HIV

Delayed differentiation of potent effector CD8$^+$ T cells reducing viremia and reservoir seeding in acute HIV infection

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CD8$^+$ T cells play a critical role in controlling HIV viremia and could be important in reducing HIV-infected cells in approaches to eradicate HIV. The simian immunodeficiency virus model provided the proof of concept for a CD8$^+$ T cell–mediated reservoir clearance but showed conflicting evidence on the role of these cells to eliminate HIV-infected cells. In humans, HIV-specific CD8$^+$ T cell responses have not been associated with a reduction of the HIV-infected cell pool in vivo. We studied HIV-specific CD8$^+$ T cells in the RV254 cohort of individuals initiating ART in the earliest stages of acute HIV infection (AHI). We showed that the HIV-specific CD8$^+$ T cells generated as early as AHI stages 1 and 2 before peak viremia are delayed in expanding and acquiring effector functions but are endowed with higher memory potential. In contrast, the fully differentiated HIV-specific CD8$^+$ T cells at peak viremia in AHI stage 3 were more prone to apoptosis but were associated with a steeper viral load decrease after ART initiation. Their capacity to persist in vivo after ART initiation correlated with a lower HIV DNA reservoir. These findings demonstrate that HIV-specific CD8$^+$ T cell magnitude and differentiation are delayed in the earliest stages of infection. These results also demonstrate that potent HIV-specific CD8$^+$ T cells contribute to the reduction of the pool of HIV-producing cells and the HIV reservoir seeding in vivo and provide the rationale to design interventions aiming at inducing these potent responses to cure HIV infection.

INTRODUCTION

Boosting HIV-specific CD8$^+$ T cell responses is explored in immune-based interventions to eradicate HIV because several observations both in HIV infection and in the nonhuman primate model of HIV suggested that these cells could play a role in controlling viral replication (*1*). Among these observations, the appearance of CD8$^+$ T cell–mediated escape mutations at the early stage of HIV infection suggests that these cells exert an immune pressure on the virus. In natural controllers with slow progression of disease, functional HIV-specific CD8$^+$ T cells have been associated with low to undetectable viremia in the absence of antiretroviral therapy (ART) (*2*–*4*). However, these functional responses are not induced in individuals not carrying specific human leukocyte antigen (HLA) molecules, and in most individuals during untreated HIV infection, CD8$^+$ T cells directed against HIV antigens fail to control viral replication (*5*–*8*). During chronic HIV infection, the dysfunction of CD8$^+$ T cell responses occurring with continuous exposure to HIV antigens in the absence of ART has been well characterized (*9*–*12*). Studies in the simian immunodeficiency virus (SIV) model suggested that viral load decline after ART initiation during chronic SIV infection was independent from CD8$^+$ T cell–mediated killing of SIV-infected cells (*13*, *14*). HIV-specific CD8$^+$ T cells are induced at the early stage of infection at high numbers, and the magnitude and survival capacity of these responses in acute infection have been associated with a lower viral load set point (*15*–*18*). Although the emergence of HIV-specific CD8$^+$ T cells has been temporally associated with viral load decline in the absence of treatment (*5*, *7*, *8*), no study has yet reported a direct correlation between these responses and viral load decline. Whether HIV-specific CD8$^+$ T cells have the ability to control viral replication at the early stage of HIV infection is still a debated question.

Cellular immune responses are also explored in immune-based interventions to control or eliminate viral reservoirs that persist in HIV-infected individuals on ART or after treatment interruption (*19*–*21*). The role of HIV-specific CD8$^+$ T cells in purging viral reservoir persisting under ART has been demonstrated in the SIV model where strong and sustained SIV-specific CD8$^+$ T cells induced by the rhesus cytomegalovirus (RhCMV)–based vaccine were subsequently able to eliminate the virus from the infected animals (*22*, *23*). However, the RhCMV vaccine induces unconventional SIV-specific CD8$^+$ T cells (*24*, *25*), and the characteristics of HIV-specific CD8$^+$ T cells that can control or eliminate HIV reservoir in human in "shock and kill" strategies are still unknown (*19*, *26*–*28*). After ART initiation, HIV-specific CD8$^+$ T cell responses decrease drastically, do not completely recover their functions, and are unable to eliminate the persistent viral reservoir (*29*–*34*). HIV-specific CD8$^+$ T cells expanded in vitro from HIV-infected individuals on ART were able to control viral replication and eliminate HIV-producing CD4$^+$ T cells in vitro, suggesting that inducing potent responses could

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be an effective strategy to control viral reservoirs (*35*–*37*). However, no evidence had been reported on the role of HIV-specific $CD8^+$ T cells in controlling viral reservoir in ART-treated individuals in vivo.

The analysis of emerging HIV-specific $CD8^+$ T cells at the earliest stages of HIV infection has been extremely limited by the difficulty to detect and recruit individuals within days of acquiring HIV. The RV254/SEARCH010 Thai cohort is a unique cohort of individuals recruited at these earliest stages of HIV infection because participants enrolled in the cohort are detected before or at peak viremia and initiate treatment immediately at entry (*38*, *39*). The elevated number of participants recruited in this cohort allowed us to group individuals enrolled at the different stages of acute infection before and at peak viral load. This study was performed on individuals recruited in the earliest stages of acute HIV infection (AHI). On the basis of the large prospective study of AHI in adults conducted in Africa and Thailand, the average number of days to reach peak viremia from the day of first positive plasma RNA in AHI is 13 days (*40*). Therefore, if the eclipse phase is added, we can estimate that the peak viral load is reached at a mean of 23 days after HIV infection. Participants in this study were grouped into three distinct groups within the first 25 days of HIV infection, two during the viral load rise, and one at peak viral load. Here, we analyzed the quality of HIV-specific $CD8^+$ T cell responses emerging in the earliest stages of acute infection and assessed whether these responses could control viral replication and HIV reservoir seeding after ART initiation.

