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Extralymphoid CD8$^+$ T Cells Resident in Tissue from Simian Immunodeficiency Virus SIVmac239Δnef-Vaccinated Macaques Suppress SIVmac239 Replication *Ex Vivo*$^\nabla$

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Live-attenuated vaccination with simian immunodeficiency virus (SIV) SIVmac239Δnef is the most successful vaccine product tested to date in macaques. However, the mechanisms that explain the efficacy of this vaccine remain largely unknown. We utilized an *ex vivo* viral suppression assay to assess the quality of the immune response in SIVmac239Δnef-immunized animals. Using major histocompatibility complex-matched Mauritian cynomolgus macaques, we did not detect SIV-specific functional immune responses in the blood by gamma interferon (IFN-γ) enzyme-linked immunospot assay at select time points; however, we found that lung CD8$^+$ T cells, unlike blood CD8$^+$ T cells, effectively suppress virus replication by up to 80%. These results suggest that SIVmac239Δnef may be an effective vaccine because it elicits functional immunity at mucosal sites. Moreover, these results underscore the limitations of relying on immunological measurements from peripheral blood lymphocytes in studies of protective immunity to HIV/SIV.

Despite over 25 years of intensive research, efforts to develop a successful prophylactic HIV vaccine have failed (6, 39). The extraordinary difficulty of developing an HIV vaccine underscores the fact that the elements comprising an effective immune response directed against HIV are poorly understood. Simian immunodeficiency virus (SIV) infection of Mauritian cynomolgus macaques (MCM) provides the best model for unraveling the correlates of protection against SIV. With SIV infection of MCM, we can select the timing, route, dose, and sequence of the infecting virus. Additionally, the limited genetic diversity of MCM facilitates selection of genetically matched individuals that can be monitored throughout the acute phase of infection and enables more frequent and invasive sampling, especially of mucosal sites.

Macaques infected with live-attenuated SIV, like SIVmac239Δnef, exhibit robust protection from pathogenic SIV infection (8, 10, 20, 25, 29, 35, 40, 44, 49, 53). While previous studies have included considerable heterogeneity in the strain of attenuated SIV, challenge strain, and macaque species used, they demonstrate collectively the broad spectrum of attenuated SIVs that effectively protect macaques against pathogenic challenge. Several studies have also shown that attenuated SIV effectively protects cynomolgus macaques against pathogenic challenge using an SIVmac239C8 virus (1–3). Like SIVmac239Δnef, this virus has a deletion in the *nef* gene, but this deletion is a considerably smaller 12-bp deletion than the 182-bp deletion in SIVmac239Δnef (24). Importantly, there are no studies that establish the protective efficacy of SIVmac239Δnef in MCM. Nevertheless, peak SIVmac239Δnef viral loads in MCM parallel the range established in rhesus macaques, between 3.2×10^3 and 9.4×10^5 (35), but fall below peak loads established in a separate study (8). The differences observed between the rhesus macaque study and our own could be due to differences in challenge dose. Long-term control of SIVmac239Δnef in MCM is also similar to that in rhesus macaques (35). It is critical to understand why live-attenuated SIV vaccines are so effective, with the ultimate goal of using these principals to develop a vaccine that is safe for use in humans.

There are several plausible explanations for why live-attenuated SIV vaccines provide effective protection against challenge with pathogenic SIV. These explanations range from viral interference to a robust vaccine-elicited immune response (19, 43, 45, 47). We currently understand several aspects of live-attenuated vaccination with SIVmac239Δnef. First, there is an inverse relationship between the degree of attenuation and the level of protection (21). This relationship suggests that vigorous viral replication is important for the generation of an effective anti-SIV immune response. Second, the greater the sequence diversity between the vaccine strain and the challenge strain, the weaker is the protection provided by the vaccine (53). This demonstrates that an adaptive immune response that recognizes similar epitopes or virus features between the vaccine and challenge strains is necessary for protection in this model. Finally, vaccination with live-attenuated SIV requires a 15- to 20-week induction phase to achieve protection in the majority of animals (8). Thus, there is a direct

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relationship between the time postvaccination and the degree of protection between 0 and 20 weeks postvaccination. This temporal relationship suggests that a fully developed memory response is required to protect against pathogenic SIV challenge. Together, these observations argue that SIV-specific $CD8^+$ T-lymphocyte responses might be important in protection as these responses would be less useful in the setting of heterologous virus challenge and require both robust viral replication and time to develop. Such responses, however, can be weak to nonexistent in the blood of vaccinated animals and frequently do not correlate with disease progression, leading some investigators to question their importance in protective immunity (25, 29, 45, 46). We hypothesize that continued replication of live-attenuated SIV in the mucosal tissues may lead to effective, compartmentalized memory T-cell responses that are important in controlling pathogenic SIV challenge.

It is possible that prophylactic mucosal immunity is required to prevent viral replication soon after SIV infection and to minimize the destruction of mucosal immune cells that occurs within the first 3 weeks of SIV infection (9, 22, 26, 30). Initial depletion of effector memory $CD4^+$ T cells in the gut-associated lymphoid tissue (GALT) combined with continuous viral replication leads to prolonged immune activation, eventual depletion of central memory $CD4^+$ T cells, and the development of AIDS. An effective mucosal immune response elicited by live-attenuated SIV vaccination may prevent the initial $CD4^+$ T-cell depletion from the gut. Several recent studies confirm a critical protective role for $CD8^+$ T cells in the genital tract after vaccination with SHIV89.6, demonstrating that a mucosal immune response is capable of protecting against or ameliorating SIV infection (14–16, 48). Another study has also demonstrated the presence of high-frequency, polyfunctional T-cell responses in the mucosal tissues of elite controllers, i.e., individuals who maintain plasma viral loads below 75 copies/ml, compared to blood from the same individual, tissues of noncontrollers, and antiretroviral drug-treated patients. This study also provides a correlation between mucosal $CD8^+$ T-cell responses and HIV control (12).

While studying gut mucosal tissues is clearly an important part of understanding HIV/SIV pathology, there are several challenges to this undertaking. First, accessing gut tissues requires invasive sampling procedures, which are primarily limited to biopsy or time-of-death studies. Biopsies are often limited in number throughout the life span of an animal, while routine necropsy is cost-prohibitive for macaque studies. Second, these tissues are nonsterile. The digestive tract is teeming with floras that contaminate experiments requiring long-term cell culture. Finally, biopsies of mucosal tissues yield very few cells. These low cell numbers make *ex vivo* experiments very difficult or impossible to perform. Investigators have developed techniques to assess gut mucosal lymphocyte function by expanding these cells *in vitro* under sterile conditions with antibiotics and then using them in enzyme-linked immunospot assays (ELISPOT) or intracellular cytokine secretion (ICS) assays (18, 42). However, these experiments still suffer from two problems: (i) cells are altered *in vitro*, which may change their functional capacity; and, (ii) these experiments still rely on indirect measures of $CD8^+$ T-cell function. These difficulties have limited research on mucosal $CD8^+$ T-cell immunity during SIV infection.

