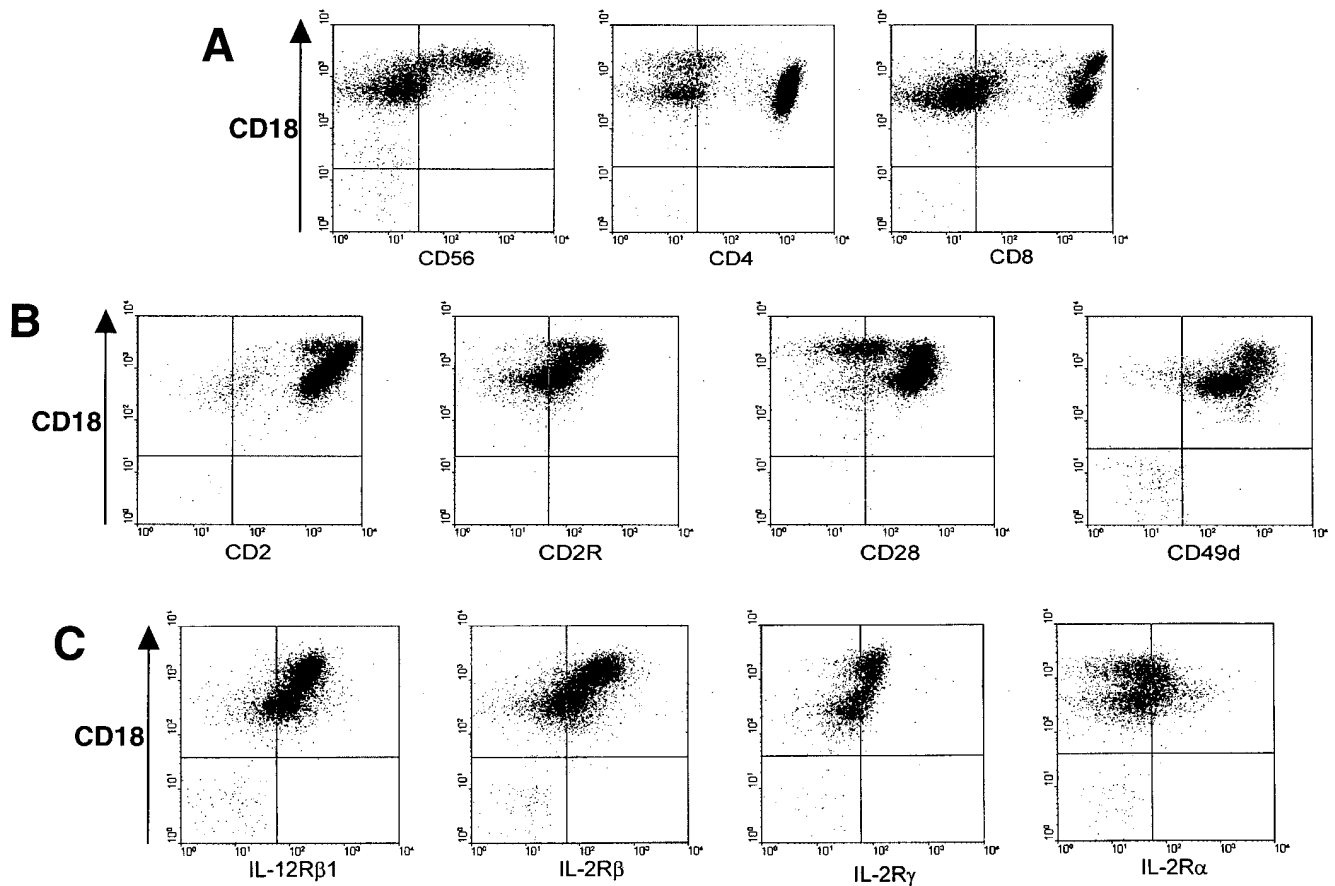


Figure 3. Adhesion molecules and receptor subunits for IL-12 and IL-2 are differentially expressed on CD18^{bright} and CD18^{dim} lymphocytes. PBMC were isolated from blood samples obtained from normal subjects and stained with CD18-FITC (*y-axis*) and lineage-specific NK or T cell markers (*A*), antibodies to adhesion molecules (*B*), or antibodies specific for the $\beta 1$ subunit of the IL-12 receptor or the α , β , or γ subunits of the IL-2 receptor (*C*) conjugated with PE (*x-axis*). Results are representative of six separate experiments using blood from different volunteer donors.

vated cell sorting (Fig. 4 *A*). The CD18 antibody used for cell sorting does not activate resting lymphocytes and neither augments nor inhibits the functional response of mitogen-activated T cells to IL-12 or IL-2 (28). Sorted CD18^{bright} and CD18^{dim} T cells were > 95% pure and differed five- to sixfold in their CD18 mean fluorescence intensity.

To examine these cell populations morphologically, cyto-spin preparations of sorted CD18^{bright} and CD18^{dim} CD8⁺ T cells were made immediately after sorting and stained with Wright-Giemsa. CD8⁺CD18^{dim} cells appeared morphologically as resting T cells, exhibiting scant cytoplasm without granules and round, homogeneous nuclei with dense chromatin (Fig. 4 *B*). In contrast, CD8⁺CD18^{bright} T cells were larger cells with abundant cytoplasm, prominent azurophilic cytoplasmic granules, and large pleomorphic nuclei with open chromatin (Fig. 4 *C*). Morphologically, CD8⁺CD18^{bright} lymphocytes closely resembled CD56⁺CD16⁺ NK cells. However, sorted CD8⁺CD18^{bright} lymphocytes were CD3⁺TCR $\alpha\beta$ ⁺CD56⁻ (data not shown), demonstrating that these lymphocytes were T cells rather than NK or NKT cells.

