

Impaired Induction of CD27 and CD28 Predicts Naive CD4 T Cell Proliferation Defects in HIV Disease¹

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Many immunological defects have been described in HIV disease, including a diminished capacity of naive CD4⁺ T cells to expand after TCR stimulation. The mechanisms underlying impaired naive CD4⁺ T cell expansion in HIV disease are not well described. Using a rigorous phenotypic definition of naive T cells, we found that cell cycle entry after TCR engagement was restricted to cells that increased surface expression of costimulatory molecules CD27 and CD28. Induction of these receptors, however, was not sufficient to result in cell cycle entry among the CD4⁺CD31⁻ naive T cell subset. Analyses of cells from HIV-infected persons indicated that naive CD4⁺CD31⁺ T cells from these subjects were impaired in their ability to enter the cell cycle after stimulation and this impairment was predicted by the relatively poor induction of costimulatory molecules on these cells. Thus, failure to increase surface expression of costimulatory molecules may contribute to the naive T cell expansion failure that characterizes HIV infection. *The Journal of Immunology*, 2007, 179: 3543–3549.

Naive T cells are the critical underpinning of adaptive immune potential. These cells provide an essential resource both for mounting immune responses against novel Ags and also for maintaining T cell homeostasis. In HIV disease, the progressive depletion of naive CD4⁺ and CD8⁺ T cells (1) predicts clinical outcome (2) and responsiveness to immunization (3). Compounding the problems associated with the decline in naive T cell numbers, function of the remaining naive CD4⁺ T cells is impaired in HIV-infected individuals (4). In particular, naive CD4⁺ T cells from HIV-infected persons have a reduced potential to progress beyond G₁ phase of the cell cycle in response to TCR activation (5) and this impairment is not predictably corrected by exogenous IL-2 (4). The mechanism that underlies naive CD4⁺ T cell proliferation failure in HIV disease is unknown.

Human naive CD4⁺ T cells can be subdivided into CD31⁺ and CD31⁻ subsets. CD31⁺ naive T cells possess higher levels of TCR excision circles (TRECs)³ reflective of recent emigration from the thymus (6). Naive CD4⁺ T cells lacking CD31 expression have proportionally fewer TRECs, presumably a consequence of homeostatic proliferation. The possibility that CD31⁺ and CD31⁻ naive CD4⁺ T cell subsets could have distinct proliferation potential in response to TCR stimulation has not been addressed previously, but seems reasonable because in mice, recently

produced naive T cells proliferate better in response to TCR engagement than do aged naive T cells (7). We therefore considered the possibility that CD31 could distinguish naive CD4⁺ T cells with good or poor expansion potential in response to TCR activation.

At a single cell level, defects in cell cycle progression of activated naive T cells could stem from insufficient TCR or costimulatory signals. To investigate this possibility, we have examined the expression of two well-characterized costimulatory molecules, CD27 and CD28, on naive CD4⁺ T cells after TCR stimulation. CD27 provides costimulatory signals for naive CD4⁺ T cells (8) and is transiently increased on the cell surface following TCR triggering (9, 10). CD28 provides a critical costimulatory signal that enhances IL-2 production and augments cell cycle progression in response to TCR stimulation (11, 12). CD28 expression also can be transiently induced by TCR stimulation (13). In this study, we test the hypothesis that induction of CD27 and CD28 costimulatory molecule expression by TCR activation is important for cell cycle progression, and that this induction may be diminished in naive CD4⁺ T cells from HIV-infected individuals.

Our findings uncover a global impairment in the ability of CD31⁻ naive CD4⁺ T cell subsets to proliferate in response to TCR stimulation, suggesting that heightened homeostatic division may impair subsequent T cell responsiveness. Moreover, in analyses restricted to the CD31⁺ naive T cell subset, we found that cells from HIV-infected individuals proliferated poorly in response to TCR stimulation. Importantly, cells capable of cell cycle progression were identified by their expression of higher levels of costimulatory molecules, suggesting that increased sensitivity to costimulation may promote cell cycle progression in naive CD4⁺ T cells after TCR engagement. In addition, poor induction of costimulatory molecules in naive CD4⁺ T cells corresponded to poor proliferation responses after cells were activated with TCR agonists. Thus, impaired induction of costimulatory molecules in naive T cells from HIV-infected individuals may underlie naive T cell expansion failure in this disease.

Materials and Methods

Subjects

These studies were approved by the Institutional Review Board of Case Western Reserve University at University Hospitals of Cleveland. Samples were obtained from 20 HIV infected individuals and 9 healthy donors. The

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Received for publication June 2, 2006. Accepted for publication July 5, 2007.

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¹ This work was supported in part by grants from the National Institutes of Health (AI38858, AI07024, and the Case/UH Center for AIDS Research, AI36219) and the William Randolph Hearst Neonatology Research Grant.

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³ Abbreviations used in this paper: TREC, TCR excision circles.

