RAPID COMMUNICATION

Fas-Mediated Apoptosis of CD4+ and CD8+ T Cells From Human Immunodeficiency Virus-Infected Persons: Differential In Vitro Preventive Effect of Cytokines and Protease Antagonists

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Human immunodeficiency syndrome (HIV) infection leads to a progressive loss of T-cell-mediated immunity associated with T-cell apoptosis. We report here that CD4+ and CD8+ T cells from HIV-1-infected persons are sensitive to Fas (CD95/APO-1)-mediated death either by an agonistic anti-Fas antibody or by the physiologic soluble Fas ligand, although showing no sensitivity to tumor necrosis factor α-induced death. CD4+ and CD8+ T-cell apoptosis induced by Fas ligation was enhanced by inhibitors of protein synthesis and was prevented either by a soluble Fas receptor decoy or an antagonistic anti-Fas antibody. Fas-mediated apoptosis could also be prevented in a CD4+ or CD8+ T-cell-type manner by several protease antagonists, suggesting the involvement of the interleukin-1β (IL-1β)-converting enzyme (ICE)-related cysteine protease in CD4+ T-cell death and of both a CPP32-related cysteine protease and a calpain protease in CD8+ T-cell death; and (2) by three cytokines, IL-2, IL-12, and IL-10, that exerted their effects through a mechanism that required de novo protein synthesis. Finally, T-cell receptor (TCR)-induced apoptosis of CD4+ T cells from HIV-infected persons involved a Fas-mediated death process, whereas TCR stimulation of CD8+ T cells led to a different Fas-independent death process. These findings suggest that Fas-mediated T-cell death is involved in acquired immunodeficiency syndrome (AIDS) pathogenesis and that modulation of Fas-mediated signaling may represent a target for new therapeutic strategies aimed at the prevention of CD4+ T-cell death in AIDS.

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inhibitor Acetyl-YVAD-aldehyde (Ac-YVAD-CHO), and the reversible CPP32 inhibitor Acetyl-DEVD-aldehyde (Ac-DEVD-CHO; Bâle Biochimie, Voisins-le-Bretonneaux, France). Additional protease inhibitors that do not inhibit ICE or CPP32 activity27-31 included acetyl n-tosyl-lys-chloromethylketone (Ac-Tox-CMK), leupeptin (Ac-LLR-CMK), and E64 (Sigma, La Verpillière, France). Cytokines included recombinant human (rh) IL-2 (provided by Roussel-Uclaf, Paris, France), rhIL-4, rhIL-7, rhIL-10, rhIL-12 (R & D Systems, Abingdon, UK), and rh tumor necrosis factor α (rhTNFa; Genzyme, Cambridge, MA). Anti-TNFα antibodies were rabbit polyclonal anti-human TNFα neutralizing antibodies (Genzyme). Other reagents were cycloheximide (CHX; Sigma), acridine orange dye (Immuno-tech), YO-PRO-1 dye (Molecular Probes, Inc, Eugene, OR), Hoechst 33342 (Bisbenzimide; Sigma), and Calcein AM (Molecular Probes).

Cells and culture conditions. Heparinized venous peripheral blood was obtained from 45 asymptomatic HIV-1-seropositive adults (Service des Maladies infectieuses, Hôpital Dron, Tourcoing, France) with CD4+ T-cell counts higher than 400/μL and from 15 HIV-seronegative healthy controls. Peripheral blood mononuclear cells (PBMC) were isolated from heparinized venous blood by Ficoll-Hypaque density gradient centrifugation and cultured in RPMI 1640 (GIBCO, Courbevoie, France) supplemented with 10% heat-inactivated fetal calf serum (Boehringer Mannheim, Meylan, France), 2 mM/L L-glutamine, 1 mM/L sodium pyruvate (GIBCO), and gentamicin (Gentalline; 8 μg/mL; Schering-Plough, Levallois-Perret, France). Three-color flow cytometer analysis (FACScan; Becton Dickinson) of freshly isolated PBMC was performed by costaining cells using MoAbs (including isotype controls) directly labeled with FITC, RA-PE, and PercP. Lymphocytes were gated under forward and size scatter light parameters. Purified CD4+ or CD8+ T cells were labeled with FITC, RA-PE, and PercP. Lymphocytes were formed by costaining cells using MoAbs (including isotype controls) labeled with YO-PRO-1 dye as described,32 or by UV fluorescent microscopy enhancing effect (from 58% to 95%) on TNFa-mediated death of the TNFa-sensitive cell line L929.