RESULTS

HIV-specific $CD8^+$ T cell expansion in the early stages of acute HIV-1 infection

The fourth-generation (4G) staging was used to group RV254/SEARCH010 participants at the earliest stages of acute infection before peak viremia (AHI 4G stages 1 and 2; $n = 22$ and 37, respectively) and at peak viremia (AHI 4G stage 3; $n = 47$) (Table 1) (*41*). HIV-uninfected matched control individuals were obtained from the RV304/SEARCH013 Thai cohort ($n = 14$). Previously, it has been demonstrated that most of the activated $CD8^+$ T cells in acute infections are directed against viral antigens (*18*, *42*, *43*). Therefore, the HIV-specific $CD8^+$ T cell response during AHI was defined by the combinations of markers Ki-67 and Bcl-2, or CD38 and HLA–antigen D related (DR). Activated $Ki\text{-}67^+Bcl\text{-}2^{lo}$ and $CD38^+HLA\text{-}DR^+$ $CD8^+$ T cells were detected at significantly higher frequencies than the HIV-control group in the earliest stage of acute infection, AHI stages 1 and 2 ($P < 0.0001$, $P = 0.0015$, and $P < 0.0001$, respectively), and increased to reach the highest frequencies in stage 3 (Fig. 1, A and B, and fig. S1, A and B). The strong positive correlation between the frequencies of $Ki\text{-}67^+Bcl\text{-}2^{lo}$ and $CD38^+HLA\text{-}DR^+$ $CD8^+$ T cells indicated that both sets of markers define the same pool of $CD8^+$ T cells during AHI (fig. S1C). This marked expansion of activated $CD8^+$ T cells was driven by HIV antigen burden in AHI as it followed the increase in plasma viral load that peaked in AHI stage 3 (Fig. 1, C and D, and fig. S1D). To confirm that the activated $CD8^+$ T cells in AHI were directed against HIV antigens in our Thai cohort, we analyzed the HIV-specific $CD8^+$ T cell responses using HLA-A*1101 tetramers in HLA-A*11 participants for HIV and Epstein-Barr virus (EBV) antigens. $Tetramer^+$ HIV-specific $CD8^+$ T cells in different stages of AHI were virtually all $Ki\text{-}67^+Bcl\text{-}2^{lo}$ (Fig. 1, E and F) and $CD38^+HLA\text{-}DR^+$ (fig. S1, E and F). In some participants, HIV-specific $CD8^+$ T cells recognizing a single dominant NEF epitope were contributing up to 50% of the total $Ki\text{-}67^+Bcl\text{-}2^{lo}$ $CD8^+$ T cells (Fig. 1G). In contrast, a few EBV-specific $CD8^+$ T cells from the same participants with AHI were $Ki\text{-}67^+Bcl\text{-}2^{lo}$ or $CD38^+HLA\text{-}DR^+$ (Fig. 1, E and F, and fig. S1, E and F). These results are in accordance with the findings of a recent report in hyperacute HIV infection cohort in South Africa (*18*) and indicate that the activated $CD8^+$ T cells in AHI consist of HIV-specific $CD8^+$ T cells that expand after viremia from the earliest stage of AHI, although we cannot exclude that AHI stage 3 activated $CD8^+$ T cells might contain a small fraction of non–HIV-specific $CD8^+$ T cells (*44*). In addition to the $CD8^+$ T cells, activated $Ki\text{-}67^+Bcl\text{-}2^{lo}$ $CD4^+$ T cells were also increased in memory $CD4^+$ T cell compartment along with AHI progression (fig. S2, A and B). However, the magnitude of activated $CD4^+$ T cells was significantly lower compared to the activated $CD8^+$ T cells in each AHI stage ($P < 0.0001$ for all the AHI stages) (fig. S2C), and the frequencies of $Ki\text{-}67^+Bcl\text{-}2^{lo}$ $CD4^+$ T cells did not correlate with plasma viral load (fig. S2D). These data confirm that HIV-specific $CD8^+$ T cells are induced as early as AHI stage 1 and expand only in AHI stage 3.

Differentiated effector HIV-specific $CD8^+$ T cells during AHI contribute to viral load decrease after ART initiation

To analyze the effector function and in vivo killing capacity of these HIV-specific $CD8^+$ T cells in the different stages of AHI, we assessed the expression of the cytolytic molecule perforin and the key transcriptional factor driving $CD8^+$ T cell effector differentiation T-bet (*45*, *46*).

Table 1. Clinical characteristic of study participants.

	HIV^- ($n = 14$)	AHI 4G stage 1 ($n = 22$)	AHI 4G stage 2 ($n = 37$)	AHI 4G stage 3 ($n = 47$)
AHI 4G staging		NAT^+ $4G^-/3G^-$	NAT^+ $4G^+/3G^-$	NAT^+ $4G^+/3G^+$ WB^- or IND
Days since HIV exposure, median [interquartile range (IQR)]	NA	14 (9–19)	16 (13–20)	19 (13–23)
Age (years), mean (SD)	32.7 (6.9)	28.8 (8.3)	28.4 (7.3)	27.8 (6.7)
Male/female ratio	8/6	20/2	36/1	45/2
CD4 count cells/μl in plasma, median (IQR)	NA	526.5 (334.3–575.5)	304 (237.5–457)	386 (295–506)
CD8 count cells/μl in plasma, median (IQR)	NA	399.5 (262–482.3)	240 (196–391)	638 (425–1058)