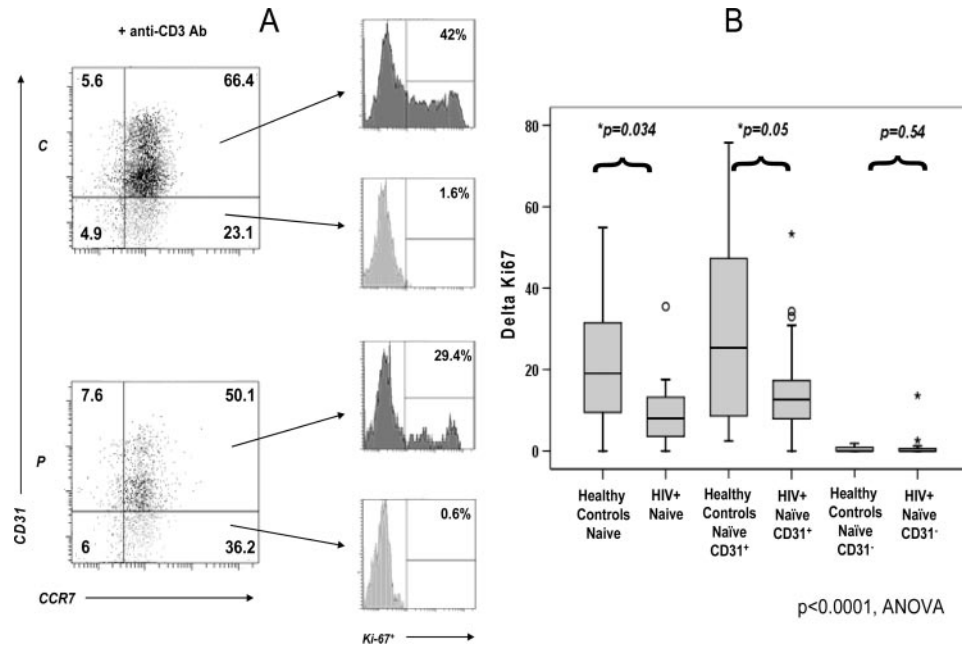


FIGURE 1. Induction of Ki-67 expression is diminished in naive CD4⁺ T cells from HIV-infected individuals and is absent in CD4⁺CD31⁻ naive T cell subsets. **A**, CD45RO-depleted PBMC from a healthy control (**C**, top) and an HIV⁺ patient (**P**, bottom) were cultured for 2 days in the presence of anti-CD3 Ab. Cells were analyzed by flow cytometry and gated for the expression of CD4, CD27, and CD28, and further evaluated for the expression of CD31 and CCR7 (dot-plots). Cells that were CCR7⁺ and either CD31⁺ or CD31⁻ were examined for expression of Ki-67 (frequency distribution histograms). **B**, Box and whiskers plot comparing δ Ki-67 (the proportion of naive T cells that were Ki-67⁺ with stimulation minus the percentage of naive T cells that were Ki-67⁺ without stimulation) in naive CD4⁺ T cells from healthy controls ($n = 9$) and HIV-infected individuals ($n = 20$). Statistical significance of $p < 0.05$ was determined by ANOVA and student two-tailed t test.

median CD4⁺ T cell count in the HIV-infected donors was 424 cells/mm³ (range 106–737) and the median plasma HIV RNA level was 6,765 copies/ml (range 50–564,000). Twelve (60%) of the HIV-infected donors were receiving highly active antiretroviral therapy and 40% were not receiving antiretroviral medications when the blood sample was taken.

Cells

Blood was collected in heparin-coated tubes and PBMCs were isolated by centrifugation over a Ficoll-Histopaque cushion. PBMCs were depleted of CD45RO⁺ cells by magnetic bead separation (AutoMACS; Miltenyi Biotec). Depletion of CD45RO⁺ cells was confirmed by flow cytometry, and the resulting T cell populations were determined to be >95% CD45RA⁺CD45RO⁻. Cells were cultured in RPMI 1640 (BioWhittaker) supplemented with 10% FBS (HyClone), 1% 2 mM L-glutamine (BioWhittaker) and 1% 10,000 μ g/ml streptomycin (BioWhittaker).

To obtain purified naive CD4⁺ T cells, the Miltenyi negative CD4 selection mixture, which depletes CD8⁺ cells, B cells, NK cells, dendritic cells, monocytes, granulocytes, and erythroid cells by magnetic bead separation (AutoMACS; Miltenyi Biotec), was supplemented with CD45RO-depletion beads. Depletion of these cells was confirmed by flow cytometry and the resulting T cell populations were determined to be >90% CD4⁺CD45RA⁺CD45RO⁻CD14⁻. Cells were cultured in RPMI 1640 (BioWhittaker) supplemented with 10% FBS (HyClone), 1% 2 mM L-glutamine (BioWhittaker), and streptomycin (BioWhittaker).

Proliferation assays and Ki-67 expression

CD45RO-depleted PBMCs were stimulated with anti-CD3 mAb (BD Pharmingen; 100 ng/ml). After 2 days in culture, cells were surface stained with fluorochrome-labeled Abs to CD4 (Pacific blue; BD Biosciences), CD27 (biotin followed by secondary stain with streptavidin-allophycocyanin-cyanine 7, Ancell), CD28 (allophycocyanin; BD Biosciences) CCR7 (PE-cyanine 7; BD Biosciences), and CD31 (PE; BD Pharmingen). Cells were washed in PBS/BSA staining buffer and then incubated in FACS PERM buffer (1 \times ; BD Biosciences). After a second wash, cells were incubated with anti-Ki67 (FITC-conjugated Ab; BD Biosciences) for 45 min in the dark. After staining, cells were washed one more time with staining buffer and analyzed on a flow cytometer (BD LSR II; BD Biosciences).