The TCR V β repertoire is oligoclonal in CD8⁺CD18^{bright} T cells but polyclonal in CD8⁺CD18^{dim} T cells. To determine whether CD8⁺CD18^{bright} T cells were comprised of a clonal or

oligoclonal T cell population distinct from CD18^{dim} T cells, we analyzed the V β repertoire of sorted CD8⁺CD18^{bright} and CD8⁺CD18^{dim} T cells. First, we examined the size spectrum of the CDR3 region for each V β subfamily to determine whether there was an indication of clonal expansion within a given V β subfamily. In T cells from normal subjects, the analysis of CDR3 size for each V β gene should show a Gaussian distribution of six to eight peaks, indicating the predominance of polyclonal T cells (32). As shown in Fig. 5, all 24 V β gene subfamilies were represented in both the CD18^{bright} and CD18^{dim} populations. Whereas the CD18^{dim} V β subfamilies were all polyclonal (Fig. 5 *A*), the CD18^{bright} T cells were notable for having a large number of V β subfamilies with either an oligoclonal or clonal pattern (Fig. 5 *B*). This finding was consistently observed in all of the individuals whose cells were analyzed. However, the V β subfamilies that were oligoclonal or clonal varied among the different normal subjects tested, with no discernible pattern.

In addition to finding abnormal V β patterns among CD18^{bright} cells that suggested clonal predominance within V β subfamilies, we also found that there was a much more uneven distribution of V β subfamily usage among CD18^{bright} cells compared with CD18^{dim} cells (Fig. 6). In some cases this was strik-

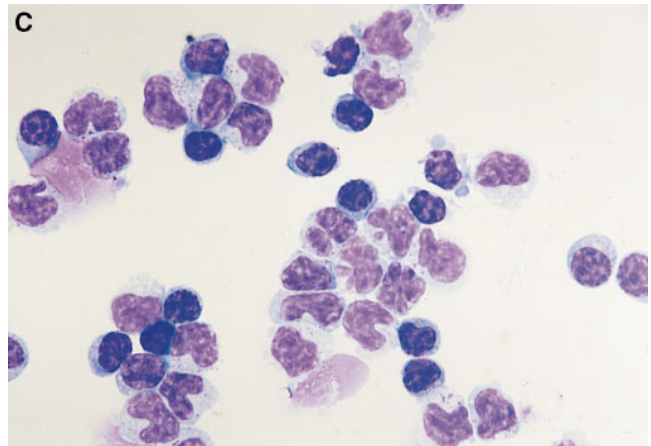
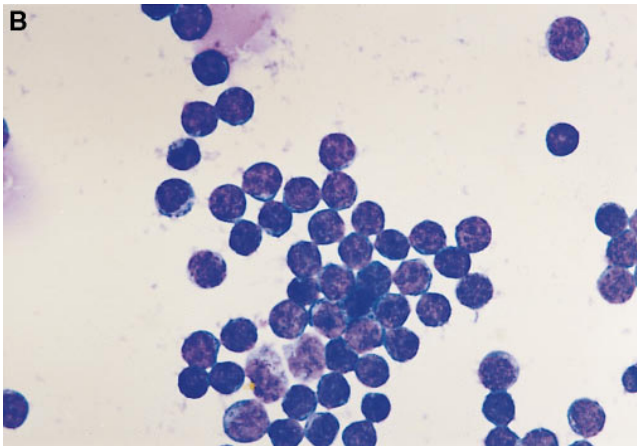
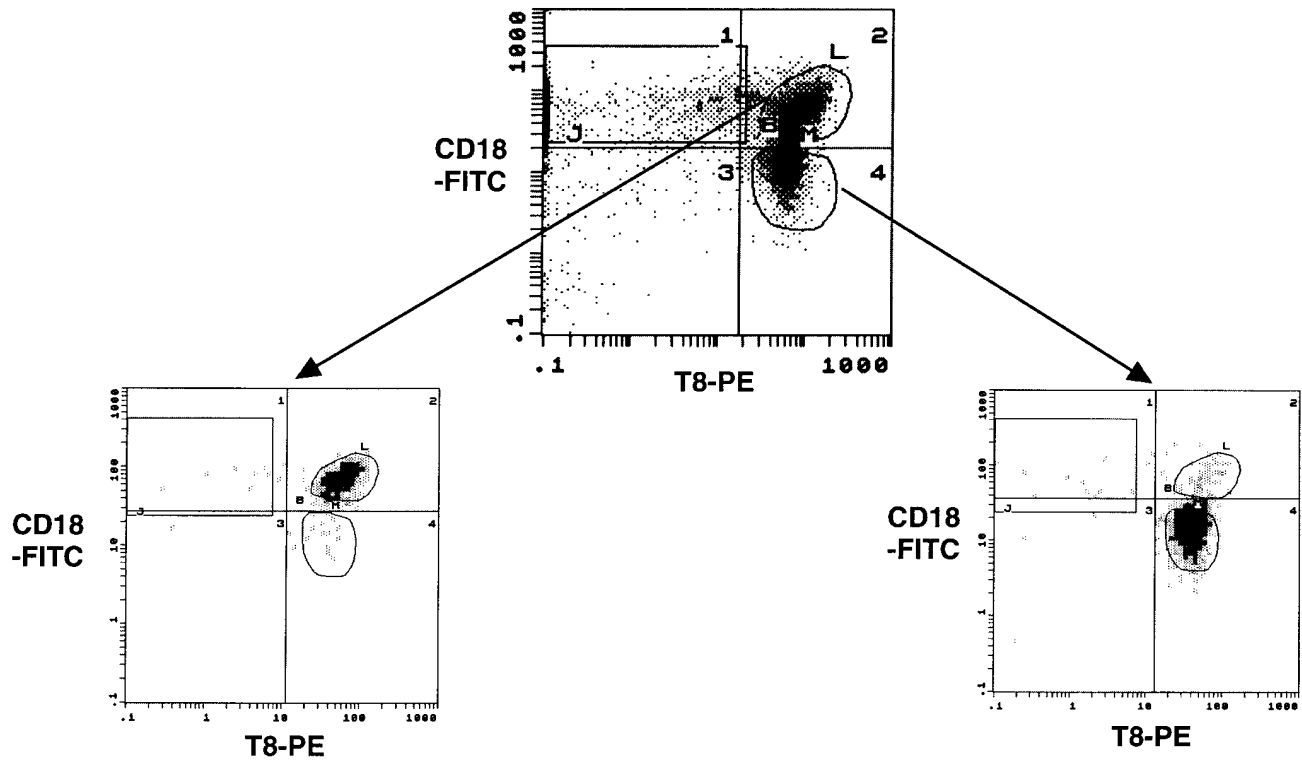
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Figure 4. $CD8^+CD18^{\text{bright}}$ T cells morphologically resemble NK cells. (A) Among $CD8^+$ T cells, the $CD18^{\text{bright}}$ and $CD18^{\text{dim}}$ subsets were isolated separately through fluorescence-activated cell sorting. $CD8^+$ T cell-enriched peripheral blood lymphocytes were obtained by depleting PBMC of monocytes, NK cells, $CD4^+$ T cells, and B cells through passage of the cells over nylon wool columns followed by treatment with antibodies recognizing lineage-specific markers and magnetic beads coated with anti-immunoglobulin antibodies. $CD8$ -enriched T cells were then stained with $CD18$ -FITC and $CD8$ -PE and sorted based on $CD18$ -FITC fluorescence intensity. Sorted cell populations were 95–98% pure. (B and C) Cytopsin preparations were made from sorted $CD18^{\text{dim}}$ (B) and $CD18^{\text{bright}}$ (C) T cells and stained with Wright-Giemsa. Stained cells were viewed under a light microscope at 100 \times magnification. Identical results were obtained in two separate experiments.