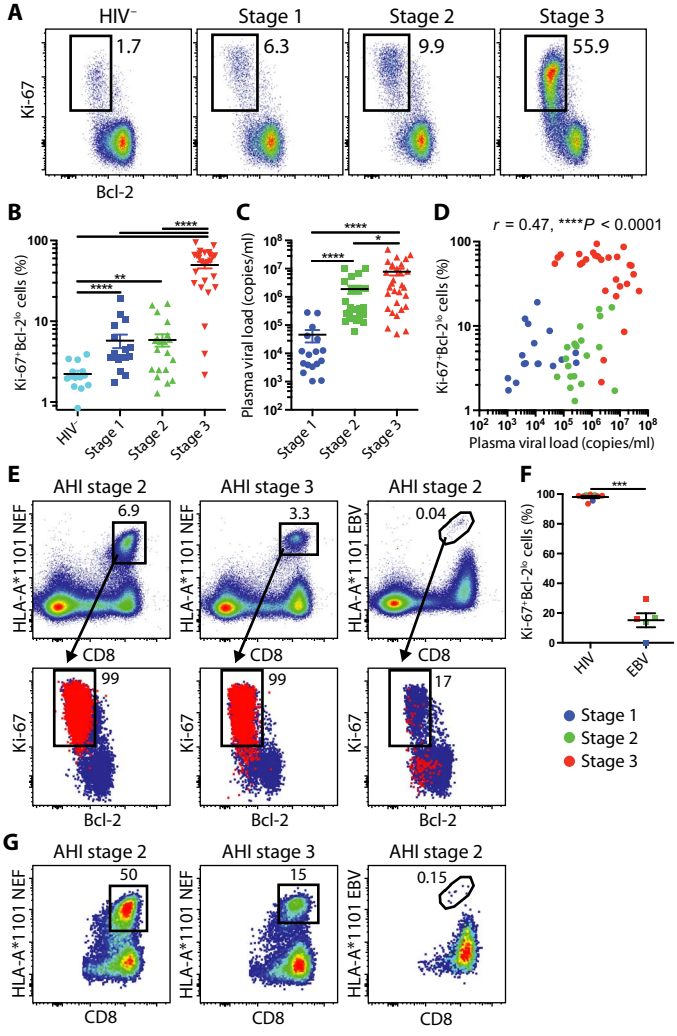

Fig. 1. HIV-specific CD8⁺ T cell expansion in acute HIV-1 infection. (**A**) Representative dot plot of Ki-67⁺Bcl-2ˡᵒ CD8⁺ T cells from AHI week 0. (**B**) Percentages of Ki-67⁺Bcl-2ˡᵒ cells in CD45RA⁻ CD8⁺ T cells from 14 HIV⁻ and 16 AHI 4G stage 1, 20 stage 2, and 27 stage 3 individuals. (**C**) Plasma viral load during the different stages of AHI week 0. (**D**) Correlation between plasma viral load and percentages of Ki-67⁺Bcl-2ˡᵒ CD8⁺ T cells. (**E**) HLA-A*1101 NEF or EBV tetramer⁺ CD8⁺ T cells in two acutely infected individuals gated on total live peripheral blood lymphocytes (PBLs) (top). Overlay of Ki-67⁺Bcl-2ˡᵒ expression on tetramer⁺ (red) and total CD45RA⁻ CD8⁺ T cells (blue) from the same participants (bottom). (**F**) Percentage of Ki-67⁺Bcl-2ˡᵒ in HIV or EBV tetramer⁺ cells from two AHI stage 1, three stage 2, and six stage 3 participants. (**G**) HLA-A*1101 NEF or EBV tetramer⁺ CD8⁺ T cells gated on Ki-67⁺Bcl-2ˡᵒ CD8⁺ T cells. Differences between groups were analyzed by Mann-Whitney tests. Associations between two variables (*P* and *r*) were analyzed by Spearman correlations. *$P < 0.05$; **$P < 0.01$; ****$P < 0.0001$.

When gating on Ki-67⁺Bcl-2ˡᵒ CD8⁺ T cells, activated CD8⁺ T cells expressed significantly higher levels of perforin and T-bet at peak viral load in AHI stage 3 compared to earlier AHI stages (Fig. 2A) ($P < 0.0001$ against stages 1 and 2). Granzyme B expression analyzed by mRNA gene expression was also significantly higher in activated CD8⁺ T cells at AHI stage 3 ($P = 0.0006$; Fig. 2B). Notably, perforin and T-bet expression were expressed at similar levels in Ki-67⁺Bcl-2ˡᵒ CD8⁺ T cells and in tetramer⁺ HIV-specific CD8⁺ T cells (fig. S3A). Because the magnitude of CD8⁺ T cell response in AHI did not correlate with viral load decline in previous studies on untreated individuals (*18*), we assessed whether these fully differentiated effector CD8⁺ T cells contribute to HIV viral load decrease after treatment initiation. To accomplish this, we analyzed the plasma viral load decrease from baseline to 2 weeks after ART initiation, where viremia was still detectable in almost all participants. Two weeks after starting ART, individuals treated in AHI stage 3 had a similar plasma HIV RNA level as participants treated in AHI stage 1 and a significantly lower plasma viremia than those treated in AHI stage 2 ($P = 0.0065$), even though they had started from a higher plasma viral load at baseline (Figs. 1C and 2C). AHI stage 3 individuals showed a significantly steeper fold decrease of plasma HIV RNA than the two other groups ($P = 0.01$ against both stages 1 and 2) (Fig. 2D and fig. S3B). The fold change in plasma viral load was strongly correlated with the percentage of Ki-67⁺Bcl-2ˡᵒ CD8⁺ T cells at baseline, as well as with the expression of perforin and T-bet in activated CD8⁺ T cells (Fig. 2, E and F). The percentage of Ki-67⁺Bcl-2ˡᵒ CD4⁺ T cells at baseline was also weakly correlated with the plasma viral load fold change ($r = 0.38$, $P = 0.002$) (fig. S3C). To assess whether the association between activated CD8⁺ T cells with plasma viral load decline after treatment was independent from activated CD4⁺ T cells, we performed a multivariate linear regression analysis. The association between plasma viral load fold change and percentage of Ki-67⁺ CD8⁺ T cells remained significant ($P < 0.001$; fig. S3C) in contrast to the percentage of Ki-67⁺CD4⁺ T cells in the multivariate model ($P = 0.67$; fig. S3C). These data indicate that HIV-specific CD8⁺ T cells before peak viremia in AHI stages 1 and 2 exhibit a delay in differentiation of effector functions, and HIV-specific CD8⁺ T cells in AHI stage 3 exhibit enhanced effector molecule expression and become fully differentiated effector CD8⁺ T cells. Furthermore, when ART is initiated, these effector CD8⁺ T cells contribute increasingly to plasma HIV viral load reduction concomitant with their level of differentiation.

Loss of cytokine secretion and survival potential of HIV-specific CD8⁺ T cells during AHI

Because HIV-specific CD8⁺ T cells in later stages of AHI after peak viremia exhibit a profound metabolic dysfunction and a lack of survival and memory potential (*17*), we analyzed whether the differentiation of effector CD8⁺ T cells was associated with a loss of survival in the earlier stages of AHI. Along with the acquisition of effector function, activated CD8⁺ T cells lose interleukin-7 (IL-7) receptor α chain (CD127) expression, from AHI stages 1 and 2 participants showing higher CD127 expression to AHI stage 3 exhibiting the lowest CD127 expression (Fig. 3A). Notably, CD127 expression was not significantly differentially expressed by tetramer⁺ HIV-specific CD8⁺ T cells and activated Ki-67⁺Bcl-2ˡᵒ CD8⁺ T cells ($P = 0.25$; fig. S3A). The mRNA expression of IL-7 receptor (IL-7R), its downstream transcription factor STAT5A (signal transducer and activator of transcription 5A), and two other transcription factors important for memory T cell development (FOXO1 and cell quiescence, FOXP1) were also significantly lower in activated CD8⁺ T cells from AHI stage 3 individuals compared to those in stages 1 and 2 ($P = 0.0022$, 0.0289, 0.0037, and 0.0401, respectively; Fig. 3B and fig. S4A). Activated CD8⁺ T cells also showed a reduced capacity to respond ex vivo to T cell receptor (TCR) engagement by the secretion of cytokines with significantly lower tumor necrosis factor–α (TNF-α) ($P = 0.0006$ against stage 1, $P = 0.0127$ against stage 2) and IL-2 ($P = 0.0083$ against stage 1, $P = 0.0002$ against stage 2) production in AHI stage 3 compared to AHI stages 1 and 2 (Fig. 3C and fig. S4B). Plasma viral load was negatively associated with the IL-2 production by activated CD8⁺ T cells and their polyfunctional ability (Fig. 3D and fig. S4C).