In separate studies of purified naive CD4⁺ cells, isolated naive CD4⁺ T cells were stimulated with surface-bound anti-CD3 mAb (5 μ g/ml; BD

Pharmingen) and soluble anti-CD28 mAb (5 μ g/ml; BD Pharmingen). Ki-67 was measured 4 days poststimulation as outlined above.

For analyses of allogeneic T cell responses, purified naive CD4⁺ T cells were incubated with irradiated T cell-depleted PBMC. The T cell-depleted PBMC were a mixed population derived from five healthy donors that had been depleted of CD3⁺ cells by magnetic beads and had been incubated overnight with LPS (20 ng/ml). These cells were irradiated (500 rads) and frozen at -80°C for storage. On the day of the assay, the irradiated cells were thawed, washed, and incubated with purified naive CD4⁺ T cells at a ratio of 1 APC:10 T cells. After 4 days in culture, cells were surface stained with fluorochrome-labeled Abs mentioned previously and anti-Ki-67 intracellular Ab.

Statistical analysis

A comparison of the Ki-67 expression and induction of CD27 and CD28 between the groups was performed using the independent samples t test and ANOVA. The Shapiro-Wilk test was used for testing normality. Spearman rank correlation analysis was performed to investigate the relationships between induction of costimulatory molecules and induction of Ki-67. For the purified naive CD4⁺ T cell experiments, groups were analyzed with the Mann-Whitney U test. Statistical significance was established at $p = 0.05$.

Results

Naive CD4⁺CD31⁺ T cells obtained from HIV-infected individuals less frequently enter cell cycle after TCR engagement

Naive CD4⁺ T cells were identified in CD45RO-depleted PBMC by coexpression of CCR7, CD27, and CD28. We found that such cells (CD4⁺CD45RO⁻CCR7⁺CD27⁺CD28⁺) expressed IL-2 but not IFN- γ when stimulated with superantigen (*Staphylococcus aureus* Enterotoxin B) plus costimulatory agonists (anti-CD28 and anti-CD49d antibodies), consistent with a naive T cell phenotype (data not shown).

We hypothesized that naive T cell subsets defined by CD31 expression might have different potential to proliferate in response to TCR activation. CD45RO-depleted PBMC were incubated with

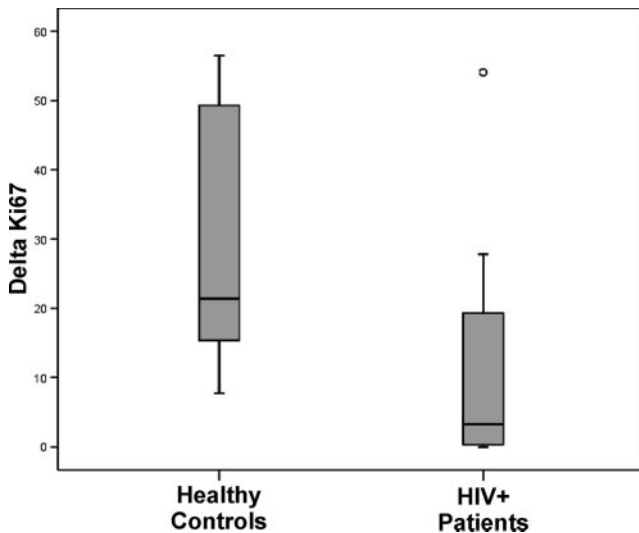


FIGURE 2. Defects in naive CD4⁺ T cells from HIV-infected persons are independent of APCs. Purified naive CD4⁺ T cells from healthy controls and HIV-infected persons were cultured for 4 days in the presence of immobilized anti-CD3 (10 μ g/ml) and soluble anti-CD28 Abs (5 μ g/ml). CD4⁺CCR7⁺CD27⁺ cells were examined for expression of Ki-67. Box and whiskers plot comparing δ Ki-67 (%) in purified naive CD4⁺ T cells from healthy donors ($n = 8$) and HIV-infected individuals ($n = 9$). *, $p = 0.02$, Mann-Whitney U test. Similar differences were noted between cells from healthy controls and HIV⁺ donors when the analysis was restricted to CD31⁺ cells, $p = 0.038$; (data not shown).

an agonistic anti-CD3 mAb and the CD4⁺CD45RO⁻CD27⁺CD28⁺CCR7⁺ cells were analyzed for Ki-67 expression among the CD31⁺ and CD31⁻ populations. Strikingly, CD31⁺ but not CD31⁻ cells were able to enter cell cycle after anti-CD3 Ab stimulation (Fig. 1A), and this was the case using cells obtained from both healthy donors and from HIV-infected persons (Fig. 1, A and B). There was little if any change in the percentage of CD31⁺ and CD31⁻ T cells after TCR stimulation (data not shown), making it unlikely that cells expressing Ki-67 originated from CD31⁻ cells that became CD31⁺ after stimulation. Moreover, depletion of CD31⁺ T cells from CD45RO depleted cell populations obtained from healthy donors resulted in nearly a complete loss of Ki-67 induction after TCR stimulation (data not shown) confirming that CD31⁺ but not CD31⁻ T cells are induced to enter cell cycle after TCR engagement by anti-CD3 Ab stimulation.