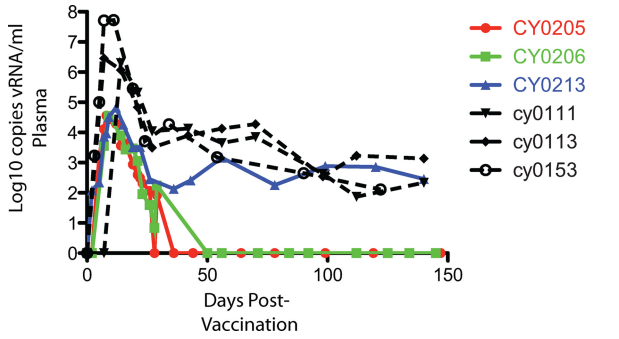

FIG. 1. Vaccination with SIVmac239Δnef. Animals were infected intravenously with 10 ng of p27 SIVmac239Δnef. Virus was measured in the plasma of vaccinated animals three times a week for the first 4 weeks and every 2 weeks thereafter until week 20. Vaccinated animals are in color and plotted against wild-type SIVmac239-infected animals represented by dashed black lines. All animals in the figure are MHC-I matched. Animal cy0153 was infected as part of an adoptive transfer experiment.

In light of these challenges, we decided to focus on the lung mucosal tissue, using $CD8^+$ T cells isolated from bronchoalveolar lavage fluid (BAL). BAL samples lung mucosa where there are a large number of resident lymphocytes that encounter respiratory pathogens. Furthermore, BAL provides a minimally invasive sampling of a mucosal tissue that can be performed frequently, and BAL harbors effector T cells similar to GALT (32). These factors make the lung an ideal site for sampling mucosal $CD8^+$ T cells.

We modified an *ex vivo* viral suppression assay that tests the ability of $CD8^+$ T cells to prevent viral replication in MCM (7, 27, 28, 36, 51, 54, 55). Using this approach, we compared the suppressive capacity of $CD8^+$ T cells isolated from lung and blood, and we found that $CD8^+$ T cells from the lung are more effective at suppressing viral replication than $CD8^+$ T cells from the blood. This assay does not manipulate lung lymphocytes *in vitro* and provides a direct measure of $CD8^+$ T-cell function. Furthermore, our data support the idea that $CD8^+$ T cells in blood and mucosal tissue are not functionally equivalent, that blood lymphocytes are not a perfect surrogate for mucosal lymphocytes, and that mucosal T cells attenuate SIV replication to a greater extent than blood T cells.

MATERIALS AND METHODS

Animal care and infections. Animals were cared for by the Wisconsin National Primate Research Center (WNPRC) according to protocols approved by the University of Wisconsin Research Animal Resources Center. All animals were infected with either molecularly cloned 50,000 50% tissue culture infective doses ($TCID_{50}$) of SIVmac239 Nef-open virus intrarectally (23) or 10 ng of p27 SIVmac239Δnef intravenously (10), kindly provided by Ronald Desrosiers. Several SIVmac239-infected animals were infected as part of adoptive transfer experiments.

Microsatellite analysis of MCM. Animals were haplotyped using our previously described panel of microsatellite markers spanning the major histocompatibility complex (MHC) region (52). These haplotypes were used to infer the MHC genotypes of the animals for purchasing MHC-matched animals.

Cell preparations. Blood was drawn from animals into EDTA tubes at the WNPRC and layered over Ficoll-Paque Plus (GE Healthcare Bioscience, Uppsala, Sweden); peripheral blood mononuclear cells (PBMC) were isolated by density centrifugation. BAL was collected by primate center staff. Briefly, saline solution was flushed into the bronchus and aspirated until fluid was no longer recovered. BAL was filtered over a 70-μm-pore-size cell strainer and then spun

TABLE 1. IFN-γ ELISPOT analysis of T-cell responses in the blood postvaccination[a]

Peptide[b]	T-cell response (no. of SFU/1 × 10^6 cells) in the indicated animal at:					
	3 wks postvaccination			8 wks postvaccination		
	CY0205	CY0206	CY0213[c]	CY0205	CY0206	CY0213
ConA	3,881	3,826	ND	4,080	9,991	1,094
Pol 241-291			ND		98.3	
Vif 41-91	83		ND			
Env 841-879	83.3		ND			
Env 321-371	153.3		ND			
Rev 40-90		118	ND			
Gag 361-411		208	ND			
Pol 641-691		199.2	ND			
Pol 681-727		104.2	ND		103.3	
Pol 757-807					98.3	

[a] Three animals were vaccinated with SIVmac239Δnef, and T-cell responses were measured using an IFN-γ ELISPOT assay and stimulation with peptides spanning the entire viral proteome. Positive responses are reported for pools of 10 overlapping 15-mer peptides. Concanavalin A (ConA) was used as a positive control.

[b] Residues are given for the indicated peptide. ConA, concanavalin A.

[c] Sufficient blood was not available from animal CY0213 to perform ELISPOT analysis 3 weeks after vaccination. ND, not done.

and resuspended in complete medium. Effector $CD8^+$ T cells were isolated using an anti-CD8ß-phycoerythrin (PE) monoclonal antibody (Beckman Coulter, Fullerton, CA) and anti-PE beads with LS columns (Miltenyi, Auburn, CA). Targets were prepared by depleting $CD8^+$ cells using the nonhuman primate CD8 cell-positive selection kit from Miltenyi.

CD8-depleted target cells were incubated in T-25 flasks at 37°C for 1 day at 1.5×10^6 cells/ml with concanavalin A at 5 μg/ml. Cells were washed after 24 h and placed in a new flask in the same volume. After 4 days, cells were washed and plated at roughly 2×10^6/ml in 48-well plates.

Virus was prepared by layering 1 ml of 9×10^9 $TCID_{50}$ of SIVmac239 over 100 μl of 20% sucrose and spinning at 14,000 rpm for 60 min. The supernatant was removed, and virus was resuspended in complete medium. Twenty-five μl of magnetic beads was added to the resuspended virus, and 30 μl of the virus-bead mix was added to each well of CD8-depleted cells. Plates were placed in the incubator for 20 min on a magnet to ensure sufficient infection of cells.

$CD8^+$ T-cell viral suppression assay (VSA). Infected targets were plated in 96-well plates at 25,000 cells/well. Effectors were plated according to the appropriate effector/target (E/T) ratio. After 4 days in culture, cells were initially surface stained with anti-CD8-Pacific Blue, anti-CD4-allophycocyanin (APC), and anti-CD3-Alexa Fluor 700 (BD Biosciences, San Jose, CA) and then stained for intracellular Gag-p27. Anti-Gag p27 antibody 55-2F12 (NIH AIDS Research and Reference Reagent Program) conjugated to fluorescein isothiocyanate (FITC) was combined with bulk permeabilization reagent (Invitrogen, Carlsbad, CA), and cells were incubated at room temperature for 15 min before being washed and fixed with 2.0% paraformaldehyde. Plates were then run on an LSRII flow cytometer (BD) using a high-throughput system and analyzed with FlowJo software, version 8.8.6 (TreeStar, Ashland, OR). All values were normalized by dividing the average percentage of p27-positive ($p27^+$) cells in each well by the average percentage of $p27^+$ cells in the control wells with no effectors.