RESULTS AND DISCUSSION

In HIV-infected persons, the percentage of peripheral blood T cells expressing the Fas receptor is higher than in uninfected controls.21,22 We observed a significant increase in Fas-positive T cells in both the memory CD4+ T cells (that normally express Fas)30 and in the CD45 RA naive CD4+ and CD8+ T cells (that normally include few Fas-positive T cells; Fig 1A), suggesting that HIV infection induces a global immune activation process that also involves the naive or virgin T-cell subpopulation. In contrast to T cells from controls, freshly isolated CD4+ and CD8+ T cells from HIV-infected persons were sensitive to apoptosis induction through Fas receptor engagement (Fig 1B), either by an agonistic anti-Fas antibody, as previously reported,21,22 or by a soluble form mimicking the ligand of the Fas receptor, a recombinant human Fas ligand. The percentages of apoptosis induced by the agonistic anti-Fas antibody in CD4+ and CD8+ T cells (mean, 13% and 14.1%, respectively) were less than that induced by the soluble recombinant Fas ligand, suggesting that anti-Fas antibody, as the cell surface-expressed Fas ligand, may be more effective in achieving Fas receptor aggregation than the secreted form of the Fas ligand. The selective involvement of Fas-mediated signaling in T-cell apoptosis was indicated (1) by the prevention of soluble Fas ligand-mediated apoptosis by the antagonistic anti-Fas antibody ZB4 and by a soluble Fas receptor decoy (human Fas Ig fusion protein) that both block Fas-Fas ligand interactions22,23 (Fig 1C); and (2) by the absence of T-cell apoptosis induction in response to TNFa (Fig 1D), another member of the Fas ligand family whose p55 receptor has a Fas-related death domain,23 even in the presence of the protein synthesis inhibitor CHX (data not shown) that had an enhancing effect (from 58% to 95%) on TNFa-mediated death of the TNFa-sensitive cell line L929.

In freshly isolated T cells from healthy individuals, antibody-mediated Fas ligation does not induce apoptosis.9,37 (Fig 1B) and even provides in some cases costimulatory signals to concomitant TCR stimulation, leading to an enhancement of TCR-induced T-cell proliferation9 (Fig 1E). However, in T cells from HIV-infected persons, antibody-mediated Fas ligation led not only to a significant induction of T-cell apoptosis (Fig 1B) but also to a significant reduction in the TCR-induced T-cell proliferation (Fig 1E) that was already severely impaired when compared with that of controls. Thus, CD4+ and CD8+ T cells from HIV-infected persons behave as potential targets for a Fas-mediated bystander death process that could be triggered by the Fas ligand expressed or secreted by activated neighboring immune cells. In this respect, T cells from HIV-infected persons resemble preactivated T-cell lines,22 suggesting that HIV infection induces a general state of immune activation that primes large numbers of T cells for death by apoptosis in response to further interaction with the Fas ligand.

Fas antibody-mediated and soluble Fas ligand-mediated apoptosis of CD4+ and CD8+ T cells from HIV-infected...
Regulation of cysteine protease activity that have been reported to be more effective than the reversible aldehyde (CHO) peptide antagonists. Experiments using reversible aldehyde competitive inhibitors MCH-2, and ICE protease activity and may therefore be less selective for either ICE (AC-YVAD-CHO) or CPP32. The chloromethylketone (CMK) protease that are either functioning downstream of one another or are each required for the activation of downstream effectors of apoptosis. Although further work will be needed to understand the precise role of each protease in the complex network of apoptosis in T cells from HIV-infected persons.