Consistent with our previous findings (4), naive CD4⁺ T cells from HIV-infected individuals had a diminished cell cycle progression after TCR stimulation when compared with naive CD4⁺ cells from healthy donors. Because CD31⁻ cells did not divide in these assays, we next restricted our analysis to CD31⁺ cells and found that even when we restricted the analyses to these cells, HIV⁺ subjects had diminished responses compared with those of healthy donors (Fig. 1B).

Because the assays described above relied on soluble anti-CD3 Ab stimulation, which is dependent on APC function, we needed to address the possibility that the defects observed in naive T cells from HIV⁺ donors was simply a consequence of defective APC. Therefore, we purified naive CD4⁺ T cells by negative selection and stimulated these cells with immobilized anti-CD3 Ab and soluble anti-CD28 Ab. Anti-CD3 alone or anti-CD28 alone resulted in poor induction of Ki-67, confirming the absence of APC costimulation (data not shown), whereas the combination of Abs induced cell cycle progression. Importantly, naive CD4⁺ T cells from HIV⁺ donors responded poorly under these experimental

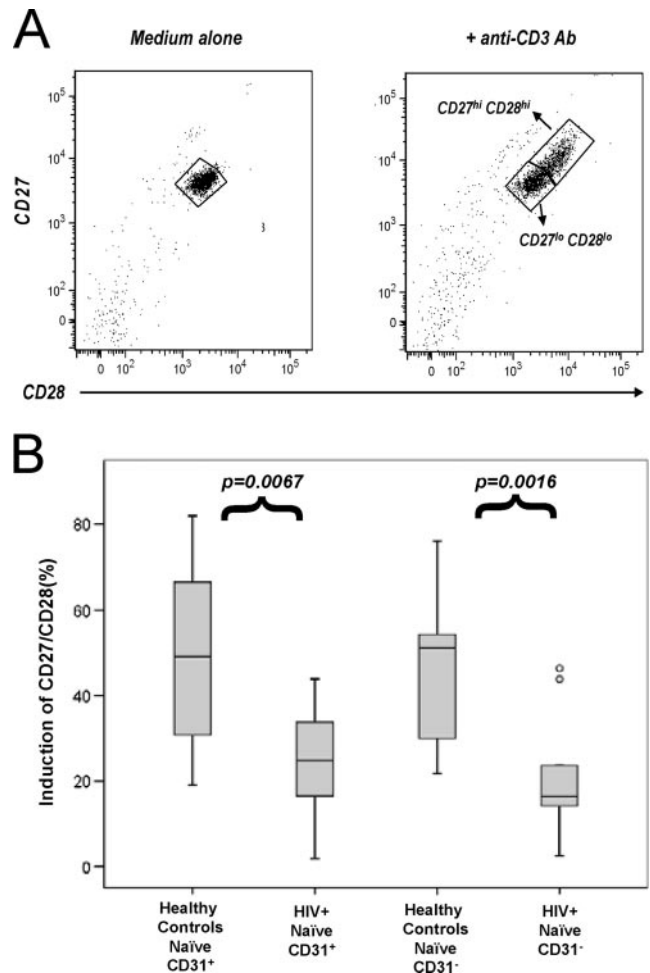


FIGURE 3. Diminished induction of costimulatory molecules (CD27 and CD28) in cells from HIV-infected persons. *A*, CD45RO-depleted PBMC were incubated in medium alone or in medium plus anti-CD3 Ab for 2 days. Expression of costimulatory molecules (CD27 and CD28) was analyzed among CD4⁺ cells after 2 days of incubation. The cells incubated in medium alone were used to establish the background level of costimulatory molecule expression so that the percentages of cells that increased costimulatory molecule expression above this level could be determined in the anti-CD3 stimulated cells. *B*, The percentages of CD31⁺ naive CD4⁺ T cells and CD31⁻ naive CD4⁺ T cells that increased surface expression of CD27 and CD28 in cells from HIV-infected persons ($n = 20$) and in cells from healthy controls ($n = 9$) after anti-CD3 Ab stimulation are shown. Statistical significance $p < 0.05$ was determined by ANOVA and student two-tailed t test.

conditions, expressing less Ki-67 than cells from healthy donors (Fig. 2). Thus, the defect in cell cycle progression is an intrinsic property of naive CD4⁺ T cell populations in HIV disease.

Naive CD4⁺ T cells in HIV infection have impaired induction of cell surface expression of CD27 and CD28 after TCR engagement

CD27 and CD28 costimulatory molecules play important roles in T cell activation process and the surface expression of these molecules increases following TCR activation (9, 10, 13). Therefore, we asked whether the induction of CD27 or CD28 expression might be impaired in naive T cells from HIV-infected individuals. We found that naive CD4⁺ T cells obtained from healthy controls increased expression of CD27 and CD28 following TCR stimulation. The increased expression of these costimulatory molecules was observed at 2 days (Fig. 3A) and also as early as 18 h after stimulation