ing, with a single $V\beta$ subfamily comprising 25–50% of the total $CD8^+CD18^{\text{bright}}$ T cells (Fig. 6). In contrast, each $V\beta$ subfamily usually comprised no more than 3–8% of the total cells within the $CD18^{\text{dim}}$ subset.

$CD8^+CD18^{\text{bright}}$ T cells proliferate and produce $IFN-\gamma$ in response to the combination of $IL-12+IL-2$, whereas $CD8^+CD18^{\text{dim}}$ T cells do not. The in vivo expansion of $CD8^+CD18^{\text{bright}}$ T cells in patients receiving subcutaneous injections

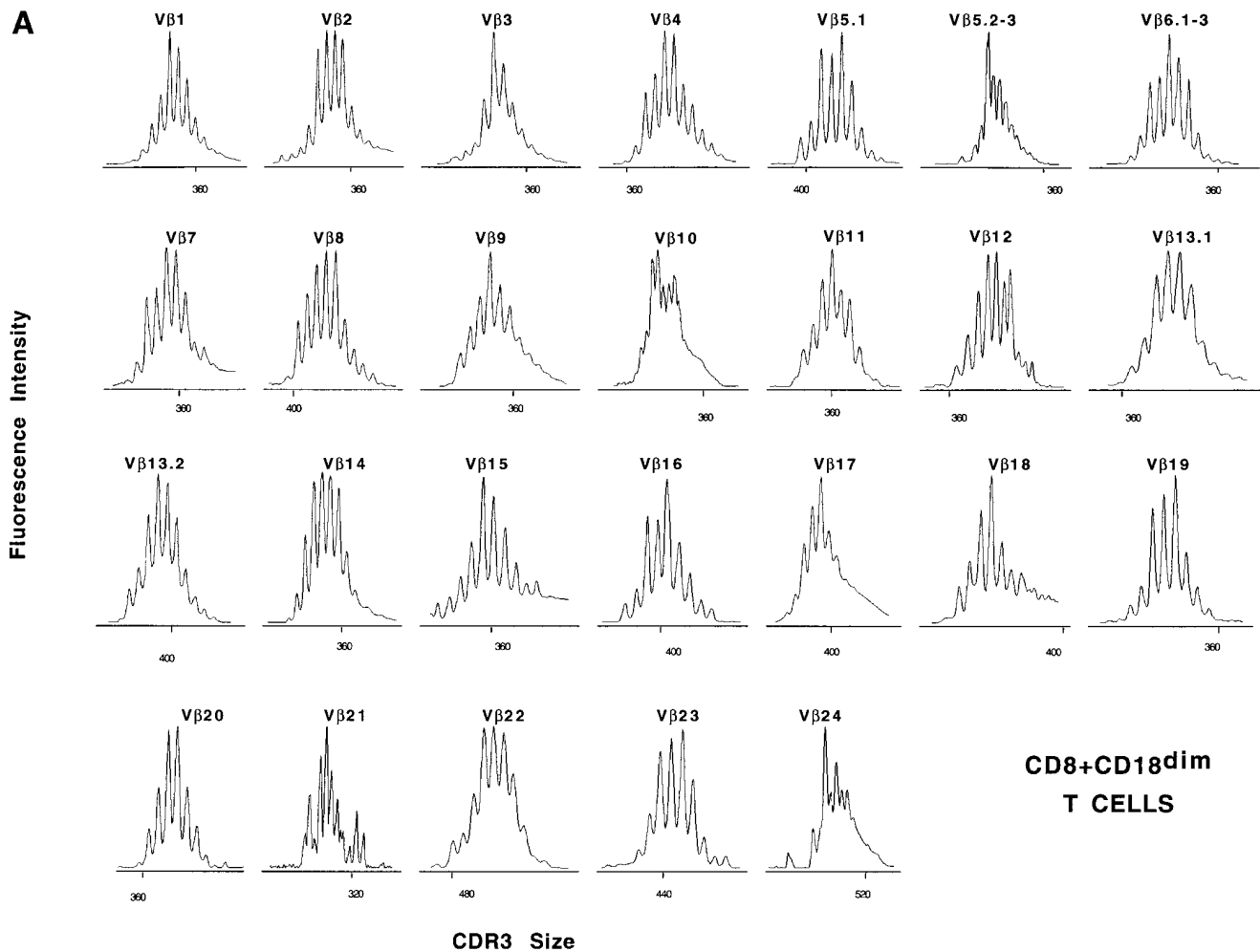


Figure 5. CD8⁺CD18^{bright} T cells exhibit oligoclonal and clonal V β subfamily patterns, whereas CD18^{dim} T cells exhibit polyclonal V β patterns. CDR3 size patterns for 24 V β gene subfamilies are displayed for sorted CD8⁺CD18^{dim} (A) and CD8⁺CD18^{bright} (B) T cells. Results shown are from one normal donor, and are representative of results obtained from three different donors.

of IL-12, as well as the relatively strong expression of IL-12 and IL-2 receptors relative to CD18^{dim} T cells, suggested that the *in vitro* responsiveness of CD8⁺CD18^{bright} T cells to IL-12 and IL-2 would be greater than CD18^{dim} T cells. To test this hypothesis, sorted CD18^{bright} and CD18^{dim} CD8⁺ T cells were stimulated with IL-12, IL-2, or the combination of IL-12+IL-2 in 96-h proliferation assays and 72-h IFN- γ assays. CD8⁺CD18^{bright} T cells did not proliferate or produce IFN- γ in response to any concentration of IL-12 alone (Fig. 7 A). Although these cells also did not produce IFN- γ in response to IL-2 alone, they exhibited a modest proliferative response to high concentrations of IL-2 (Fig. 7 A). The limited functional responsiveness to 1 nM IL-2 was consistent with the observed expression of intermediate affinity (K_d = 1 nM) $\beta\gamma$ IL-2 receptors on CD8⁺CD18^{bright} T cells (Fig. 3 C). CD8⁺CD18^{dim} T cells could neither proliferate nor produce IFN- γ in response to IL-12 or IL-2 alone (Fig. 7 B).