Assays performed using vaccinated animals utilized different but MHC-matched animals for effectors and targets. In assays testing effector cells from SIVmac239-infected animals, all VSAs used an autologous system. Six of the naïve animal assays were performed in an allogeneic MHC-matched system, and three were autologous.

Tetramer analysis. Peptide-major histocompatibility complex class I tetramer analysis was performed as previously described (4). Briefly, either freshly isolated PBMC and BAL or thawed PBMC were stained with $Gag_{386-394}$-GW9/*Mafa*-A1*063, QP8/*Mafa*-A4*0101, and HL9/*Mafa*-B*5101 conjugated to either PE or APC. Cells were incubated at 37°C in complete medium for 1 h and then surface stained with anti-CD4-peridinin chlorophyll protein (PerCP), anti-CD8-Pacific Blue, and anti-CD3 Alexa Fluor 700. Cells were subsequently washed twice and fixed for analysis by flow cytometry using an LSRII instrument (BD). We tested each vaccinated animal at two separate time points in the PBMC and two vaccinated animals at a single time point in the BAL.

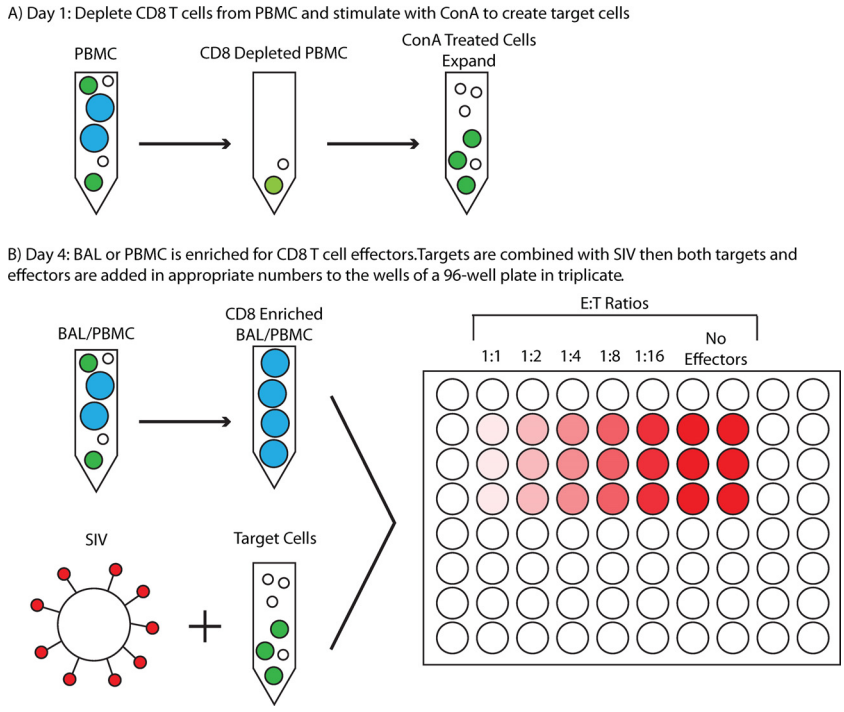

FIG. 2. Viral suppression assay schematic. (A) Lymphocytes were separated from the blood using Ficoll density centrifugation, and $CD8^+$ T cells were magnetically separated from the lymphocyte preparation. The CD8-depleted cells were then activated with concanavalin A to create targets. (B) The target cells were combined with SIVmac239 using a previously described magnetofection system. Effector cells were obtained by magnetically enriching for $CD8ß^+$ cells. The targets and effectors were then combined in a 96-well plate, which was stained after 4 days for Gag-p27 and other surface markers.

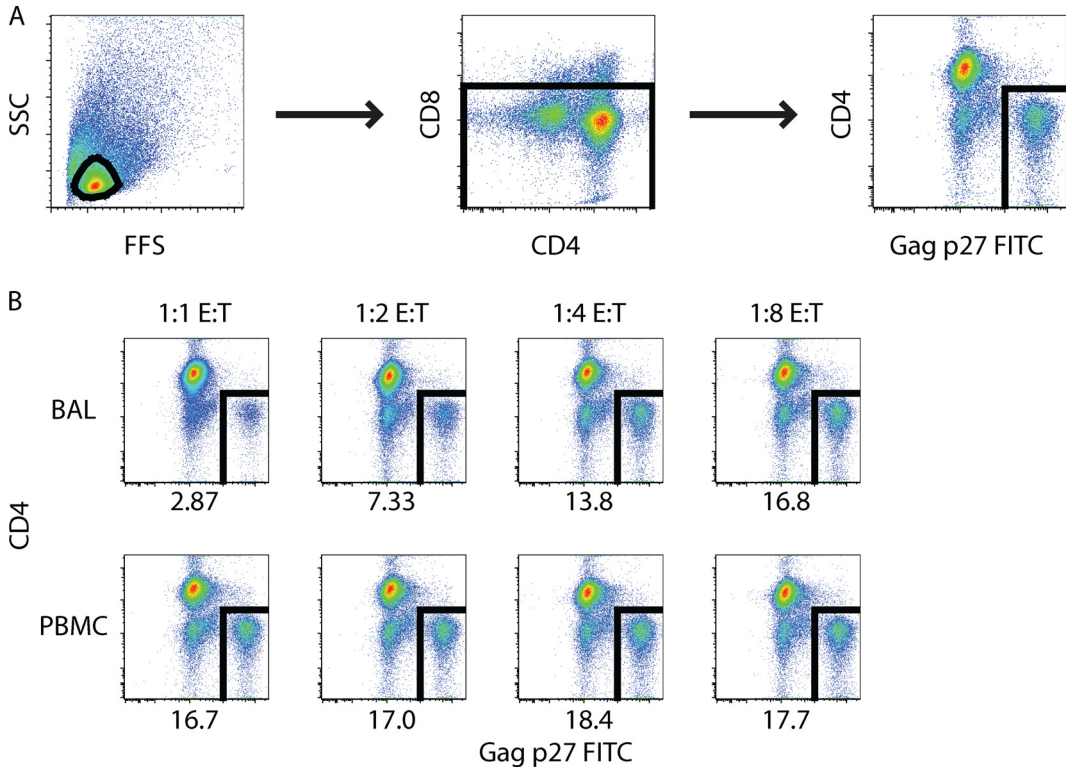

FIG. 3. $CD8^+$ T cells from BAL suppress viral replication at several E/T ratios. (A) The gating strategy used throughout the analysis to determine the number of $p27^+$ target cells is shown. Cells were first gated for lymphocytes based on their light scatter properties; then $CD8^-$ cells were selected. The $p27^+$ cells were then quantified as a percentage of the target cells. FFS, forward scatter; SSC, side scatter. (B) Data from a representative assay are shown. The percentages of $p27^+$ cells gated as drawn on the right of each dot plot are shown at each E/T ratio.