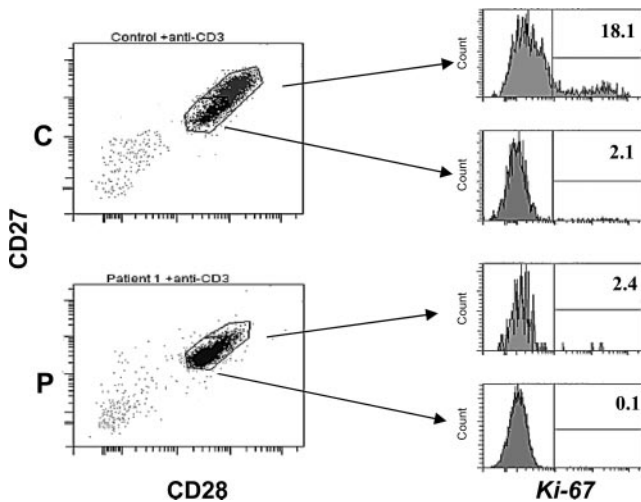


FIGURE 4. Ki-67 induction in cells that increase expression of costimulatory molecules CD27 and CD28. Expression of costimulatory molecules (CD27 and CD28) was analyzed among CD45RO-depleted CD4⁺ T cells after 2 days of incubation with anti-CD3 Ab. The cells were gated on CD4⁺CCR7⁺ cells and further analyzed for expression of CD27 and CD28 (dot-plots). A background gate was drawn around CD27CD28 double-positive cells using cells from unstimulated cultures (lower gate) and a second gate (upper gate) was drawn around cells that increased expression of CD27 and CD28 above the background levels after TCR engagement. The cells in the lower gate and cells in the upper gate were analyzed for Ki-67 expression (frequency distributions histograms). Representative results are shown for a healthy control (C) and an HIV-infected patient (P). Numbers indicate the percentage of Ki-67⁺ cells.

with anti-CD3 Ab (data not shown). Strikingly, CD4⁺CD31⁺ and CD4⁺CD31⁻ naive T cells from HIV-infected individuals demonstrated dramatic impairments in the induction of these costimulatory molecules following TCR stimulation (Fig. 3B). Induction of CD27 also was diminished in purified naive CD4⁺ T cells from HIV-infected persons that had been activated by immobilized anti-CD3 Ab and soluble anti-CD28 (data not shown), further indicating that the defects were intrinsic to the naive T cells.

Cell cycle entry is largely restricted to naive CD4⁺ T cells that increase costimulatory molecule surface expression after TCR engagement

To determine whether the induction of CD27 and CD28 was associated with cell cycle progression, we gated on cells with ele-

vated costimulatory molecule expression and evaluated the expression of Ki-67 in these cells 2 days poststimulation. Cells that increased surface expression of CD27 and CD28 after TCR activation were enriched for Ki-67⁺ cells, whereas cells that did not increase CD27/CD28 expression above the background of unstimulated cells, rarely expressed Ki-67 (Fig. 4). Interestingly, in three separate experiments, we found that naive CD4⁺ T cells stimulated with allogeneic APC (T cell-depleted PBMC) also increased surface expression of CD27/CD28, and again the induction of Ki-67 was restricted to the CD27/CD28 bright cells (representative experiment in Fig. 5). Thus, increased cell surface expression of CD27 and CD28 occurs in response to anti-CD3 Ab or in response to allogeneic stimulation, potentially facilitating cell cycle progression. The proportions of CD4⁺CD31⁻ naive T cells that increased surface expression of costimulatory molecules after TCR stimulation tended to be slightly reduced, but not significantly different from CD4⁺CD31⁺ naive T cells (Fig. 3B). The density of costimulatory molecule expression measured as the change in mean fluorescent intensity of CD27 or CD28 staining after TCR stimulation, however, was significantly lower among the CD4⁺CD31⁻ cells (δ mean fluorescent intensity CD31⁺ cells = 14886 and 7659 for CD27 and CD28, respectively; $p < 0.01$). These results demonstrate that CD4⁺CD31⁻ cells respond to TCR stimulation by increasing costimulatory molecule expression, however, the induction of these costimulatory molecules is not sufficient to permit cell cycle progression among these cells.

Next, we asked whether providing increased costimulatory signals with agonistic anti-CD28 Ab would enhance TCR-mediated recruitment of naive CD4⁺ T cells into the cell cycle. CD27 expression alone was used to quantify costimulatory molecule induction because CD28 was bound by the agonistic Ab. Interestingly, addition of the anti-CD28 agonistic Ab to cultures containing anti-CD3 agonist markedly enhanced cell cycle entry, even among naive CD4⁺ T cells that failed to increase surface expression of CD27 (Fig. 6). Thus, increasing costimulatory agonist activity might compensate for the lack of increased costimulatory molecule expression thereby promoting cell cycle progression of naive T cells that otherwise would be incapable of division.