**Fig 1.** Fas expression and Fas-mediated apoptosis in CD4+ and CD8+ T cells from HIV-infected persons. (A) Expression of the Fas (CD95) molecule by memory (CD45 RO) and naive (CD45 RA) CD4+ (CD4) and CD8+ (CD8) T cells was assessed by 3-color flow cytometry analysis on freshly isolated PBMC from asymptomatic HIV-infected persons (●) and from uninfected controls (○) using directly labeled MoAbs. Results represent the percentages of CD4+ and CD8+ T cells (Total; n = 18 HIV-infected persons and 10 controls) and of CD45RO- (RO) and CD45RA- (RA) positive CD4+ or CD8+ T cells (n = 6 HIV-infected persons and 5 controls) expressing CD95. Each circle represents results from a different individual, and bars represent the mean values in each group. (B) Percentages of apoptotic cells were assessed in purified CD4+ (CD4) and CD8+ (CD8) T cells from asymptomatic HIV-infected persons (●) or uninfected controls (○) 18 hours after incubation in the absence (--) or presence (+) of either an agonistic anti-Fas IgM MoAb (Fas mAb, left panel; 1 μg/mL) or a soluble recombinant Fas ligand (FasL, right panel; 1:200 dilution). Incubation with an IgM isotype control MoAb (1 μg/mL) did not induce any significant apoptosis in CD4+ and CD8+ T cells from 5 HIV-infected persons (symbols are the same as in [A]). (Left panel) n = 45 HIV-infected persons and 14 controls. (Right panel) CD4 (n = 10 HIV-infected persons and 4 controls); CD8 (n = 8 HIV-infected persons and 4 controls). (C) Percentages of apoptotic cells were assessed in purified CD4+ (CD4) or CD8+ (CD8) T cells from an asymptomatic HIV-infected person were preincubated for 1 hour in the absence or presence of either an antagonistic anti-Fas MoAb (ZB4, IgG1 isotype, 1 μg/mL), a human Fas receptor decoy (hFas Fc, 10 μg/mL), or an IgG1 isotype control MoAb (IgG1; 1 μg/mL) and then incubated for 18 hours with the soluble recombinant Fas ligand (Fasl, 1:200 dilution). Percentages of apoptosis prevention were calculated as described in the Materials and Methods. Results are from one representative experiment of three. (D) Percentages of apoptotic cells were assessed in purified CD4+ T cells (CD4) or CD8+ T cells (CD8) from 4 asymptomatic HIV-infected persons (solid symbols) or 2 uninfected controls (open symbols) 18 hours after incubation in the absence (--) or presence (+) of rTNFa (25 IU/mL) (2) or the agonistic anti-Fas MoAb (1 μg/mL) (3). Each symbol represents results from one individual. L929, the TNFa-sensitive L929 cell line (L929) incubated for 18 hours in the absence (--) or presence (+) of TNFa (25 IU/mL). (E) PBMC from 8 asymptomatic HIV-infected persons expressing CD95. Each circle represents results from one individual.