Previous studies have demonstrated that resting NK cells, while producing little IFN- γ in response to IL-12 or IL-2 alone, can produce large amounts of IFN- γ in response to the combination of IL-12+IL-2 (1). It has also been shown that among

resting T cells, a small fraction can substantially increase IFN- γ mRNA synthesis in response to IL-12+IL-2 (1). Although CD8⁺CD18^{bright} T cells did not proliferate or produce IFN- γ in response to IL-12 alone, concentrations of IL-12 as low as 1–10 pM synergized with 1 nM IL-2 to greatly increase proliferation and IFN- γ production (Fig. 7 A). In contrast, CD8⁺CD18^{dim} T cells remained functionally unresponsive to the combination of IL-12+IL-2 (Fig. 7 B). CD4⁺CD18^{dim} T cells also did not respond to IL-12 and IL-2, alone or in combination (data not shown). Although CD4⁺CD18^{bright} T cells were few in number and comprised only a small fraction (< 5%) of all CD4⁺ cells, they too could be isolated through cell sorting and exhibited the same functional response to IL-12 and IL-2 as CD8⁺CD18^{bright} T cells (data not shown).

IL-12 and IL-2 augment the cytolytic activity of CD8⁺CD18^{bright} T cells. The generation of LAK activity from peripheral blood lymphocytes has been ascribed to the cytokine-induced stimulation of non-MHC-restricted cytolytic activity among circulating NK cells (33). Overnight incubation of NK cells *in vitro* with either IL-2 or IL-12 can augment their lysis of certain tumor cells (5). The *in vitro* stimulation of resting

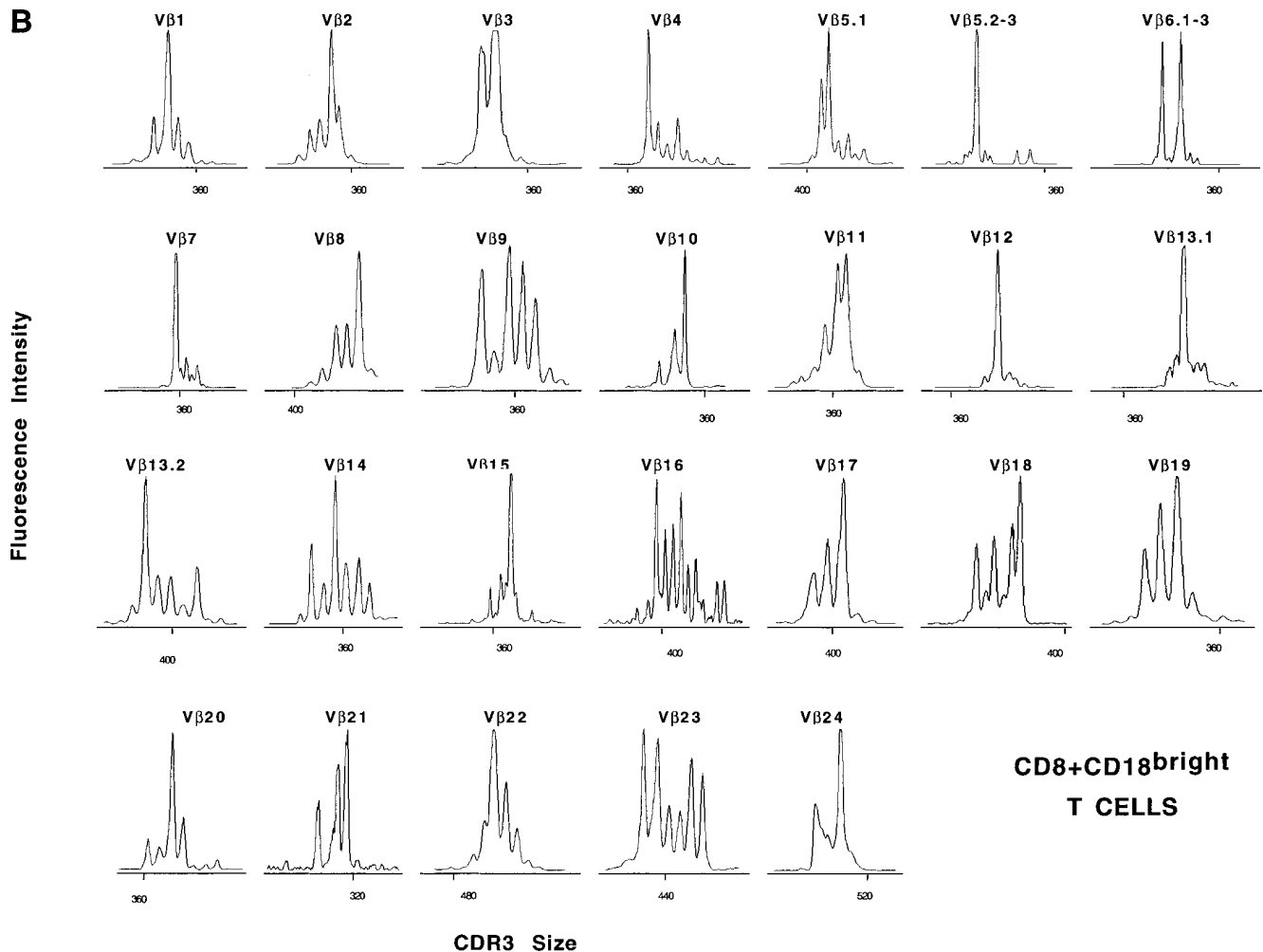


Figure 5 (Continued)