Naive CD4⁺ cell cycle progression is related to induction of costimulatory molecule expression in health and in HIV infection

To ascertain whether the defects in cellular proliferation observed in TCR-activated naive CD4⁺ T cells from HIV-infected individuals were a consequence of impaired induction of costimulatory

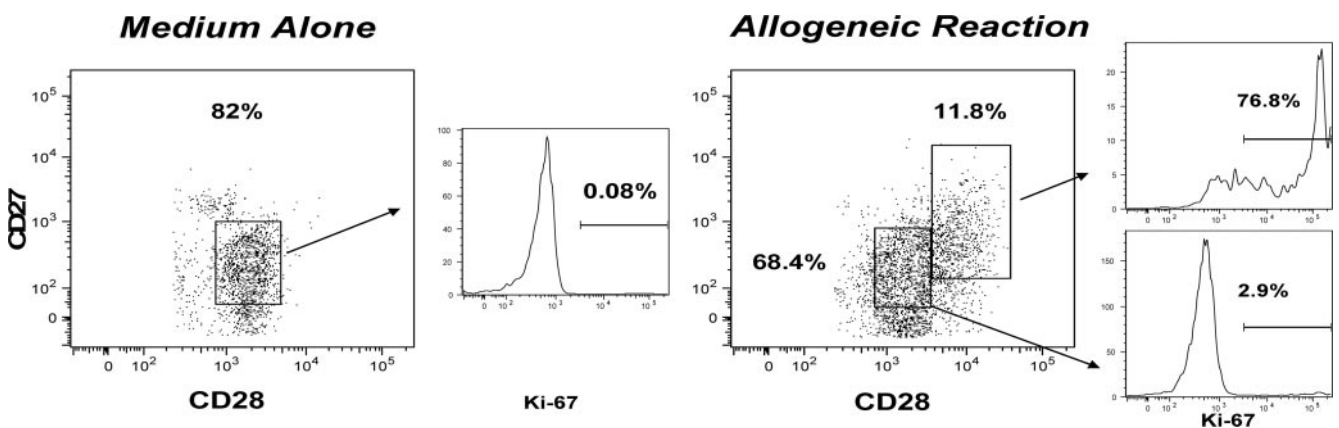


FIGURE 5. Induction of costimulatory molecules and Ki-67 in naive CD4⁺ T cells after alloantigen stimulation. CD45RO-depleted PBMC were incubated in medium alone or with irradiated allogeneic T cell-depleted PBMC and induction of CD27 and CD28 was examined after 4 days of incubation. The CD4⁺ cells that increased expression of costimulatory molecules and the cells that did not increase surface expression of costimulatory molecules after allogeneic stimulation were compared for intracellular expression of Ki-67. The y-axis label for frequency distribution histograms represents cell number.

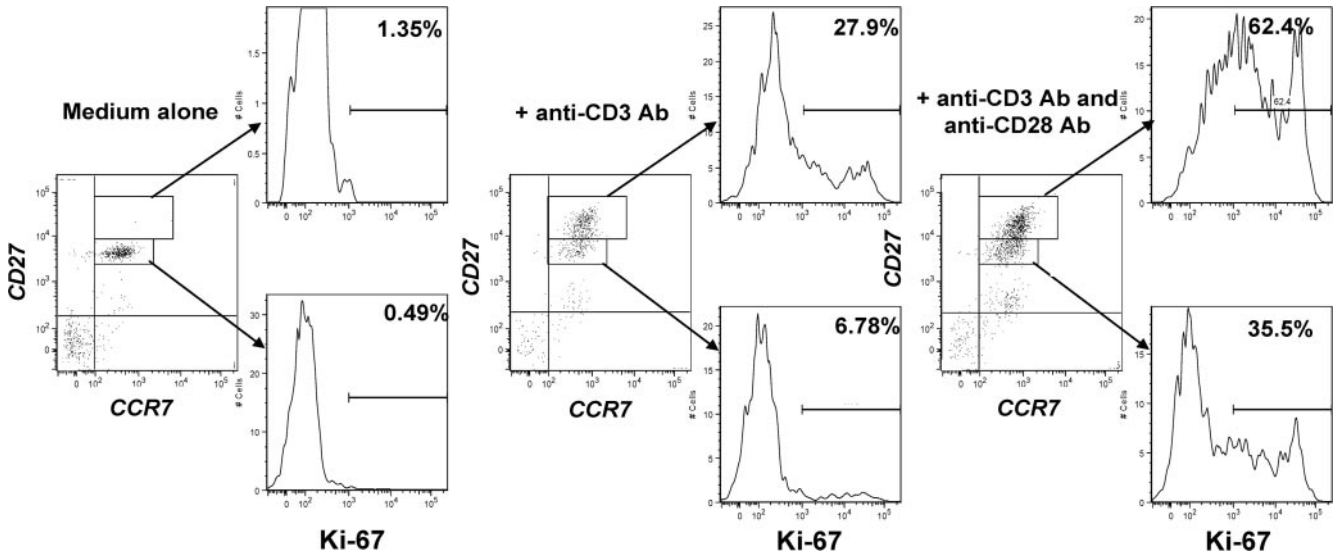


FIGURE 6. Anti-CD3 and anti-CD28 agonistic Abs induce cell cycle progression even among naive CD4⁺ T cells that fail to increase surface expression of CD27. CD45RO-depleted PBMCs from a healthy control were incubated for 48 h in medium alone or in medium supplemented with anti-CD3 Ab, anti-CD28 Ab, or anti-CD3 Ab plus anti-CD28 Ab. Cells were gated for CD4⁺ cells and further assessed for expression of CCR7 and CD27 (dot-plots). CCR7⁺ cells that had either increased surface expression of CD27 above resting levels or had maintained resting levels of CD27 expression were analyzed for Ki-67 expression (frequency distribution histograms). Ki-67 expression in cells incubated with the anti-CD28 Ab alone was similar to Ki-67 expression in cells incubated in medium alone (data not shown). Data shown are representative of two experiments.

molecule expression, we assessed the relationship between the induction of Ki-67 expression and the induction of costimulatory molecules among these cells after activation (Fig. 7, A and B).