IFN-γ ELISPOT assays. PBMC were isolated by Ficoll-Hypaque gradient centrifugation. A total of 1×10^5 cells were incubated in duplicate overnight with pools of overlapping 15-mer peptides spanning the entire SIV proteome in gamma interferon (IFN-γ) ELISPOT plates (Mabtech, Columbus, OH). Medium alone was used as a negative control; concanavalin A was used as a positive control. Plates were developed according to the manufacturer's instructions. Spots were imaged and counted objectively with an ELISPOT reader (AID, Strasberg, Germany). The mean number of spot-forming units (SFU) in background wells (medium alone) was subtracted from the mean of the experimental wells. Responses were considered positive if the mean of the sample and background wells differed by more than two standard deviations.

Plasma virus analysis. Plasma virus concentration was determined using previously described methods (52). Briefly, viral RNA was reverse transcribed and then quantified using a SuperScript III Platinum One-Step Quantitative RT-PCR System (Invitrogen, Carlsbad, CA) on a LightCycler 2.0 (Roche, Indianapolis, IN). The final reaction mixtures (20 μl) contained 0.2 mM deoxynucleoside triphosphates, 3 mM $MgSO_4$, 0.015% bovine serum albumin, 150 ng of random hexamers (Promega, Madison, WI), 0.8 μl of SuperScript III reverse transcriptase and Platinum *Taq* DNA polymerase in a single enzyme mix, 600 nM amplification primers (5′-GTCTGCGTCATCTGGTGCATTC-3′ and 5′-CACTAG CTGTCTCTGCACTATGTGTTTTG-3′), and 100 nM probe (5′-6FAM-CTTCCTCAGTGTGTTTCACTTTCTCTTCTGCG-BHQ1-3′, where 6FAM is 6-carboxyfluorescein and BHQ1 is Black Hole Quencher 1). The reverse transcriptase reaction was performed at 37°C for 15 min and then at 50°C for 30 min. An activation temperature of 95°C for 2 min was followed by 50 amplification cycles of 95°C for 2 min and 62°C for 1 min, with ramp times set to 3° per s. Serial dilutions of an SIV Gag *in vitro* transcript were used to generate a standard curve for each run. Copy numbers were determined by interpolation onto the standard curve with the LightCycler software, version 4.0.

Statistics. Parametric *t* tests were performed using GraphPad Prism, version 5.0a for Macintosh (GraphPad Software, San Diego, CA [www.graphpad.com]). Paired *t* tests were used for analyses comparing measurements within animals, and unpaired *t* tests were used for comparisons of measurements between different animals. Error bars on graphs represent the standard error of the mean.

RESULTS

Live-attenuated vaccination does not induce high-frequency functional T-cell responses in the blood. We vaccinated three MHC-matched Mauritian cynomolgus macaques with SIVmac239Δnef. Plasma viral loads of SIVmac239Δnef peaked between 1×10^4 and 1×10^5 copies of viral RNA (vRNA)/ml of plasma and were controlled to undetectable levels within 4 to 8 weeks in two of three animals (Fig. 1). Animal CY0213 had a higher acute-phase viral load that remained detectable until 20 weeks postvaccination. In Fig. 1, the dashed lines in black represent animals infected with wild-type SIVmac239. All animals in the figure are MHC class I (MHC-I) matched, demonstrating that SIVmac230Δnef infection is acutely attenuated in the MCM.

To explore the mechanisms responsible for controlling SIVmac239Δnef replication, we performed a full SIV proteome IFN-γ ELISPOT assay using peptide pools of 15-mers overlapping by 11 amino acids. However, high-frequency SIV-specific T-cell responses were not detected in the blood (Table 1). Animals mounted three to four responses by 3 weeks postvaccination. Only one animal, CY0206, mounted a response against a single pool that was detected at both 3 and 8 weeks postvaccination. Although the three macaques were MHC matched, we did not detect responses against the same peptide pools by IFN-γ ELISPOT assay. The low reproducibility and lack of high-frequency immune responses in the blood of our vaccinated animals are consistent with recently published data using rhesus macaques in which often transient T-cell re-

sponses were of similarly low frequency in the vaccine phase 1 month prior to challenge (35) and also concur with a second study using a different attenuated SIV in the rhesus macaque model (29). The low-level replication of SIVmac239Δnef may ultimately preclude the generation of high-frequency peripheral immune responses. It is also possible that transient responses were mounted between the time points studied but were not detected due to our sampling interval. In this light, we next explored whether we could detect functional lymphocytes at other anatomic sites using avant-garde techniques.

Development and application of a novel viral suppression assay. To compare $CD8^+$ T-cell responses in blood and an easily accessible mucosal tissue, we elected to sample $CD8^+$ T cells from the lung. Resident lung lymphocytes were obtained using BAL by flushing the lungs with saline. We repeatedly recovered approximately 10-fold fewer lymphocytes from BAL than from blood during our lymphocyte isolations. The low cell recovery in BAL precludes widespread peptide-specific evaluations of $CD8^+$ T-cell activity and is minimally sufficient for very focused ELISPOT, intracellular cytokine secretion, or tetramer analyses, which typically use 100,000 to 500,000 cells per test. Therefore, we examined the functional capacity of $CD8^+$ lymphocytes isolated from these tissues. Specifically, we modified an *ex vivo* viral suppression assay that requires only 150,000 $CD8^+$ effector cells (Fig. 2).

The gating strategy used to identify SIV-infected cells on the basis of intracellular Gag p27 levels is shown in Fig. 3A. We first gated lymphocytes based on forward and side scatter characteristics and then selected CD8-depleted cells to assess the percentage of targets that were $p27^+$. We tested four to six E/T ratios for the ability of $CD8^+$ T cells from both PBMC and BAL to suppress viral replication (Fig. 3B). The representative data shown in Fig. 3B display an example of the inverse relationship between the number of $CD8^+$ effector cells in BAL and the percentage of $p27^+$ cells.

$CD8^+$ T cells from lung suppress viral replication rapidly after live-attenuated vaccination. BAL $CD8^+$ T cells in the SIVmac239Δnef-vaccinated macaques rapidly suppressed viral replication (Fig. 4) in contrast to $CD8^+$ T cells from PBMC. We observed suppression by 8 days postvaccination in animal CY0206 (Fig. 4A), at 3 weeks postvaccination in animal CY0205 (Fig. 4B), and at 3 weeks postvaccination in animal CY0213 (Fig. 4C). BAL $CD8^+$ T cells suppressed viral replication by up to 80% compared to only 0 to 10% for the corresponding cells in PBMC. The response in the BAL and PBMC of animal CY0205, the only animal that was sampled weekly, remained consistent at time points after 4 weeks postvaccination (Fig. 5).