peripheral blood T cells with IL-12 or IL-2 has not been shown to generate non-MHC-restricted cytolytic activity. Because CD8⁺CD18^{bright} T cells appeared to differ from other circulating T cells in their ability to be activated by IL-12 and IL-2 and exhibited a striking morphologic, immunophenotypic, and functional resemblance to NK cells, we analyzed the ability of these cytokines to stimulate cytolytic activity by this T cell subset. To assess non-MHC-restricted killing, we measured the ability of CD8⁺CD18^{bright} T cells to kill the COLO cell line derived from a patient with colonic adenocarcinoma. Although freshly sorted CD8⁺CD18^{bright} T cells could not lyse COLO cells without *in vitro* activation, the killing of COLO cells was significantly augmented after an overnight incubation with either IL-12 or IL-2 alone (Fig. 8). Stimulation of CD8⁺CD18^{bright} T cells with the combination of IL-12+IL-2 further increased the killing of COLO cells in an additive manner. CD8⁺CD18^{dim} T cells, on the other hand, exhibited relatively little cytolytic activity against COLO, even when IL-12 and IL-2 were used together (Fig. 8). Neither CD4⁺CD18^{bright} nor CD4⁺CD18^{dim} T cells exhibited cytolytic activity against COLO in response to IL-12, IL-2, or the combination of IL-12+IL-2 (data not shown).

To assess CD3-mediated cytolytic activity, we measured the ability of CD8⁺CD18^{bright} T cells to kill the OKT3 hybridoma cell line (4). Fig. 8 demonstrates that CD3-triggered killing of OKT3 target cells by sorted CD8⁺CD18^{bright} effector cells was greater than that observed with CD8⁺CD18^{dim} cells. The further augmentation of CD3-triggered killing by IL-12 or IL-2 was also more substantial among CD18^{bright} compared with CD18^{dim} T cells, although stimulation of CD18^{bright} T cells with IL-12+IL-2 did not have an additive effect on CD3-triggered killing. Although CD4⁺CD18^{dim} cells could not lyse OKT3 cells, even after overnight stimulation with IL-12 or IL-2, CD4⁺CD18^{bright} cells exhibited modest cytolytic activity against OKT3 target cells in response to IL-2 but not in response to IL-12 (data not shown).

Discussion

In this report, a subpopulation of CD8⁺ T cells has been shown to expand *in vivo* in response to subcutaneously administered IL-12. Whereas previous studies have demonstrated that parenterally administered IL-2 can lead to NK cell expansion in cancer patients (34) or the modest expansion of CD4⁺ T

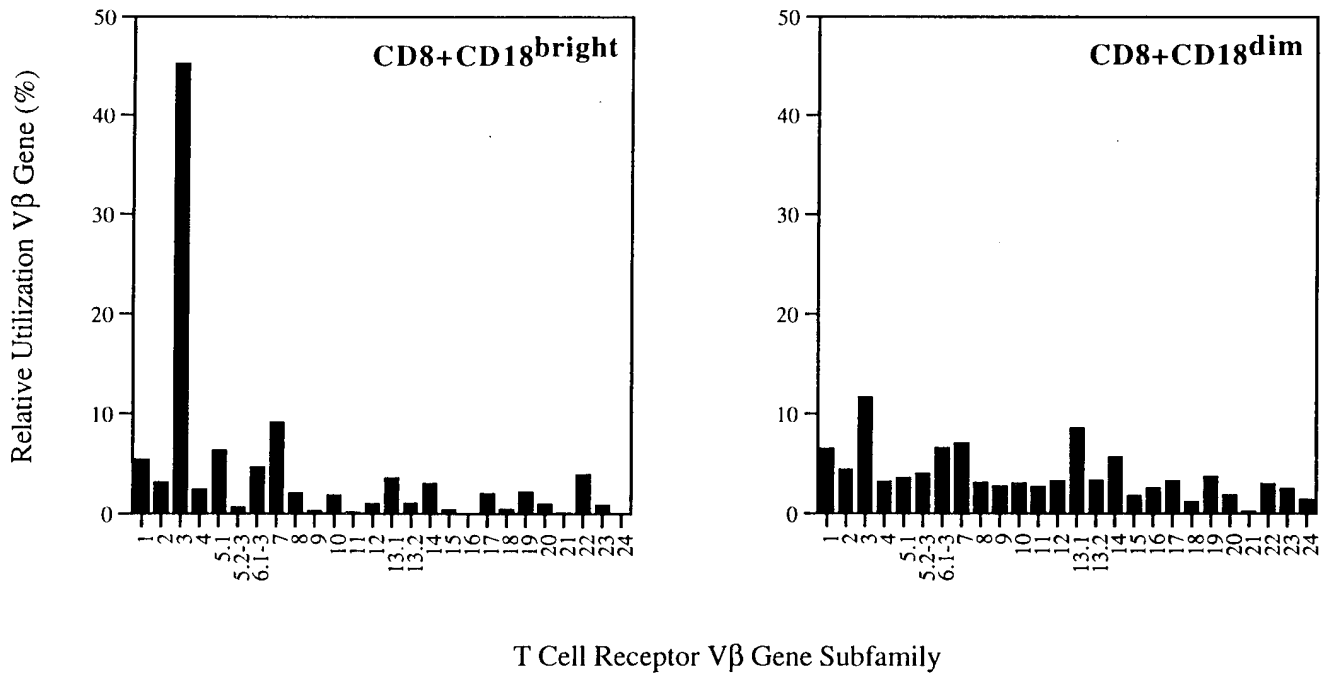


Figure 6. TCR V β gene representation in CD8⁺CD18^{bright} versus CD8⁺CD18^{dim} T cells. Use of 24 TCR V β gene subfamilies was evaluated in sorted CD8⁺CD18^{bright} and CD8⁺CD18^{dim} T cells. Results shown are from one donor, and are representative of results obtained from three different donors.

cells in patients infected with HIV (35, 36), this is the first study to show the *in vivo* expansion of CD8⁺ T cells in humans in response to a cytokine.