Analyses of the whole naive CD4⁺ T cell population demonstrated a clear relationship between induction of costimulatory molecules and cell cycle progression only in cells from healthy donors but not

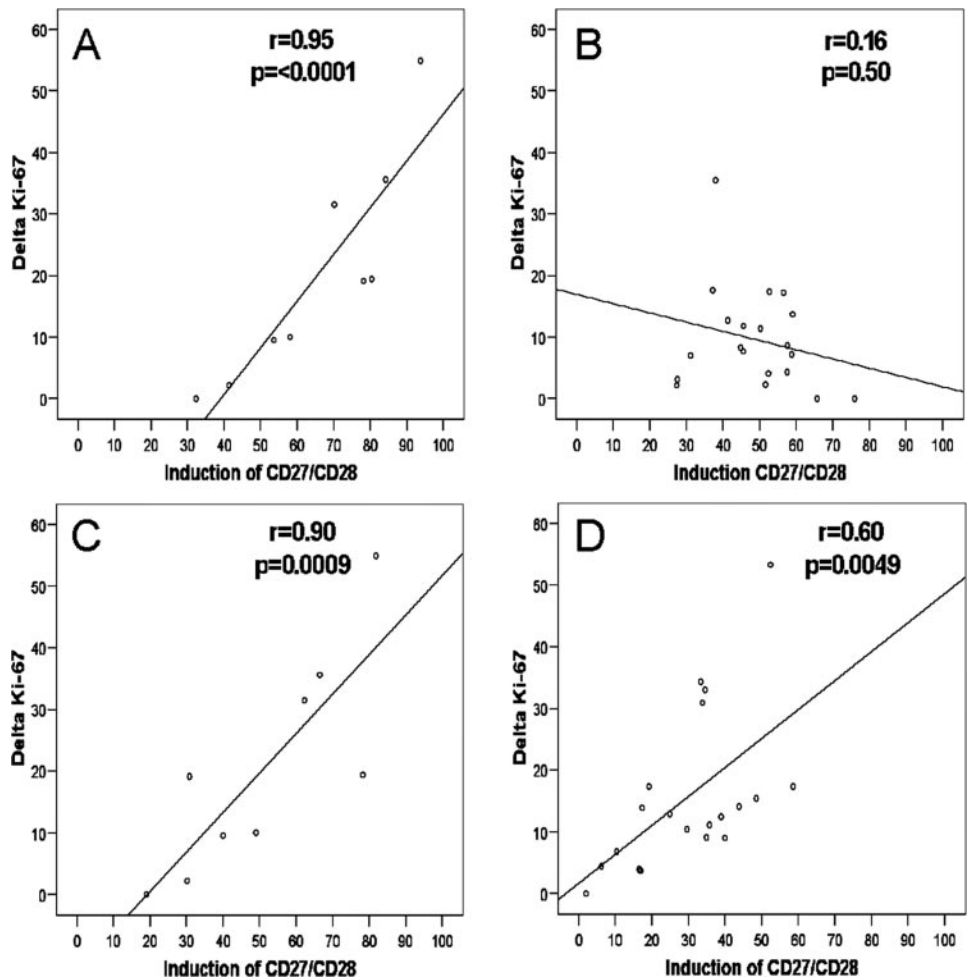


FIGURE 7. Induction of costimulatory molecule expression correlates with cell cycle progression. As described in Fig. 1, the change in Ki-67 expression is shown in relation to the induction of CD27 and CD28 among all naive CD4⁺ T cells (A and B) and among CD31⁺ naive CD4⁺ T cells (C and D) in healthy controls (A and C) and HIV⁺ subjects (B and D).

in HIV infection. Nevertheless, by restricting the analysis to CD4⁺CD31⁺ cells, we found that the magnitude of CD27/CD28 induction was directly and significantly related to the expression of Ki-67 (Fig. 7, C and D) in cells from both healthy donors and HIV-infected individuals. To further assess the importance of the costimulatory molecules in this model of T cell activation, we studied the effect of blocking costimulation with Abs that bind CD80 and CD86. The addition of these Abs to naive CD4⁺ T cells from three different donors resulted in inhibition of Ki-67 induction by anti-CD3 Ab ranging from 62 to 80%. Overall, these findings suggest that increased expression of CD27/CD28 during naive T cell activation may be an important determinant of cellular proliferation and that a defect in this response could underlie or contribute to the proliferation failure of naive CD4⁺ T cells in HIV-infection.