At the 1:1 and 1:2 E/T ratios, we found that PBMC $CD8^+$ T cells did not suppress viral replication either before or after vaccination (Fig. 6). In stark contrast, BAL $CD8^+$ T cells suppressed viral replication postvaccination at both the 1:1 E/T ($P = 0.0071$) and 1:2 E/T ($P = 0.0047$) ratios at the time of greatest suppression. Furthermore, BAL $CD8^+$ T cells postvaccination suppressed viral replication to a greater extent than BAL $CD8^+$ T cells prevaccination at both the 1:1 E/T ($P = 0.016$) and 1:2 E/T ($P = 0.028$) ratios. Baseline VSAs were performed prevaccination because target and effector cells were from different, albeit MHC-matched, animals. We did not observe any background viral suppression due to potential

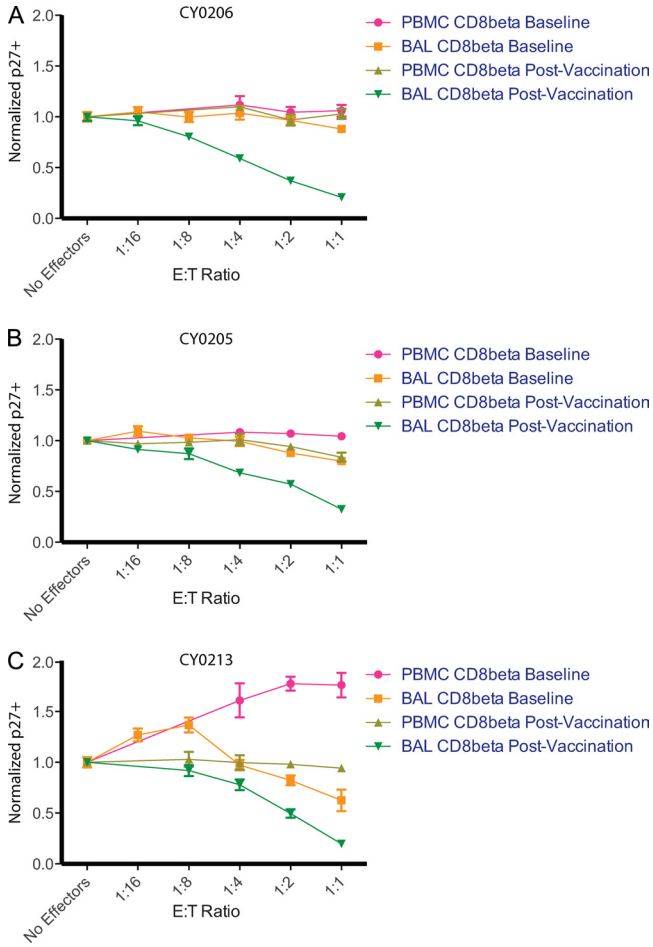

FIG. 4. $CD8^+$ T cells from SIVmac239Δnef-vaccinated animals suppress viral replication early after infection. $CD8^+$ T cells isolated from BAL and PBMC in SIVmac239Δnef-vaccinated macaques were compared in viral suppression assays both before and after vaccination. All values were normalized by dividing the average percentage of $p27^+$ cells in each well by the percentage of $p27^+$ cells in the control wells with no effectors. (A) Eight days postvaccination in animal CY0206. (B) Three weeks postvaccination in animal CY0205. (C) Three weeks postvaccination in animal CY0213.

differences in minor antigens although we noted that PBMC effector cells in animal CY0213 appeared to stimulate infection in the baseline assay (Fig. 4). PBMC in this animal did suppress viral replication compared to baseline levels but did not suppress viral replication compared to control wells within the same assay. These results suggest that SIVmac239Δnef may be generating a localized immune response at a mucosal site. Importantly, these results demonstrate that immune responses that are absent or undetectable in blood may be detectable in other tissues.

Differences in the antiviral efficacy of mucosal and blood $CD8^+$ T cells from SIVmac239-infected cynomolgus macaques. We looked retrospectively at viral suppression in wild-type SIVmac239-infected MCM. These macaques represented a heterogenous population of MCM with various immunogenic backgrounds, plasma viral loads, and durations of infection. We observed minimal to modest suppression of viral replication by PBMC and BAL $CD8^+$ T cells from uninfected animals. However, in SIV-infected animals, BAL $CD8^+$ T cells

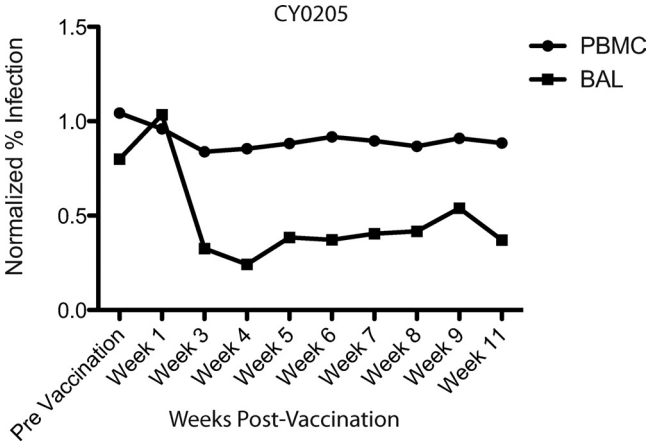

FIG. 5. Consistent suppression of viral replication by BAL-derived $CD8^+$ T cells. Viral suppression by $CD8^+$ T cells from BAL and PBMC was measured weekly for animal CY0205. The graph shows measurements of $p27^+$ cells at the 1:1 E/T ratio; all values were normalized by dividing the average percentage of $p27^+$ cells in the experimental wells by the percentage of $p27^+$ cells in the control wells with no effectors.

suppressed viral replication far more efficiently than PMBC $CD8^+$ T cells (Fig. 7). Moreover, we found that this difference was preserved in E/T ratios as low as 1:4, below which very few effector cells are present (data now shown).

At the 1:1 and 1:2 E/T ratios, BAL $CD8^+$ T cells from SIV-infected animals exhibited the most potent suppression of viral replication (Fig. 7A and B). BAL $CD8^+$ T cells from infected animals suppressed viral replication significantly better than BAL $CD8^+$ T cells from uninfected animals at both E/T ratios ($P < 0.0001$); they also exhibited more potent suppression than PBMC $CD8^+$ T cells from infected animals at both E/T ratios ($P = 0.002$). Of note, BAL $CD8^+$ T cells from uninfected animals also had a weak tendency to suppress viral replication compared to the corresponding PBMC $CD8^+$ T cells at both the 1:1 E/T ($P = 0.005$) and 1:2 E/T ($P = 0.025$) ratios. This weak suppression could result from the naturally activated phenotype of $CD8^+$ T cells isolated from extralymphoid tissues, where effector memory cells predominate. These cells are likely already primed against other pathogens and may be responding and secreting cytokines in response to other antigens present in the lung, thereby leading to non-SIV-specific suppression. Finally, PBMC $CD8^+$ T cells from infected animals suppressed more effectively than PBMC $CD8^+$ T cells from uninfected animals at both the 1:1 E/T ratio ($P = 0.0003$) and 1:2 E/T ratio ($P = 0.004$); this suggests that SIV-suppressive $CD8^+$ T cells are systemic after wild-type SIVmac239 infection. The animals were sampled at different time points postchallenge, thereby making it difficult to assess the relationship between viral suppression and viral loads. However, based on viral loads taken at the time of the viral suppression assay, there did not appear to be any correlation between viral load and viral suppression in PBMC or BAL (data not shown).