Persons could be prevented by pretreatment with the Ac-YVAD-CMK peptide, an irreversible competitive inhibitor of the ICE cysteine protease family (Fig 2A and B), whereas the control Ac-TOS-CMK protease inhibitor peptide had no effect (Fig 2A), suggesting that Fas-mediated death signaling in T cells from HIV-infected persons shared the ICE-dependent downstream effector pathway recently described in T-cell lines. The family of ICE-related cysteine proteases, involved in various degrees in the effector pathway of apoptosis, has now been shown to include at least 6 members, ICE, CPP32/YAMA, ICH-1/NEDD-2, ICH-2/TX, MCH-2, and ICE rel III. The chloromethylketone (CMK) YVAD peptide is an irreversible competitive inhibitor of ICE protease activity and may therefore be less selective than the reversible aldehyde (CHO) peptide antagonists. Experiments using reversible aldehyde competitive inhibitors of cysteine protease activity that have been reported to be specific for either ICE (Ac-YVAD-CHO) or for CPP32 (Ac-DEVD-CHO) suggested that Fas-mediated death signaling in T cells from HIV-infected persons may involve the preferential activation of ICE in the CD4+ T cells and of CPP32 in the CD8+ T cells (Fig 2A). The leupeptin (Ac-LLR-CHO) protease antagonist that does not inhibit ICE33 or CPP3233 had no inhibitory effect on Fas-mediated apoptosis of CD4+ and CD8+ T cells (Fig 2A). As also shown in Fig 2A, E64, an inhibitor of the calcium-dependent protease calpain that does not inhibit ICE32,33 was as effective as Ac-DEVD-CHO in inhibiting Fas-mediated CD8+ T-cell apoptosis, although having no effect on Fas-mediated CD4+ T-cell death. Together, these findings suggest that the Fas-induced apoptosis involves an ICE-related cystein protease in CD4+ T cells; and in CD8+ T cells, both a CPP32-related cystein protease and a calpain-related protease that are either functioning downstream from one another or are each required for the activation of downstream effectors of apoptosis.
to confirm the precise nature of the proteases involved, our findings strongly suggest, at this stage, that the Fas-mediated death pathway requires the activation of different proteases in CD4+ and CD8+ T cells from HIV-infected persons.

The magnitude of Fas-mediated T-cell apoptosis (the net difference between the percentages of Fas-induced apoptosis and spontaneous apoptosis) showed individual variations (Fig 1B), but the levels of the preventive effect achieved by protease antagonists did not depend on the magnitude of Fas-mediated apoptosis. For example, in the experiments shown in the Fig 2A, the mean preventive effect of Ac-YVAD-CMK on Fas-induced apoptosis of CD4+ T cells from 14 HIV-infected persons was 58%. In the 2 of 14 cases in which Fas ligation induced the highest percentages of CD4+ T-cell apoptosis (29.5% and 16.7%), the preventive effects of Ac-YVAD-CMK were 58% and 67%, respectively. Also, T-cell treatment with the protein synthesis inhibitor greatly enhanced the magnitude of Fas-mediated apoptosis (Fig 2C). In such conditions, Ac-YVAD-CMK conserved its preventive effect. For example, in the experiments shown in Fig 2F, in the absence of CHX, the mean percentage of Fas-induced apoptosis in CD4+ T cells from 4 HIV-infected persons was 14% and the mean preventive effect of Ac-YVAD-CMK was 43%; in the presence of CHX, the mean percentage of Fas-induced apoptosis increased to 25%, and the mean preventive effect of Ac-YVAD-CMK remained at 35%.