Discussion

In this study, we have examined the proliferation function of naive CD4⁺ T cell subsets in health and in HIV disease. We selected CD31 as marker for distinguishing two naive CD4⁺ T cells subpopulations. CD31 is 130-kDa glycoprotein expressed on a variety of cell types including endothelial cells and a subset of lymphocytes (14). This surface molecule is expressed by naive T cells possessing higher levels of TRECs consistent with recent emigration from the thymus (6). CD4⁺CD31⁻ naive T cells by contrast express lower levels of TRECs presumably due to extensive homeostatic cell division (6) and are observed at higher frequencies in elderly persons (15). Our results suggest that naive CD4⁺CD31⁺ but not CD4⁺CD31⁻ T cells undergo cell cycle progression after TCR engagement by soluble anti-CD3 Ab. It is possible that naive CD4⁺CD31⁻ represent “dead-end” naive T cells, analogous to memory T cells that have undergone extensive proliferation and differentiation but lack a general capacity for further expansion (16). In any case, this raises the possibility that CD31⁻ naive T cells might accumulate in HIV infection, leading to reduced overall function of the naive CD4⁺ T cell pool. Thus, it will be important to determine whether naive CD4⁺CD31⁺ cells are depleted in HIV infection and if the numerical depletion of the CD4⁺CD31⁺ naive T cell subset predicts poor immunologic responsiveness, as might be assessed for example in vaccine trials.

Unlike the CD4⁺CD31⁻ cells, CD4⁺CD31⁺ naive T cells more readily enter cell cycle after TCR stimulation. The increased proliferative potential of CD4⁺CD31⁺ cells indicates that these cells are likely to play a more substantial role in generating immunity to neoantigen than CD4⁺CD31⁻ cells. Importantly, we demonstrate in this study that in HIV infection even CD31⁺ naive T cells have significant functional impairments, and these defects are independent of possible APC dysfunction. Correlative analyses of cellular dysfunction with clinical indices such as plasma HIV RNA, CD4 cell counts, age and CD4 nadir failed to demonstrate any significant relationships. This may reflect the complex nature of these defects or insufficient numbers to uncover these potential relationships. In any case, our studies suggest that the numeric depletion of CD31⁺ naive T cells in HIV infection is likely to be compounded by intrinsic functional impairments in these cells as well.

Our observations also highlight the potential importance of increasing costimulatory molecule expression on naive T cells following TCR triggering. TCR activation results in the induction of CD28 and CD27 expression on the surface of naive CD4⁺ T cells. This increased surface expression of CD27 and CD28 was observed before expression of Ki-67 (24 h vs 48 h), suggesting that naive T cells may rely on heightened sensitivity to signals through these receptors to enter the cell cycle. Indeed, our observations indicate that only the cells that express these costimulatory mol-

ecules at increased levels are subsequently induced to express Ki-67 in circumstances where the anti-CD3 Ab alone is used to activate cells. In contrast, by increasing signaling through CD28 with agonistic Abs, cells that were less capable of increasing costimulatory molecule surface expression were better able to progress into the cell cycle. We propose that the additional agonistic signaling provided by anti-CD28 Abs replaced the requirement for heightened sensitivity normally provided by increasing the density of costimulatory molecules. Consequently, even cells without increased costimulatory molecule expression could undergo cell cycle progression. Further studies will be needed to ascertain whether increased surface expression of costimulatory molecules on activated naive T cells results in increased sensitivity to natural costimulatory ligands.

Importantly, this model may not be applicable to CD4⁺CD31⁻ naive cells. These cells did not proliferate after TCR stimulation, even though they did increase the surface expression of CD28 and CD27. It could be argued that the CD4⁺CD31⁻ cells express less surface density of costimulatory molecules compared with CD4⁺CD31⁺ cells, thereby not reaching a critical threshold of sensitivity for costimulation, however, it should be noted that these cells failed to enter cell cycle even when additional costimulation was provided with anti-CD28 agonistic Abs (data not shown). Thus, CD4⁺CD31⁻ cells appear to be intrinsically less able to expand in response to TCR activation even in the presence of additional costimulatory signals.

The poor induction of costimulatory molecule expression on the surface of naive CD4⁺ T cells from HIV-infected persons may be a critical determinant of cellular proliferation defects in these cells. We propose that the relative lack of costimulatory molecules may render the cells less able to receive these critical signals, resulting in cell cycle arrest instead of cell cycle progression. If this can be confirmed, then agents that can enhance CD28 and CD27 expression on T cells might be useful adjuvants in HIV disease. Alternatively, as we have shown in this study, use of costimulatory agonists may provide sufficient signal to bypass this limitation.

Finally, our previous studies demonstrated that CD4⁺ T cells (5, 17) and particularly naive CD4⁺ T cells (4) from HIV-infected persons failed to progress efficiently into the cell cycle after TCR activation. These studies relied on agonistic Abs targeted to the V β 3 TCR chain for stimulation of a subset of naive T cells and used CD62L expression and CD45RO depletion to identify naive T cells. In the present study, we have used more restricted criteria for defining naive CD4⁺ T cells that, according to other published observations, should provide at least 98% confidence that the cells so identified are truly naive (18). This represents a substantial refinement of previous studies that relied on only one or two cell surface markers to define and examine the function of naive T cells in HIV infection. Moreover, because anti-CD3 Ab does not restrict activation to a single V β family, our current studies provide evidence that defects observed previously with anti-V β 3 agonistic Abs are reflective of a defect that is apparently broadly shared among circulating naive CD4⁺ T cells. Thus, with this work, we provide more evidence that naive CD4⁺ T cell expansion defects are characteristic of HIV infection and we propose that these defects may play an important role in the immunodeficiency of HIV infection and AIDS.

Acknowledgment

We thank Dr. Robert Asaad for obtaining blood samples used in this study.

Disclosures

The authors have no financial conflict of interest.

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