Phenotype and specificity of $CD8^+$ T cells from PBMC and BAL. At the completion of the 4-day assay, there were generally fewer $CD8^+$ T cells in wells with BAL effectors than in wells with PBMC effectors (Fig. 7C). These differences may be due to the activated phenotype of $CD8^+$ T cells isolated from mucosal tissues, which typically harbor short-lived effector T cells that may not survive for long periods in culture. We assessed the percentage of $CD8^+$ T effector memory cells in both the BAL and PBMC at the time point of greatest suppression in each vaccinated animal. Very few central memory T cells, defined on the basis of CD28 expression within the $CD3^+$ $CD8^+$ $CD95^+$ T-cell population, were present in the lung. However, it is unclear whether this would explain the observed differences in suppression (Fig. 8). It may be that the lung lymphocytes are less robust and that the process of isolation and enrichment leads to increased cell death. Also, the *in vitro* tissue culture microenvironment might be sufficiently different from that in the lung to compromise the expansion of BAL $CD8^+$ T cells in comparison to $CD8^+$ T cells derived from PBMC. Furthermore, PBMC $CD8^+$ T cells could expand more vigorously *in vitro* due to the greater central memory component, which is associated with an increased proliferative capacity. Overall, however, these differences emphasize the ability of lung $CD8^+$ T cells to suppress viral replication. Thus, despite the lower numbers of $CD8^+$ T cells present in the BAL wells, these cells still exhibited a very strong antiviral effect.

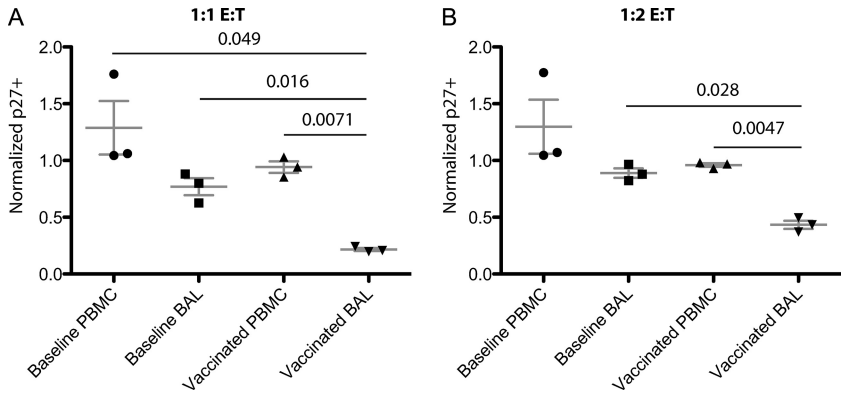

FIG. 6. $CD8^+$ T cells isolated from the lung suppress viral replication postvaccination. Measurements represent the time of greatest suppression from the three vaccinated animals postvaccination. These postvaccination time points were 8 days for CY0206, 4 weeks for CY0205, and 3 weeks for CY0213. Significant *P* values are indicated above the horizontal lines. E/T ratios are shown above the panels. All values were normalized by dividing the average percentage of $p27^+$ cells in experimental wells by the percentage of $p27^+$ cells in the control wells with no effectors.

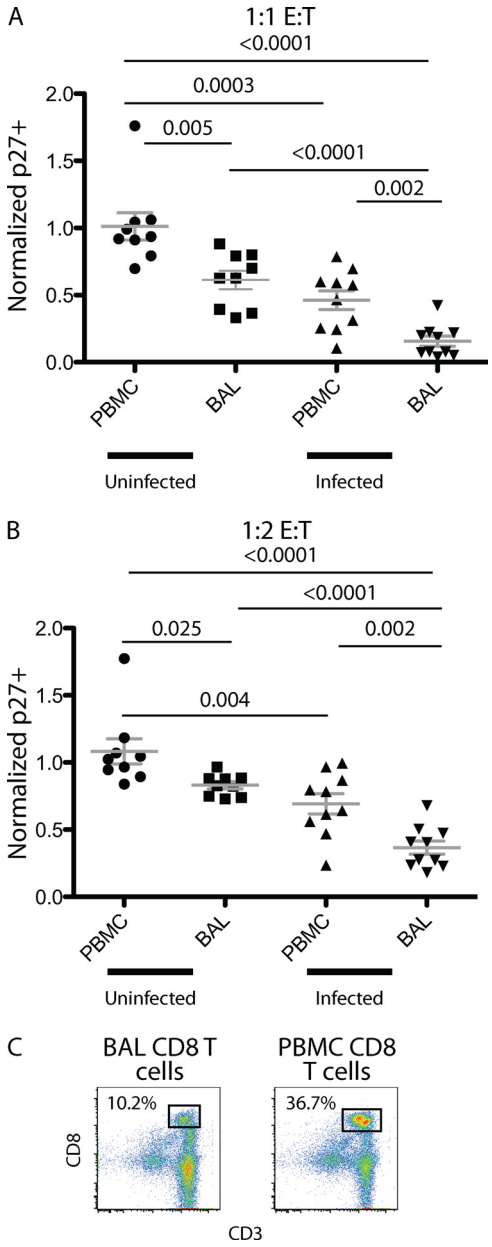

FIG. 7. $CD8^+$ T cells from BAL suppress viral replication to a greater extent than $CD8^+$ T cells from PBMC. (A and B) Several infected and uninfected animals were used to assess viral suppression at different E/T ratios, as indicated above the panels. Significant *P* values are indicated above the horizontal lines. All values were normalized by dividing the average percentage of $p27^+$ cells in experimental wells by the percentage of $p27^+$ cells in the control wells with no effectors. (C) The percentage of lymphocytes that were $CD8^+$ T cells was measured in the wells at the end of the assay. Higher frequencies of $CD8^+$ T cells were present in PBMC samples at the end of the assay.