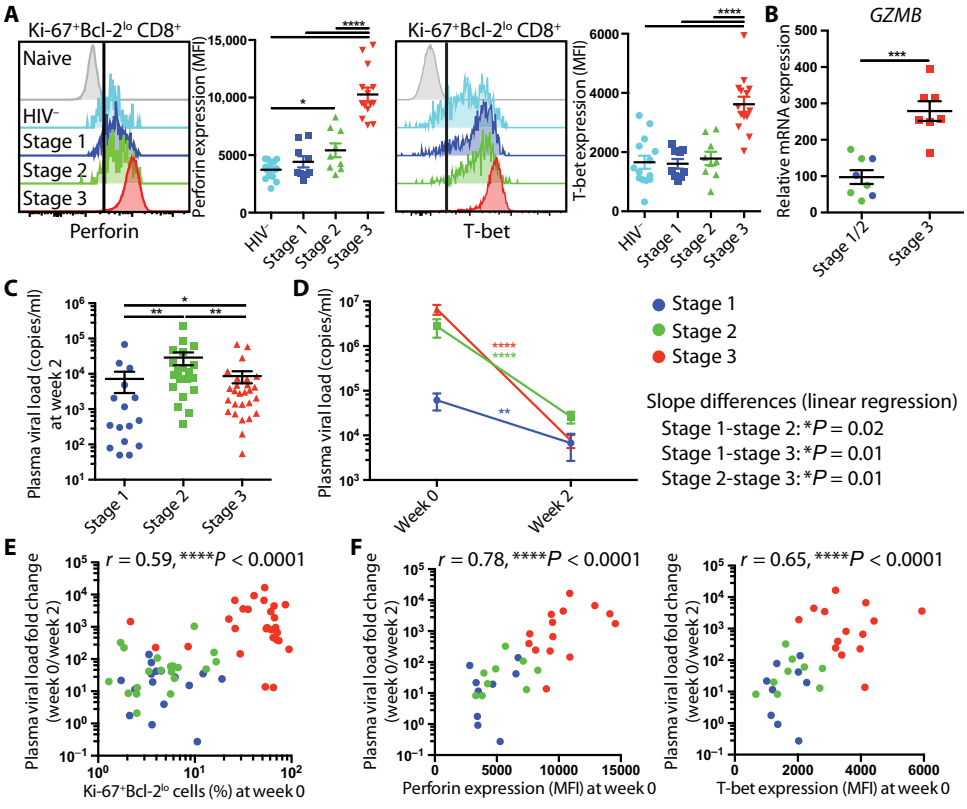

Fig. 2. Fully differentiated effector HIV-specific CD8$^+$ T cells in AHI contribute to viral load decrease after ART initiation. (**A**) Expression of perforin and T-bet in naïve CD8$^+$ T cells and Ki-67$^+$Bcl-2^{lo} CD45RA$^-$ CD8$^+$ T cells from 14 HIV$^-$ and 9 AHI stage 1, 9 stage 2, and 14 stage 3 individuals. (**B**) mRNA expression of granzyme B in CD38$^+$HLA-DR$^+$ CD8$^+$ T cells from AHI stages 1/2 and 3 individuals. (**C**) Plasma viral load at week 2 in individuals who initiated ART in AHI stages 1 to 3. (**D**) Plasma viral load decrease between week 0 and week 2 after ART initiation in AHI stages 1 to 3 individuals. Differences between week 0 and week 2 were analyzed by Wilcoxon test. Slope differences are based on linear regression among stages and shown as *P* values. (**E**) Correlation between percentage of Ki-67$^+$Bcl-2^{lo} cells in CD45RA$^-$ CD8$^+$ T cells at week 0 and plasma viral load fold change (week 0/week 2). (**F**) Correlation between expression of effector molecules perforin and T-bet in Ki-67$^+$Bcl-2^{lo} CD8$^+$ T cell at week 0 and plasma viral load fold change (week 0/week 2). Differences between groups were analyzed by Mann-Whitney tests. Associations between two variables (*P* and *r*) were analyzed by Spearman correlations. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ****$P < 0.0001$.

Coinciding with this loss of function and autocrine IL-2 production, activated CD8$^+$ T cells from AHI stage 3 participants showed a lower cell recovery after in vitro culture and a higher number of apoptotic cells as measured by annexin V$^+$ CD8$^+$ T cells compared to activated CD8$^+$ T cells from AHI stages 1 and 2 individuals (Fig. 3, E and F, and fig. S5A). The increased apoptosis was also associated with a higher plasma viral load (Fig. 3G). As we had previously shown that HIV-specific CD8$^+$ T cells up-regulated mitochondrial dysfunction and oxidative stress pathways inducing increased cell death in the later stage of AHI after peak viral load (*17*), we tested whether this metabolism defect due to hyperproliferation was already detected at the earlier stages of AHI. Activated CD8$^+$ T cells in AHI stage 3 participants exhibited elevated mitochondrial mass, mitochondrial membrane potential activity, and total reactive oxygen species (Ros) levels compared to activated CD8$^+$ T cells in the earlier stages of AHI (fig. S5, B to D). The percentage of apoptotic activated CD8$^+$ T cells correlated with mitochondria membrane potential activity and total Ros levels (Fig. 3H), suggesting that this enhanced cell death in vitro was driven by a hyperactive mitochondria metabolic state. These data indicate that the HIV-specific CD8$^+$ T cells at peak viremia are fully differentiated short-lived effector cells lacking memory potential, whereas at the earliest stages of AHI, although less prone to exert immediate effector functions, HIV-specific CD8$^+$ T cells exhibit a higher survival capacity and memory potential.