In primates receiving doses of intravenous or subcutaneous IL-12 for five consecutive days, lymphopenia (including decreases in the number of CD4⁺ and CD8⁺ T cells) was observed by day 2 and was noted to resolve within a day of stopping the IL-12 (37). In humans receiving intravenous IL-12 on a similar schedule, transient lymphopenia was also observed 24 h after the first dose (13). In our study of patients with cancer receiving subcutaneous injections of IL-12, doses of IL-12 were given every other day (three times a week) for 2 wk instead of daily for 1 wk, and blood samples were drawn before administering the IL-12 dose at days 1 and 8 of a treatment cycle rather than 24–48 h after the start of dosing. Rather than observing lymphopenia, we noted the selective expansion of a CD18^{bright} population of CD8⁺ T cells that occurred by the second week of each cycle and usually diminished during the following week of rest before the start of the next IL-12 cycle. This cyclical expansion of CD8⁺CD18^{bright} T cells was accompanied by a parallel upregulation of IL-12R β 1 expression (in the second week of a cycle, returning to baseline level during the week of rest). The strong, cyclical upregulation of IL-12R β 1 was also seen on NK cells, but no NK cell expansion was detected. CD18^{dim} T cells (including CD8⁺ T cells and the majority of CD4⁺ T cells) exhibited relatively weak IL-12R β 1 upregulation and also did not increase in number. Whereas NK cells have been viewed as the primary lymphocyte population in the peripheral blood capable of responding to IL-2 or IL-12 without additional activation, our findings in patients receiving subcutaneous IL-12 suggest that CD8⁺CD18^{bright} T

cells are a second lymphocyte population poised to respond to endogenous or exogenous Th1-type cytokines.

The immunophenotypic, morphologic, and functional analysis of CD8⁺CD18^{bright} T cells performed in this study demonstrates that this small population of circulating T cells bears a striking resemblance to NK cells. Like the majority of NK cells, CD8⁺CD18^{bright} T cells express intermediate affinity $\beta\gamma$ IL-2 receptors as well as the β 1 subunit of the IL-12 receptor, and stain brightly for LFA-1, CD2, and CD49d. This expression of cytokine receptors and adhesion molecules raises the possibility that CD8⁺CD18^{bright} T cells might, like NK cells, be capable of migrating to tumor sites and mediating non-MHC-restricted tumor cell lysis after activation by IL-2 or IL-12. CD8⁺CD18^{bright} T cells exhibit a modest proliferative response to IL-2 only at concentrations that are high enough to saturate their intermediate affinity IL-2 receptors, and demonstrate non-MHC-restricted cytolytic activity in response to IL-2 alone. However, they do not produce IFN- γ in response to IL-2 alone. Although CD8⁺CD18^{bright} T cells do not proliferate or produce IFN- γ in response to IL-12 alone, they do exhibit non-MHC-restricted cytolytic activity with IL-12 alone. Because it has been shown that expression of the IL-12R β 1 subunit alone is not sufficient to mediate IL-12-induced signaling or functional responses (22, 38, 39), it is likely that CD8⁺CD18^{bright} T cells also express IL-12R β 2 in order to form functional high affinity IL-12 receptors.

Although CD8⁺CD18^{bright} T cells demonstrated little functional responsiveness to IL-12 or IL-2 alone, the combination of IL-12+IL-2 synergistically augmented proliferation and IFN- γ production, while having an additive effect on non-MHC-restricted killing of tumor cells. NK cell activation with