Finally, we performed tetramer analysis of PBMC and BAL samples from vaccinated animals to assess the physical frequency of SIV-specific responses in both tissues. We tested acute and early chronic-phase PBMC samples with three tetramers (data not shown). Extremely modest cognate $CD8^+$ T-cell populations were observed with nearly background levels, as expected in a control, uninfected animal. A single high-frequency response, specific for the $Gag_{386–394}$-GW9/*Mafa*-A1*063 epitope, was detected in animal CY0213 (Fig. 9). Notably, the frequency of $CD8^+$ T cells detected with the $Gag_{386–394}$-GW9/*Mafa*-A1*063 tetramer in BAL was almost 6.5-fold higher than in PBMC at the same time point (Fig. 9). Thus, despite the modest responses, these results indicate that the increased suppression by BAL $CD8^+$ T cells may be due to a higher frequency of SIV-specific T cells in the mucosal tissues after SIVmac239Δnef vaccination.

DISCUSSION

An understanding of the correlates of protection in HIV/SIV infection remains elusive. By comprehending the elements of an effective immune response against the virus, it may be possible to develop technologies that engender these same responses in vaccinated individuals. Here, we modified an *ex vivo* viral suppression assay that directly tests the ability of $CD8^+$ T cells to suppress SIV replication. These assays are similar to those described previously (7, 27, 28, 54, 55) and to assays reported recently for the investigation of Gag-specific $CD8^+$ T cells in HIV controllers (37). However, in this study, we tested the ability of $CD8^+$ T cells derived from both blood and lung to suppress viral replication.

We found that cells isolated from the blood of macaques vaccinated with live-attenuated SIV were not effective at suppressing viral replication. While other investigators have reported vigorous $CD8^+$ T-cell responses in the blood of SIVmac239Δnef-vaccinated macaques, recent studies have demonstrated that indirect measurements of $CD8^+$ T-cell function may not represent whether a cell is truly functional (7, 51). The weak responses we detected by IFN-γ ELISPOT assays in the blood correlate well with the lack of viral suppression that we observed. Furthermore, we also measured very low frequencies of SIV-specific responses in the blood by tetramer analysis. Additional studies have also reported the use of viral suppression assays to demonstrate the importance of $CD8^+$ T-cell function after vaccination with SIVmac239Δnef, SIVmac239Δ3, and simian-human immunodeficiency virus (SHIV) in rhesus macaques (13, 50) and SIVmac251 challenge in cynomolgus macaques (11). In contrast to our experiments, these assays reported viral suppression after vaccination by PBMC $CD8^+$ T cells. These differences could potentially be explained by the use of higher E/T ratios, different readouts between assays, differences in the duration of the assay, and, most importantly, the presence of $CD8^+$ natural killer cells. Ultimately, using a combination of approaches, we measured very few high-frequency $CD8^+$ T-cell responses in the blood of vaccinated macaques and were unable to measure viral suppression by these cells.

We found that $CD8^+$ T cells isolated from the lung of vaccinated macaques were extremely effective at suppressing viral replication by 8 to 28 days postvaccination. This BAL $CD8^+$ T cell-mediated suppression was maintained at nearly all time points tested postvaccination; in parallel, we were never able to detect strong suppression by PBMC $CD8^+$ T cells from the same animals. In contrast to our vaccine results, we found that $CD8^+$ T cells isolated from animals that were infected with SIVmac239 could suppress viral

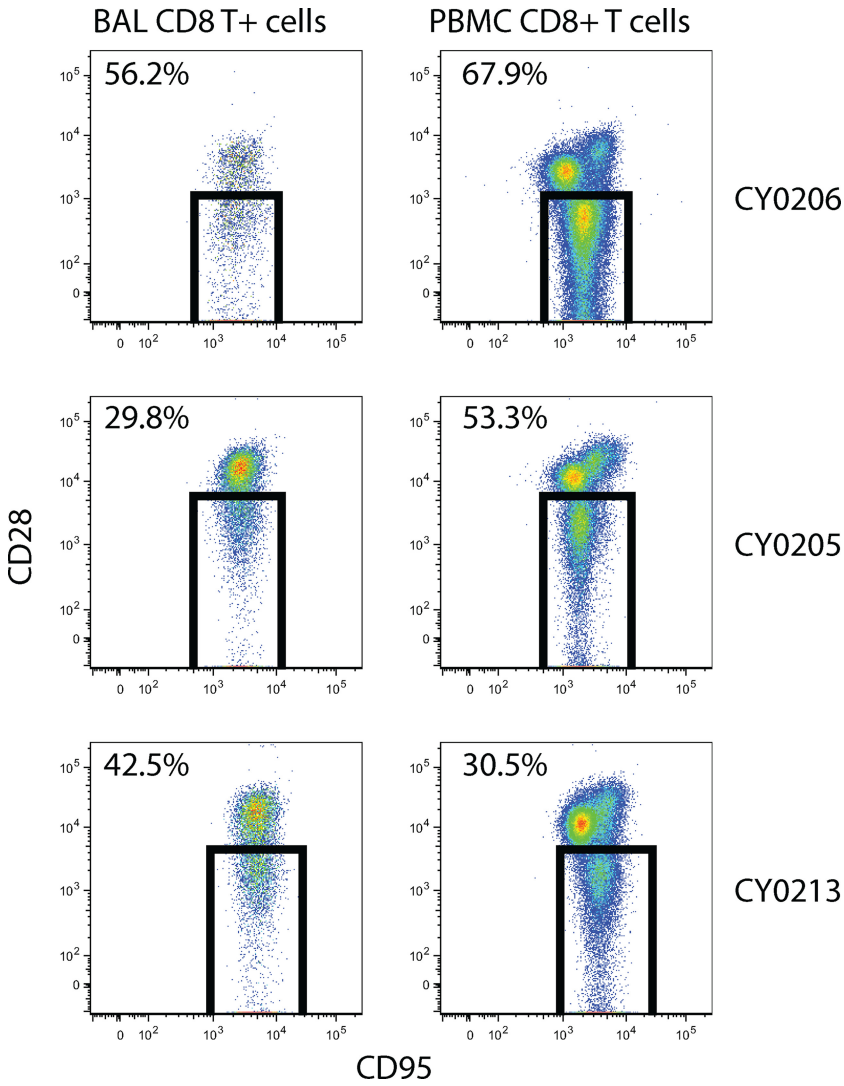

FIG. 8. $CD8^+$ T cell effector memory populations from lung and blood. Cells from animals CY0206, CY0205, and CY0213 were stained with anti-CD28-APC and anti-CD95-PerCP-Cy5.5 to define memory status. Gating is based on lymphocytes and $CD8^+$ T cells. The percentage of effector memory $CD8^+$ $CD28^-$ $CD95^+$ cells is shown in each case.

replication regardless of tissue type. However, BAL $CD8^+$ T cells were more effective at suppressing viral replication than $CD8^+$ T cells isolated from the PBMC of the same animals. Despite the increased suppression by BAL, the lung is depleted of effector $CD4^+$ T cells during SIV infection, and animals that progress rapidly to AIDS face severe depletion of BAL $CD4^+$ T cells (32, 33). Thus, while it is likely due to a variety of different factors, it remains unclear what leads to the development of these effective $CD8^+$ T cells in the lung.