Differential fate of HIV-specific CD8$^+$ T cells 2 weeks after ART initiation in AHI

After vaccination with live attenuated viruses, antigen-specific CD8$^+$ T cell responses have been reported to increase for 1 to 2 weeks in peripheral blood as viral antigenemia decreases (*43*, *47*). After this expansion, the virus-specific CD8$^+$ T cell response contracts and generates memory cells that will persist long term. In untreated HIV infection, HIV-specific CD8$^+$ T cells also continue to increase for 1 to 2 weeks in peripheral blood after peak viremia (*5*, *18*). Because individuals in the RV254 cohort initiate ART immediately after being diagnosed as HIV$^+$ and are followed longitudinally, we had the opportunity to determine whether HIV-specific CD8$^+$ T cells would continue to proliferate during the first 2 weeks of viral load decline. As shown in Fig. 2C, plasma viral load decreased 2 weeks after ART initiation in all groups. We analyzed HIV-specific CD8$^+$ T cell responses by tetramer staining in HLA-A*11 participants and Ki-67 expression in all participants at baseline and 2 weeks after ART initiation. The percentage and absolute number of tetramer$^+$ HIV-specific CD8$^+$ T cells increased during this period in individuals in AHI stages 1 and 2, whereas tetramer$^+$ HIV-specific CD8$^+$ T cells from those in AHI stage 3 started contracting during this period (Fig. 4, A and B). In all AHI groups, tetramer$^+$ HIV-specific CD8$^+$ T cells started to lose their activated Ki-67$^+$Bcl-2^{lo} phenotype but still had significantly higher frequencies of Ki-67$^+$Bcl-2^{lo} CD8$^+$ T cells compared to EBV-specific CD8$^+$ T cells 2 weeks after ART initiation ($P < 0.0001$; Fig. 4C and fig. S6A). HIV-specific CD8$^+$ T cells from all groups exhibited a similar expression of perforin and CD127 at week 2 but a higher T-bet in those treated in AHI stages 1 and 2 compared to stage 3 (fig. S6B). Although the tetramer$^+$ cells showed decreased Ki-67 expression, overall activated CD8$^+$ T cells from participants treated in AHI stages 1 and 2 continued to proliferate with significantly higher Ki-67$^+$ CD8$^+$ T cells at week 2 compared to baseline ($P = 0.0210$ and 0.0094, respectively; Fig. 4D). In contrast, activated CD8$^+$ T cells from AHI stage 3 participants markedly declined between week 0 and week 2 after ART initiation. The proliferating effector CD8$^+$ T cells from participants treated in stages 1 and 2 did not produce perforin to levels similar to those measured in fully differentiated effector CD8$^+$ T cells from participants in AHI stage 3 at week 0 (Fig. 4E). Ki-67$^+$ CD8$^+$ T cells reached similar frequencies in all AHI stages 2 weeks after ART initiation (fig. S6C). In AHI stage 3 individuals, the frequency of Ki-67$^+$ CD8$^+$

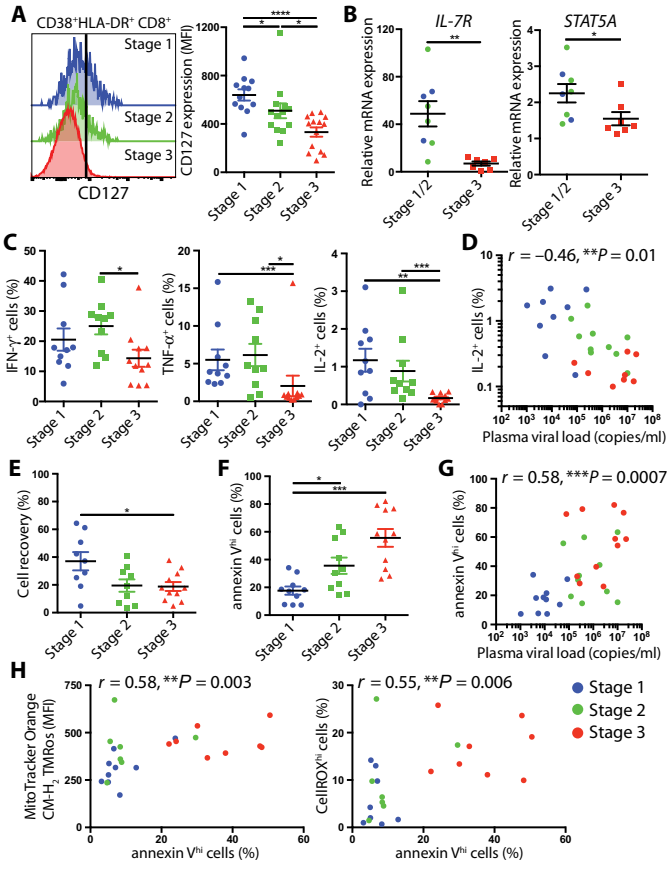

Fig. 3. Loss of cytokine secretion and survival potential of HIV-specific CD8$^+$ T cells during AHI. (**A**) Expression of CD127 on CD38$^+$HLA-DR$^+$CD45RA$^-$ CD8$^+$ T cells from 12 AHI stage 1, 13 stage 2, and 14 stage 3 individuals. (**B**) mRNA expression of IL-7R and STAT5A in CD38$^+$HLA-DR$^+$ cells. (**C**) Interferon-γ (IFN-γ), TNF-α, and IL-2 production by CD38$^+$HLA-DR$^+$ cells from 9 AHI stage 1, 10 stage 2, and 11 stage 3 individuals after anti-CD3 and CD28-antibody stimulation. (**D**) Correlation between plasma viral load and percentages of IL-2$^+$–secreting cells within CD38$^+$HLA-DR$^+$ cells. (**E**) Percentage of live nonapoptotic cell recovery of CD38$^+$HLA-DR$^+$ effector CD8$^+$ T cells from AHI stages 1 to 3 individuals based on their absolute cell numbers after 24 hours in vitro. (**F**) Percentages of apoptotic annexin V^{hi} cells in ex vivo CD38$^+$HLA-DR$^+$ cells. (**G**) Correlation between plasma viral load and percentages of annexin V^{high} cells in CD38$^+$HLA-DR$^+$ CD8$^+$ T cells. (**H**) Correlation between ex vivo apoptotic CD38$^+$HLA-DR$^+$ cell percentage and staining intensity of MitoTracker Orange CM-H$_2$TMRos (mitochondria membrane potential activity, left) or CellROX Deep Red (total Ros level, right) from eight AHI stage 1, eight stage 2, and eight stage 3 individuals. Differences between groups were analyzed by Mann-Whitney tests. Associations between two variables (*P* and *r*) were analyzed by Spearman correlations. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ****$P < 0.0001$.