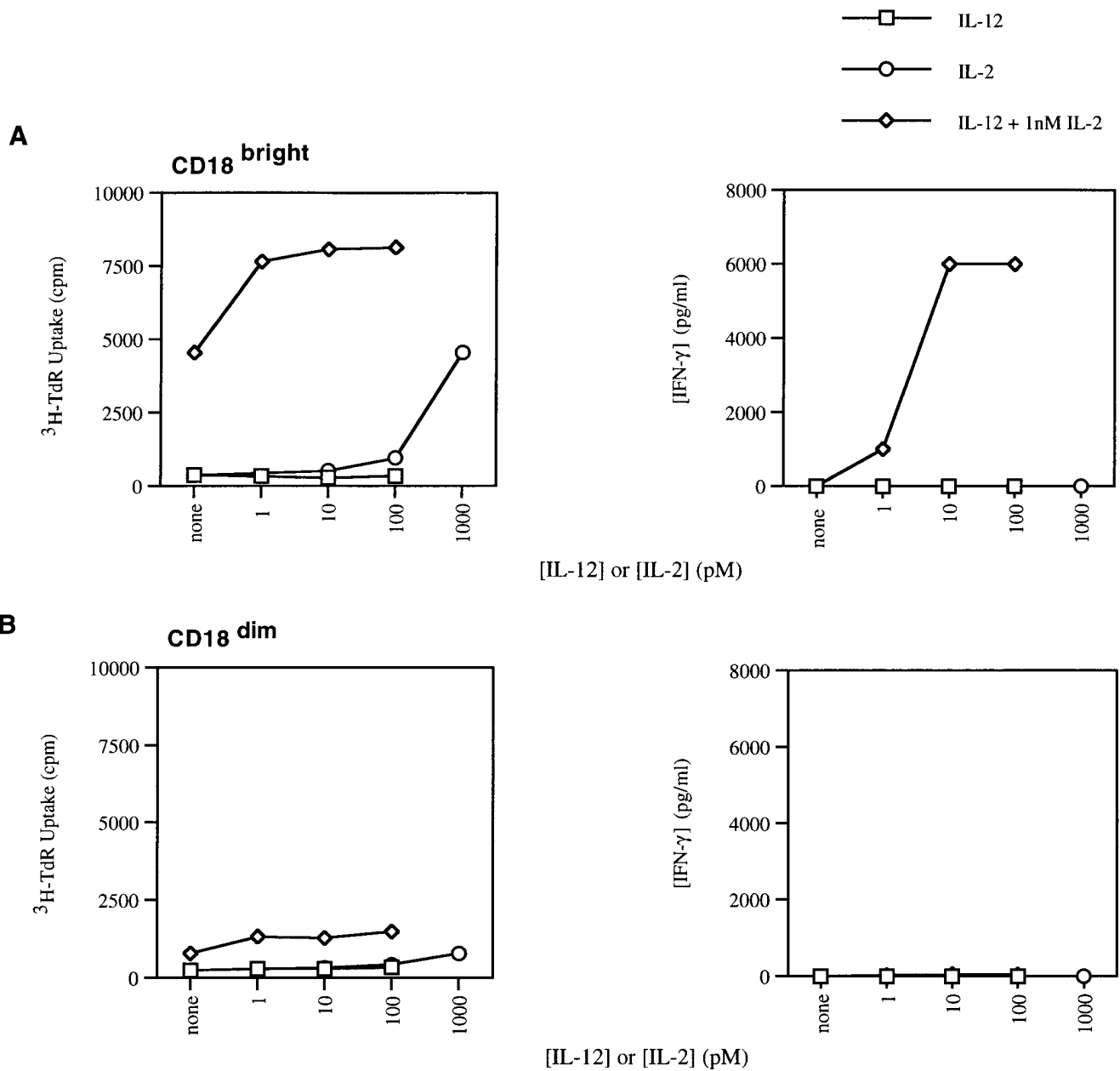


Figure 7. Differential functional response of CD8⁺CD18^{bright} and CD8⁺CD18^{dim} T cells to IL-12, IL-2, and IL-12+IL-2. Sorted CD8⁺CD18^{bright} (A) and CD8⁺CD18^{dim} (B) T cells were incubated with medium alone or the indicated concentrations of IL-12, IL-2, or IL-12+IL-2 in a 96-h proliferation assay or 72-h IFN-γ assay as described in Methods. Similar results were obtained in six separate experiments using cells from different volunteer donors.

IL-12+IL-2 has similar effects on IFN-γ production (1) and cytolytic activity (5). The observation that CD8⁺CD18^{bright} T cells only proliferate or produce IFN-γ in response to IL-12 in the presence of IL-2 suggests that signaling through the IL-12 receptor alone, though capable of stimulating modest cytolytic activity, is unable to mediate proliferation or IFN-γ production in these cells. Although IL-12 receptor expression is stronger on CD18^{bright} compared with CD18^{dim} T cells, it appears as though the differential expression of intermediate affinity IL-2 receptors on these T cell subsets also contributes significantly to the control of IL-12 responsiveness.

The functional synergy between IL-12 and IL-2 in CD8⁺CD18^{bright} T cells does not appear to be due to changes in the expression of IL-12 or IL-2 receptors. When CD8⁺CD18^{bright} T cells were cultured in IL-12 for up to 96 h, no increase in IL-2 receptor expression was observed (Gollob, J.A., and J. Ritz, unpublished observations). Likewise, when cells were cultured in IL-2, we did not observe any increase in IL-12Rβ1 expression. As IL-12Rβ2 antibodies are not currently available, we cannot exclude the possibility that IL-2 may upregulate IL-12Rβ2 expression on CD8⁺CD18^{bright} cells during a 72–96 h incubation with IL-12+IL-2, and that this may contribute to the

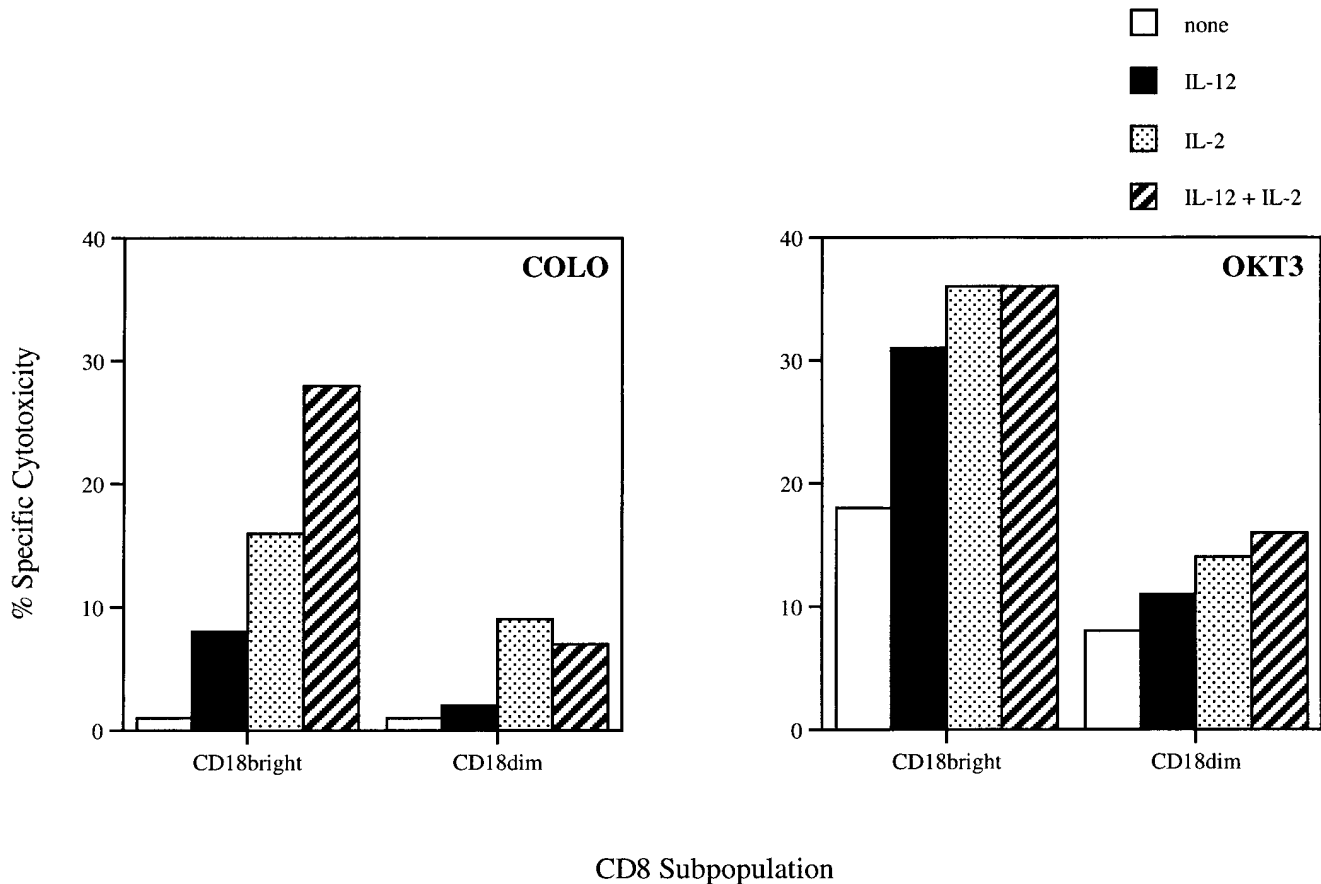


Figure 8. The cytolytic activity of CD8⁺CD18^{bright} T cells is augmented by IL-12 and IL-2. Sorted CD8⁺CD18^{bright} and CD8⁺CD18^{dim} T cells were incubated overnight with either medium alone, 1 nM IL-12, 1 nM IL-2, or IL-12+IL-2. ⁵¹Cr-labeled COLO or OKT3 target cells were then added at a 5:1 effector:target ratio and a 4-h cytotoxicity assay was performed as described in Methods. Results are representative of four separate experiments.