The finding that Fas-mediated death of CD4+ and CD8+ T cells was enhanced by the protein synthesis inhibitor CHX (Fig 2C) suggested that Fas-induced death signaling in T cells from HIV-infected persons was partly under an active repression by newly synthesized proteins of short half life. Cytokines are a family of soluble mediators of cell signaling that are potent regulators of T-cell activation and differentiation and exert most of their effects on target cells through...
de novo protein synthesis as a consequence of cytokine receptor-mediated nuclear translocation of the signal transducers and activators of transcription (Stat) proteins. We have previously shown that IL-12, a cytokine that upregulates CD4+ Th1-cell functions, has a preventive effect on Fas-mediated apoptosis of CD4+ T cells from HIV-infected persons. As shown in Fig 2D, preincubation of T cells from HIV-infected persons for 2 hours with three different cytokines (IL-2, IL-10, or IL-12) had a highly significant preventive effect on death of CD4+ and/or CD8+ T cells. IL-2, a cytokine that is produced by activated CD4+ T cells and is involved in T-cell–mediated immunity, had a preventive effect on Fas-mediated death of both CD4+ and CD8+ T cells. Two other cytokines secreted by immune accessory cells (monocytes/macrophages and/or B cells), IL-12, and IL-10, acted in a cell-type specific way. IL-12 selectively prevented Fas-mediated apoptosis of CD4+ T-cell death, although having no preventive effect on CD8+ T-cell death; IL-10 prevented Fas-mediated CD8+ T-cell death, although having no preventive effect on CD4+ T-cell death (Fig 2D). Like that of protease antagonists, the preventive effect of cytokines did not depend on the magnitude of Fas-mediated T-cell death. As shown in Fig 2E, IL-10 was able to almost completely prevent apoptosis in a case in which the percentage of Fas-induced apoptosis in CD8+ T cells (36 hours after incubation with the anti-Fas antibody) reached 41%. Although these preventive effects of IL-10 (Fig 2E), IL-2, and of IL-12 lasted for more than 36 hours, IL-10 during this period also showed a delayed enhancing effect on Fas-mediated apoptosis of CD4+ T cells (data not shown). Flow cytometry analysis of purified CD4+ and CD8+ T cells from HIV-infected persons using double-color analysis with FITC-labeled anti-Fas MoAb and PE-labeled anti-CD4 or CD8 MoAb indicated that none of these cytokines induced any significant modification in the percentage of CD4+ and CD8+ T cells expressing the Fas molecule or in the densities of Fas molecules expressed on the CD4+ and CD8+ T-cell surface. For example, the mean fluorescence intensity of Fas labeling on CD4+ T cells was 8.29 ± 6.26 or 8.68 ± 6.93 after preincubation with medium alone or IL-12, respectively, and the mean fluorescence intensity of Fas labeling on CD8+ T cells was 8.43 ± 5.13 or 8.08 ± 5.09 after preincubation with medium alone or IL-10, respectively. These data indicated that cytokines exerted their effect through modulation of Fas-mediated signal transduction. The IL-2, IL-4, and IL-7 cytokines bind to the same type 1 cytokine receptor family that share one common receptor subunit, the IL-2Rγc, as well as the Jak (Janus kinase) and 3 signal transduction pathways, but do not activate the same Stat proteins. Although IL-7 showed a small preventive effect on Fas-mediated death of CD4+ T cells from HIV-infected persons (Fig 2D), the absence of preventive effect of IL-7 on Fas-mediated death of CD8+ T cells as well as the absence of preventive effect of IL-4 on Fas-mediated death of CD4+ and CD8+ T cells (Fig 2D) underlines the selectivity of the effect of cytokines on Fas-mediated death signaling. In contrast to the ICE family protease antagonist that retained its preventive effect on Fas-mediated T-cell apoptosis in the presence of the protein synthesis inhibitor CHX (Fig 2F), the preventive effect of cytokines on T-cell sensitivity to Fas ligation was completely abrogated by CHX treatment (Fig 2F). These data suggest that cytokines do not exert a direct inhibitory effect on ICE family protease activity, but rather act by activating selective transcription factors inducing de novo synthesis of proteins that interfere with Fas-mediated death signaling.

CD4+ and CD8+ T cells from HIV-infected persons undergo apoptosis not only in response to direct Fas ligation, but also to TCR stimulation7,9,12 (Fig 3A). As shown in Fig 3B, TCR-induced apoptosis of CD4+ T cells was prevented by either a Fas ligand antisense phosphorothioate oligonucleo-
from HIV-infected persons. (A) Percentages of apoptotic cells were assessed in purified CD4+ (CD4+ and CD8+ (CD8+) T cells from 14 asymptomatic HIV-infected persons shown in (A) were incubated for 18 hours after incubation in the absence (−) or presence (+) of an anti-TCR/CD3 MoAb (CD3 mAb, 1 μg/mL). (B) Purified CD4+ (CD4+) and CD8+ (CD8+) T cells from the asymptomatic HIV-infected persons shown in (A) were incubated for 18 hours with an anti-TCR/CD3 MoAb (1 μg/mL) after 2 hours of preincubation in the absence or presence of (1) the antagonistic anti-Fas MoAb 4B4 (1 μg/mL; n = 8); (2) an antisense oligonucleotide to the Fas ligand (1 μg/mL; n = 8); (3) a control oligonucleotide (1 μg/mL; n = 8); or (4) the ICE protease antagonist Ac-YVAD-CMK (20 μmol/L; n = 4). Percentages of apoptosis prevention were determined as described in the Materials and Methods. Each circle represents results from one individual; bars represent mean values in each group.