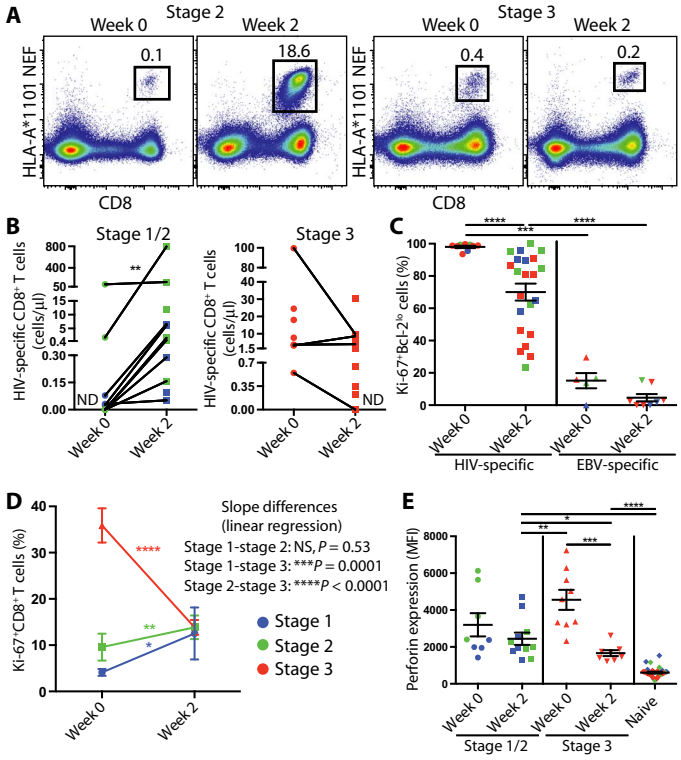

Fig. 4. Differential fate of HIV-specific CD8$^+$ T cell 2 weeks after ART initiation in AHI. (**A**) Tetramer$^+$ HLA-A*1101 Nef-specific CD8$^+$ T cells in total live PBLs at week 0 and 2 weeks after ART initiation. (**B**) Tetramer$^+$ HIV-specific CD8$^+$ T cell absolute number per microliter based on total CD8$^+$ T cell count for AHI stages 1 to 3 individuals. ND, not detected. (**C**) Percentage of Ki-67$^+$Bcl-2^{lo} cells in HIV-specific or EBV-specific tetramer$^+$ CD8$^+$ T cells from 7 AHI stage 1, 5 stage 2, and 11 stage 3 individuals at week 0 and week 2 on ART. (**D**) Percentage of Ki-67$^+$ cells in CD8$^+$ T cells from 14 stage 1, 20 stage 2, and 34 stage 3 individuals at week 0 and week 2. Differences between week 0 and week 2 were analyzed by Wilcoxon test. Slope differences are based on linear regression among stages and shown as *P* values. (**E**) Perforin expression in Ki-67$^+$ and naïve CD8$^+$ T cells at week 0 and week 2. Differences between groups were analyzed by Mann-Whitney tests. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; ****$P < 0.0001$.

T cells at week 2 was not associated with the percentage of proliferating Ki-67$^+$ CD8$^+$ T cells at week 0 (fig. S6D), suggesting that the decline of effector CD8$^+$ T cells did not uniformly occur in the effector T cell pool. The frequency of HIV-specific CD8$^+$ T cells still present 2 weeks after treatment initiation in participants treated in AHI stage 3 shows the ability to delay the decline of effector CD8$^+$ T cells during the contraction phase of the response. These data show that upon viral load decay after ART initiation, HIV-specific CD8$^+$ T cells continue to expand in individuals treated before peak viremia in AHI stages 1 and 2, whereas HIV-specific CD8$^+$ T cells start contracting in individuals treated at peak viremia.

HIV-specific CD8$^+$ T cells persisting 2 weeks after ART initiation contribute to limited seeding and persistence of the HIV reservoir in AHI stage 3 individuals

Because participants enrolling in the RV254 cohort initiate ART in the earliest stages of AHI and remain virally suppressed during the study, we had the opportunity to assess whether HIV-specific CD8$^+$ T cells affect the establishment of the persistent viral reservoir. We focused our analysis on the time point 2 weeks after ART initiation, where HIV-specific CD8$^+$ T cells are still present and new infections of target cells are limited by ART. In AHI stage 3 individuals, the frequency of Ki-67$^+$ CD8$^+$ T cells at week 2 no longer correlated with plasma viral load at week 2 as it did at baseline (Fig. 5A). The participants treated in AHI stage 1 harbored the lowest HIV DNA copy number compared to the other groups at week 2 (Fig. 5B). After 48 weeks on ART, the reservoir reached very low levels in this group (64% undetectable) (fig. S7A). In contrast, total HIV DNA was detectable and not significantly different between participants treated at AHI stage 2 and those treated at AHI stage 3 at week 2 ($P = 0.40$) or 48 of ART ($P = 0.53$) (Fig. 5B and fig. S7A). Both groups exhibited a wide range of HIV DNA content, with some individuals having a very small reservoir size undetectable

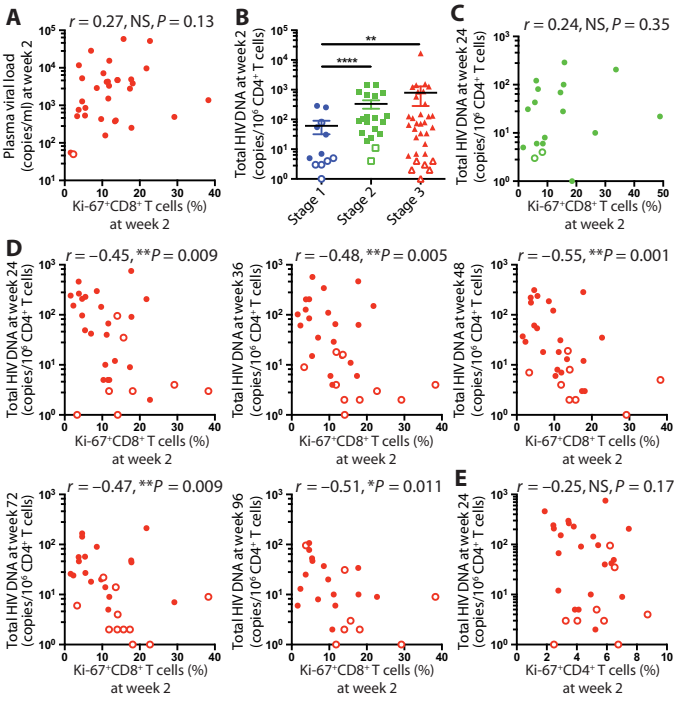

Fig. 5. HIV-specific CD8$^+$ T cells persisting 2 weeks after ART initiation contribute to limited seeding and persistence of the HIV reservoir. (**A**) Correlation between percentage of Ki-67$^+$ CD8$^+$ T cells from 34 stage 3 individuals and plasma viral load at week 2. Open circle represents the detection limit. NS, not significant. (**B**) Total HIV DNA copies per 10^6 CD4$^+$ T cells among AHI stages 1 to 3 individuals at week 2. For samples in which no positive cells were detected, the limit of detection based on cell input is plotted as an open symbol. (**C**) Correlation between percentage of Ki-67$^+$ cells in total CD8$^+$ T cells from 20 stage 2 individuals at week 2 and total HIV DNA copies per 10^6 CD4$^+$ T cells at week 24. (**D**) Correlation between percentage of Ki-67$^+$ CD8$^+$ T cells at week 2 and total HIV DNA copies per 10^6 CD4$^+$ T cells at weeks 24, 36, 48, 72, and 96 in AHI stage 3 individuals. (**E**) Correlation between percentage of Ki-67$^+$CD4$^+$ T cells at week 2 and total HIV DNA copies per 10^6 CD4$^+$ T cells at week 24. Differences between groups were analyzed by Mann-Whitney tests. Associations between two variables (*P* and *r*) were analyzed by Spearman correlations. **$P < 0.01$; ****$P < 0.0001$.