functional synergy between IL-12 and IL-2. However, our analysis of signaling in sorted CD18^{bright} T cells stimulated for only 15 min with IL-12, IL-2, or IL-12+IL-2 showed strong synergy between IL-12 and IL-2 at the level of p38 MAP kinase activation and STAT1 and STAT3 serine phosphorylation (Gollob, J.A., C.P. Schnipper, E.A. Murphy, J. Ritz, and D.A. Frank, manuscript submitted for publication). Furthermore, a specific inhibitor of p38 MAP kinase blocked the functional synergy between IL-12 and IL-2. These findings suggested that the functional synergy between IL-12 and IL-2 is occurring through the modulation of signaling at a point that is distal to IL-12 or IL-2 receptor expression.

The CD18^{bright} T cells described in this report share phenotypic and functional similarities with T cells described in previous studies as memory T cells and effector T cells (24, 40–42). Like memory and effector T cells, CD18^{bright} cells are capable of significant IFN- γ production and proliferation when provided with the appropriate stimuli. The strong expression of adhesion molecules such as CD2, CD11a, CD18, CD29, and CD49d is also characteristic of both memory and effector cells. The NK cell-like morphology and the ability to mediate CD3-directed cytotoxicity without pre-activation are more characteristic, however, of an effector rather than a memory T cell.

Our analysis of the CD8⁺CD18^{bright} TCR V β repertoire provides evidence that this is an oligoclonal population of T cells, whereas the CD4⁺ and CD8⁺ cells that are CD18^{dim} are polyclonal with V β subfamilies always evenly represented. Based on these findings, we believe that CD8⁺CD18^{bright} T cells are probably T cells comprised of effector and memory cells that have previously encountered antigen and have undergone selective clonal expansion in vivo. In contrast, CD18^{dim} T cells appear to be naive, quiescent cells that have not undergone selective clonal expansion. We have shown that the effector function of CD8⁺CD18^{bright} T cells can be elicited in a TCR-independent manner through combined stimulation with IL-12+IL-2. It remains to be determined whether these T cells can also exhibit rapid recall responses to distinct antigens that would be consistent with a memory function as well.

Because CD8⁺CD18^{bright} T cells are capable of TCR-independent activation through stimulation with IL-12+IL-2, as well as activation through the TCR by antigen presented in the context of MHC class I molecules, what is their role in the immune response to neoplastic cells or infectious pathogens? NK cells are considered to be the primary effector cell in early, innate immunity to pathogens by virtue of their responsiveness to cytokines, production of IFN- γ and TNF, and ability to

mediate non-MHC-restricted cell lysis. However, although CD8⁺CD18^{bright} T cells have probably been previously activated through the TCR by specific antigens and are likely to be an important component of acquired immune responses when rechallenged with antigen, they may also play a key role in early, innate immunity that is not antigen specific. Both neutrophils and antigen-presenting cells are capable of producing IL-12 when pathogens are first encountered, but IL-12 by itself is not capable of mediating significant NK cell or T cell activation. However, antigen-presenting cells also produce IL-15, which like IL-2 activates T and NK cells through the IL-2R β and IL-2R γ subunits (43, 44). Therefore, the early phase of a cellular immune response may consist of NK cell and CD8⁺CD18^{bright} T cell activation through combined stimulation with IL-12+IL-15, resulting in non-MHC-restricted killing and the production of Th1 cytokines such as IL-2 and IFN- γ . These cytokines would further enhance the innate immune response, and facilitate the formation of an acquired, TCR-dependent immune response.

Our observation that CD8⁺CD18^{bright} T cells upregulate IL-12 receptor expression and expand in patients receiving IL-12 suggests that they, along with NK cells, are being activated in vivo by IL-12. However, because our in vitro analysis demonstrated that IL-12 alone does not activate these CD8⁺ T cells, it is likely that, in vivo, IL-12 is also inducing the production of IL-15 and/or IL-2, either of which could then activate CD8⁺CD18^{bright} T cells in conjunction with IL-12. Although the in vivo upregulation of IL-12 receptor expression on NK cells in response to IL-12 administration is an indication that they too are being activated along with CD8⁺CD18^{bright} T cells, only the CD8⁺ T cells were observed to expand. If, as our in vitro data suggest, the proliferation of CD8⁺CD18^{bright} T cells is due to combined stimulation with exogenous IL-12 and endogenous IL-2 and/or IL-15, the lack of NK cell proliferation in vivo would be consistent with the in vitro response of NK cells to stimulation with IL-12+IL-2. Previous studies have shown that stimulation with IL-12+IL-2 augments both T and NK cell IFN- γ production. However, although stimulation with IL-12+IL-2 enhances T cell proliferation, the addition of IL-12 inhibits IL-2-induced NK cell proliferation (5).

Regarding the expansion of CD8⁺CD18^{bright} T cells in our patients receiving IL-12, we do not yet know whether this represents a polyclonal or oligoclonal/clonal expansion. Future studies with additional patients will be required to determine this. It is also important to consider that the expansion of CD8⁺CD18^{bright} T cells in patients treated with IL-12 may not be solely due to the proliferative effect of cytokines. For example, IL-12 alone or IL-12 in conjunction with IL-15 or IL-2 may also prevent activation-induced apoptosis in this CD8⁺ T cell population. It will be important to determine whether these CD8⁺ T cells are mediating the antitumor effect of IL-12, and if so, whether the antitumor effect is antigen-specific or non-specific. Regardless of whether they mediate the killing of tumor cells through a TCR-dependent mechanism or through 'natural' killing that is non-MHC-restricted, the in vivo activation of CD8⁺CD18^{bright} T cells with combination cytokine therapy using IL-12+IL-2 or IL-12+IL-15 might be an effective way to expand these effector/memory cells in cancer patients with or without pre-existing antitumor responses or in conjunction with tumor vaccines. Through this approach, it might be possible to generate more clinically effective immune-based cancer therapies.

Acknowledgments

This paper is dedicated to the memory of Samuel J. Kowal, M.D.

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