Fig 3. Involvement of Fas in TCR-induced apoptosis of CD4+ cells from HIV-infected persons. (A) Percentages of apoptotic cells were assessed in purified CD4+ (CD4+) and CD8+ (CD8+) T cells from 14 asymptomatic HIV-infected persons (8) and from 6 uninfected controls (8) 18 hours after incubation in the absence (−) or presence (+) of an anti-TCR/CD3 MoAb (CD3 mAb, 1 μg/mL). (B) Purified CD4+ (CD4+) and CD8+ (CD8+) T cells from the asymptomatic HIV-infected persons shown in (A) were incubated for 18 hours with an anti-TCR/CD3 MoAb (1 μg/mL) after 2 hours of preincubation in the absence or presence of (1) the antagonistic anti-Fas MoAb 4B4 (1 μg/mL; n = 8); (2) an antisense oligonucleotide to the Fas ligand (1 μg/mL; n = 8); (3) a control oligonucleotide (1 μg/mL; n = 8); or (4) the ICE protease antagonist Ac-YVAD-CMK (20 μmol/L; n = 4). Percentages of apoptosis prevention were determined as described in the Materials and Methods. Each circle represents results from one individual; bars represent mean values in each group.

tide, the antagonistic Fas antibody 4B4, or the ICE protease family antagonist Ac-YVAD-CMK, indicating that TCR-induced apoptosis of CD4+ T cells from HIV-infected persons involved a Fas-mediated signaling pathway resulting from an interaction between the Fas receptor and the Fas ligand, whose expression is induced in normal murine and human T-cell lines by TCR stimulation.25,35,49 These data are consistent with our previous finding that IL-12, which prevents TCR-induced apoptosis of CD4+ T cells,9,22 also prevents CD4+ T-cell apoptosis induced by Fas ligation22 (Fig 2D).

In contrast, treatment with the Fas ligand antisense oligonucleotide with the antagonistic Fas antibody 4B4 or with Ac-YVAD-CMK had no significant preventive effect on TCR-induced apoptosis of CD8+ T cells (Fig 3B). Ac-YVAD-CHO and CPP32 Ac-DEVD-CHO were also devoid of preventive effect on TCR-induced CD8+ T-cell death (data not shown). These findings are consistent with our observation that IL-10 that prevents CD8+ T-cell apoptosis induced by Fas ligation (Fig 2D) is devoid of any preventive effect on CD8+ T-cell apoptosis induced by TCR stimulation (data not shown).

It has been recently reported that TCR-induced death of preactivated mature murine CD4+ T cells occurs through a Fas-mediated mechanism, whereas TCR-induced death of preactivated CD8+ T cells occurs through a p75 TNF receptor-mediated mechanism.39 However, the addition of TNFα did not induce apoptosis in CD4+ or CD8+ T cells from HIV-infected persons (Fig 1D), and the addition of anti-TNF antibodies showed no preventive effects on TCR-induced apoptosis of either CD4+ or CD8+ T cells from HIV-infected persons (data not shown). Therefore, our findings suggest that TCR-induced CD8+ T-cell apoptosis in HIV infection occurs through a Fas-independent, TNF-independent, CD8+ T-cell killing process whose mechanism remains to be assessed.

Together, our findings imply (1) that Fas-mediated death signaling could play an important role in a bystander death process of both CD4+ and CD8+ T cells from HIV-infected persons through contacts with the Fas ligand that may be expressed or secreted by activated T cells or NK cells,a situation that could occur in vivo in lymphoid organs and tissues that contain high densities of activated immune cells; (2) that several protease antagonists and cytokines have the capacity to prevent T-cell sensitivity to Fas-mediated death signals. Finally, beyond HIV infection, a general implication of our findings is that the general and potent regulatory role of cytokines on the activation and differentiation of defined T-cell populations may operate through the regulation of T-cell sensitivity to Fas-mediated death signaling.
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