or less than 10 HIV DNA copies per 10^6 CD4$^+$ T cells. This allowed us to determine whether HIV-specific CD8$^+$ T cells during the contraction phase control the frequencies of HIV-infected CD4$^+$ T cells that harbor HIV DNA. AHI stage 2 individuals exhibited Ki-67$^+$ CD8$^+$ T cell frequencies similar to those in AHI stage 3 2 weeks after ART initiation, which did not correlate with HIV DNA copy number at weeks 24, 36, and 48 (Fig. 5C and fig. S7B). In comparison, in participants treated in AHI stage 3, the percentage of effector CD8$^+$ T cells persisting 2 weeks after ART initiation tended to correlate with HIV DNA copy number at week 2 (fig. S7C) and strongly negatively correlated with total HIV DNA copies in CD4$^+$ T cells at weeks 24, 36, 48, 72, and 96 as HIV reservoir stabilized over time (Fig. 5D). In contrast, the frequency of HIV-specific CD8$^+$ T cells before treatment did not correlate with the size of the HIV reservoir or with HIV DNA copy number at week 2 (fig. S7D). The percentage of Ki-67$^+$CD4$^+$ T cells 2 weeks after ART initiation did not correlate with the HIV reservoir over time (Fig. 5E and fig. S8), suggesting that the former correlation was not driven by sustained activated CD4$^+$ T cells. These results indicate that fully differentiated HIV-specific CD8$^+$ T cells still proliferating 2 weeks after ART initiation contribute to limit the seeding of the HIV reservoir.

DISCUSSION

We demonstrated that HIV-specific CD8$^+$ T cells exhibit a delay in expansion and differentiation before peak viremia in AHI stages 1 and 2 on the first 18 days of HIV infection. These cells, although generated as early as stage 1, are not expanding fast enough and are not acquiring effector functions to control HIV replication. These results echo the previously reported SIV-specific CD8$^+$ T cell responses characterized in the mucosa early after SIV challenge described as "too little, too late" to control viral replication in the early stages of infection (*48*, *49*). After this initial lag period, HIV-specific CD8$^+$ T cells expand massively and become fully differentiated in AHI stage 3 corresponding to peak viremia about 19 days after HIV infection, concomitant or just after the systemic proinflammatory cytokine burst (*50*). This full differentiation allows them to kill effectively HIV-producing cells when ART is initiated shortly after this expansion. However, when treatment is not initiated at that stage, these effector CD8$^+$ T cells reach a hyperproliferation state that could be described as "too strong for too long" and push them to terminally differentiated effector cells that can kill infected cells but setting the stage for antigenic-driven exhaustion seen in chronic HIV infection if treatment is not initiated. These observations were obtained on a homogeneous cohort of participants infected with the CRF01-AE virus and would need to be repeated in different individuals infected with another clade.

In our previous work, we reported a discordant cytokine production and cytolytic capacity of HIV-specific CD8$^+$ T cells in primary infection (*17*). HIV-specific CD8$^+$ T cells from subjects enrolled in early/acute infection after peak viremia had an impaired capacity to secrete cytokines in response to TCR restimulation, but displayed a higher cytolytic activity compared to HIV-specific CD8$^+$ T cells in chronic infection. We report here a similar impairment in the ability of HIV-specific CD8$^+$ T cells in AHI stage 3 to secrete cytokines upon TCR restimulation, and we can infer from the level of perforin expression in these cells that they still have intact cytolytic potential although we could not formally measure it. The best evidence for the in vivo killing activity of HIV-specific CD8$^+$ T cells is the strong association between the effector molecule expression of these cells and the reduction of plasma viral load after treatment initiation. Supporting that association, the elimination of infected cells producing viral particles is independent of the level of CD4$^+$ T cell activation. However, we cannot exclude that other mechanisms are contributing to the steeper viral load reduction when ART is initiated in AHI stage 3.

Two weeks after treatment initiation, we reported a distinct fate of HIV-specific CD8$^+$ T cells depending on the AHI stage when viral load was suppressed. HIV-specific CD8$^+$ T cells from donors in AHI stages 1 and 2 continue to expand by week 2 of ART, whereas HIV-specific CD8$^+$ T cells from donors in stage 3 contract. All of them reach similar expression levels of perforin and CD127 at week 2. However, HIV-specific CD8$^+$ T cells from donors in AHI stages 1 and 2 at week 2 did not expand to frequencies nor reached the levels of perforin expression observed in the stage 3 donors at week 0. This might explain the differential impact of these cells on the seeding of the viral reservoir between the groups. The increased frequencies of HIV-specific CD8$^+$ T cells 2 weeks after treatment could also be explained by the recirculation of these cells from tissues rather than expansion. Analyzing the immune responses induced in tissues over the course of AHI is of utmost importance to have a complete understanding of the dynamics between the virus and the host response and should be the subject of future studies. We observed a negative association between the proliferating CD8$^+$ T cells still proliferating 2 weeks after treatment initiation

in AHI stage 3 donors and the total HIV DNA measurement on ART. One reason why this association was stronger after long-term ART compared to earlier time points might be that the HIV reservoir takes time to stabilize after treatment initiation. Nevertheless, because we do not have any indication on the long-term impact of HIV-specific $CD8^+$ T cells on the HIV reservoir, our data are only suggesting that the fully differentiated effector $CD8^+$ T cells delayed in contraction after ART initiation are associated with a lower reservoir seeding.

Here, we measured total HIV DNA by ultrasensitive polymerase chain reaction (PCR), an assay that is known to overestimate the size of the replication-competent reservoir (*51*). Our choice was driven by the fact that the frequency of infected cells is extremely low in these individuals. Therefore, it is likely that any other assay using the relatively limited amount of blood available would have given negative results. Although we acknowledge the limitations of PCR-based assays, our method provides a sensitive estimate of the size of the reservoir in these participants treated very early in AHI and in whom the frequency of infected cells is too low to be measured by functional assays.

We demonstrated here that during a very short window of time, potent HIV-specific $CD8^+$ T cells were able to decrease the number of HIV-producing cells and even, more importantly, decrease the seeding of the persistent viral reservoir after ART initiation. These results provide the proof of concept that numerous and potent HIV-specific $CD8^+$ T cells able to delay their contraction in vivo can limit the seeding of the HIV reservoirs. Fully differentiated HIV-specific $CD8^+$ T cells are still present 2 weeks after ART initiation, but their numbers decline drastically, and interventions aiming at prolonging their survival in vivo might have a profound impact on the HIV reservoir size. The remaining challenge over the next few years will be to find ways to induce and maintain these potent HIV-specific $CD8^+$ effector T cells by immune interventions. Even in a group of individuals captured in a small window of time, we observed a high heterogeneity in both the viral reservoir size and the induced immune responses. This heterogeneity might lead to different outcomes in future interventions. In individuals treated as early as stage 1 of AHI, the seeded HIV reservoir is extremely low and HIV-specific $CD8^+$ T cell responses have been generated with promising ability to develop into memory $CD8^+$ T cells (*52*–*55*). However, upon ART treatment, it is likely that the recalled $CD8^+$ T cell response will show a similar delay in expansion and differentiation as in AHI, and it is unlikely that the presence of these memory cells will change the outcome of viral rebound if treatment is interrupted. Therefore, strategies aiming at boosting these memory $CD8^+$ T cell responses before analytical treatment interruption need to be developed to eliminate or at least control HIV reservoirs in the absence of ART (*28*, *56*).

MATERIALS AND METHODS

Study design

One hundred six HIV-infected individuals from the RV254/SEARCH010 study and 14 HIV^- healthy individuals from the Thai RV304/SEARCH013 study were included in this study. They all signed informed consent approved by the Chulalongkorn University and Walter Reed Army Institute of Research institutional review board. The RV254 cohort is a unique cohort of HIV-infected subjects recruited during the earliest phase of acute infection and who initiated ART immediately. This cohort provides the best setting to analyze the immune response induced during the earliest stage of AHI before immune damages caused by HIV. The longitudinal follow-up of subjects from AHI to the virally suppressed phase allowed us to identify immune correlates of limiting HIV reservoir seeding. For all the experiments, participant ID and AHI stages of specimens were randomized, and the samples were randomly numbered to perform the experiments. The AHI stages were recovered to perform statistical analyses. No outliers were excluded from the analyses. However, specimens from patients who did not start ART at week 0 visit were excluded from further analysis for later time points. To analyze HIV-specific HLA-A1101–restricted $CD8^+$ T cells, participants positive for HLA-A*1101 were selected (*57*). All primary data are in the Supplementary Materials (table S1).

Classification of AHI stages

In the RV254/SEARCH010 study, samples from HIV test clients in Bangkok, Thailand, were tested for 4G enzyme immunoassay (EIA) [p24, HIV immunoglobulin M (IgM) and IgG], HIV nucleic acid test (NAT), and third-generation (3G) EIA (HIV IgM and IgG). They were classified into 4G stage 1 (NAT^+/4G EIA^-/3G EIA^-), stage 2 (NAT^+/4G EIA^+/3G EIA^-), and stage 3 (NAT^+/4G EIA^+/3G EIA^+/Western blot–negative or indeterminate) as previously described (*41*). All individuals started ART treatment within 5 days after enrollment, and their week 0 (AHI before ART treatment) and week 2 (2 weeks after ART treatment initiation) samples were analyzed in this study.

Flow cytometry analysis

Thawed peripheral blood mononuclear cells (PBMCs) were first stained for cell surface markers, and then fixed/permeabilized for intracellular staining. Detailed methods and related reagents are found in Supplementary Materials and Methods.

Gene expression analysis

$CD38^+HLA\text{-}DR^+$ effector $CD8^+$ T cells were isolated from PBMCs and then subjected for reverse transcription–high-throughput quantitative PCR (qPCR) with a 96.96 BioMark Dynamic Array (Fluidigm) (*58*). Detailed methods and related reagents are found in Supplementary Materials and Methods.

Quantification of total HIV DNA

Purified $CD4^+$ T cells were digested, and the cell lysate was used to preamplify total HIV DNA and human CD3 gene as previously described (*59*). Real-time PCR was performed with the amplified samples, specific primer sets for total HIV DNA and human CD3 gene, and Rotor-Gene probe master mix (Qiagen) on a Rotor-Gene Q instrument (Qiagen) according to the manufacturer's instructions.

Statistical analysis

Statistical analyses were performed using the nonparametric Mann-Whitney test for group comparisons, and the Wilcoxon matched-pairs signed-rank test for the comparisons of HIV virus load and Ki-67^+ $CD8^+$ T cells from same patients between weeks. The nonparametric Spearman test was used for all the correlation analyses, and linear regression analysis was used to test whether the slopes of fold change of plasma viral load and percentage of Ki-67^+ $CD8^+$ T cells were significantly different. Here, $P < 0.05$ was considered significant.

SUPPLEMENTARY MATERIALS

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Materials and Methods

Fig. S1. HIV-specific $CD8^+$ T cell expansion in AHI.

Fig. S2. $CD4^+$ T cell activation in acute HIV-1 infection.

Fig. S3. Characteristics of effector $CD8^+$ T cells and plasma viral load during different stages of AHI.
Fig. S4. Loss of memory potential and polyfunctionality of HIV-specific $CD8^+$ T cell in AHI.
Fig. S5. Mitochondrial function of HIV-specific $CD8^+$ T cell during different stages of AHI.
Fig. S6. HIV-specific $CD8^+$ T cells 2 weeks after ART initiation during AHI.
Fig. S7. Association between HIV-specific $CD8^+$ T cells and HIV reservoir after ART initiation during AHI.
Fig. S8. Association between activated $CD4^+$ T cells and HIV reservoir after ART initiation during AHI.
Table S1. Primary data.

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Delayed differentiation of potent effector CD8$^+$ T cells reducing viremia and reservoir seeding in acute HIV infection

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Peak HIV viremia pushes CD8$^+$ T cells

Aside from CD4$^+$ T cell death, the immune system in chronically infected HIV patients is dysfunctional, including the inability of CD8$^+$ T cells to control the virus. Animal studies with simian immunodeficiency virus have suggested that early CD8$^+$ T cell responses may be capable of reducing viral burden, but getting access to patient samples at the earliest stage of infection is challenging. Takata *et al*. examined a large cohort of acutely infected patients that were given antiretroviral therapy (ART) upon enrollment in the study to evaluate T cell activation and HIV viral load over time, allowing them to parse out immune function (or dysfunction) based on acute stages of infection. They saw that CD8$^+$ T cell responses were a little slow to ramp up but that activated CD8$^+$ T cells present after initiation of ART could reduce the magnitude of the viral reservoir. These findings confirm that targeting CD8$^+$ T cells at the early stage of infection could lead to viral eradication.

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