Recent studies have demonstrated an increased level of SIV-specific T cells present in BAL after vaccination with an SIV protein-encoding vector based on the rhesus cytomegalovirus (17). Thus, the previously reported T-cell effector memory localization in extralymphoid tissues such as BAL may explain the increased suppression of SIV replication by BAL $CD8^+$ T cells (34). However, in our studies, the disparity in viral suppression between BAL and PBMC did not appear to stem from consistent differences in the distribution of $CD8^+$ T-cell effector memory populations between PBMC and BAL as defined by CD28 and CD95 expression. Indeed, while the populations did appear different between the two sites, they did not display consistent patterns that might explain the differences in virus suppression.

Several studies have also addressed the differences between $CD8^+$ T-cell responses in blood and mucosal tissues. A study using *in vitro* expanded $CD8^+$ T cells from the mucosa and PBMC in chronically HIV-infected individuals showed similarity in the specificity and magnitude of $CD8^+$ T-cell responses in both tissues (18). Several other studies have also used different methods to show that responses are generally similar between gut and mucosal tissues including T-cell receptor sequencing and tetramer staining (31, 38, 41). These findings suggest that the differences in the levels of viral suppression between the two tissues may be related to the quality of the response and not cell frequency. In agreement with this idea, it

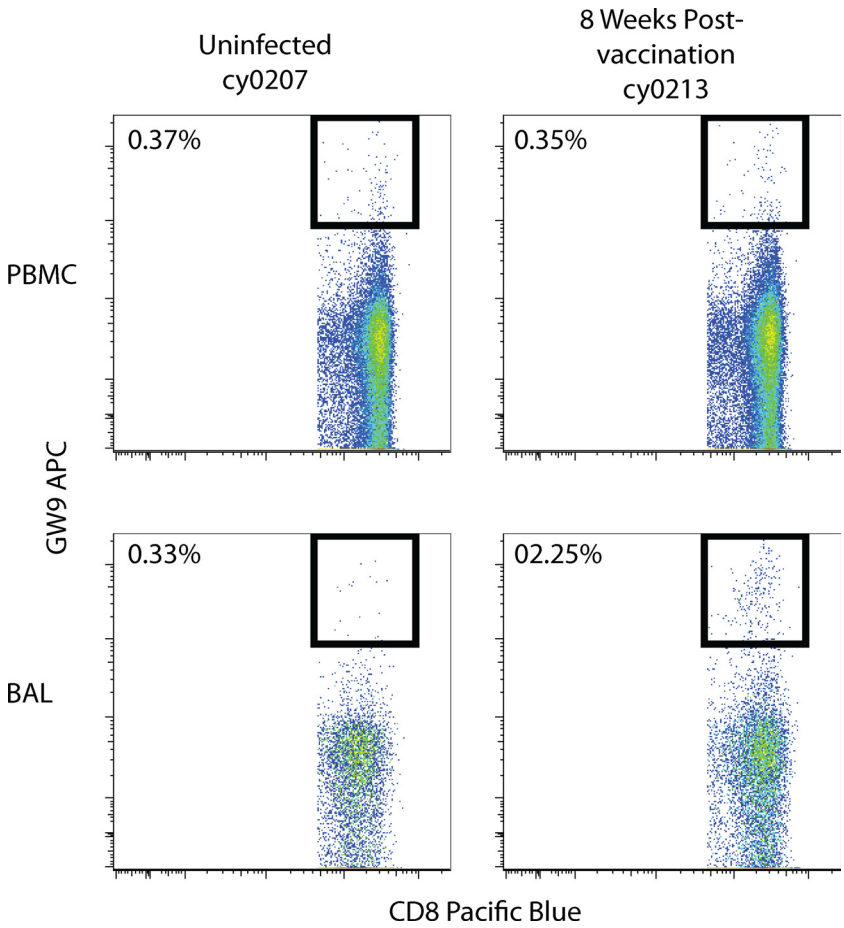

FIG. 9. $Gag_{386–394}$-GW9/*Mafa*-A1*063 tetramer analysis of PBMC and BAL from uninfected animal CY0207 and animal CY0213 at 8 weeks postvaccination. Plots depict the percentages of $CD3^+$ $CD4^-$ $CD8^+$ tetramer-positive cells. The $Gag_{386–394}$-GW9/*Mafa*-A1*063 tetramer was the only one of three that detected a positive response above background. GW9 APC, $Gag_{386–394}$-GW9/*Mafa*-A1*063 conjugated to APC.

was recently reported that there are higher frequencies and greater functionality of HIV-specific cells in BAL than in blood (5). We also measured SIV-specific responses at higher frequencies in BAL than blood by tetramer analysis. Although this response was detected at a very low frequency and although two other $CD8^+$ T-cell responses were undetectable by tetramer analysis, the higher frequency of SIV-specific $CD8^+$ T cells in BAL may help explain the effective viral suppression mediated by BAL $CD8^+$ T cells that we consistently observed. While it would be expected that we detect the BAL tetramer-positive cells by ELISPOT assay in PBMC at low levels, we did not observe positive IFN-γ ELISPOT assay responses using pools of 15-mers overlapping this region. It is possible that these responses were missed because pools of 15-mers are not as sensitive as using the minimal optimal peptide. Additionally, it is plausible that the tetramer-positive cells we detected either are not secreting IFN-γ or are secreting other cytokines that we did not study. Ultimately, the lack of detectable responses in the PBMC matches well with the lack of responses detected by tetramer analysis in the PBMC. SIVmac239Δnef may replicate primarily in the mucosal tissues, generating responses that are at very low frequency and difficult to detect in the PBMC. Importantly, these results demonstrate that measurements of immunity in blood during vaccination may be underestimating the magnitude of the elicited immune response.

The early detection of $CD8^+$ T-cell responses in the lung initially seems incongruent with previous reports that protection requires a 15- to 20-week induction phase. However, it is entirely possible that these early responses need to develop into a long-lived memory response to be effective after wild-type SIVmac239 challenge. It may also be the case that continued replication and adaptation of SIVmac239Δnef with the immune response leads to $CD8^+$ T-cell responses against both the infecting strain and potential escape mutations. This coevolution of host immunity and virus may help to explain the effectiveness of SIVmac239Δnef and the reason for the lengthy induction phase. Nevertheless, the ability of mucosal $CD8^+$ T cells to suppress viral replication early after vaccination contrasts with the long induction phase required for protection against pathogenic challenge. Still, the generation of immune responses in the lung is concurrent with the rapid decline of SIVmac239Δnef plasma loads. This early suppression may help to explain the rapid and better control of acute-phase SIVmac239Δnef plasma loads, which are consistently lower than acute-phase wild-type SIVmac239 plasma loads (data not shown).

Ultimately, these results further cement the differences in

immune responses that exist in different anatomical compartments of an HIV/SIV-infected individual. Future work must assess the ability of this assay to define *in vivo* disease outcome. While researchers frequently rely on easily accessible blood draws to obtain immune readouts, this tissue is not a perfect proxy for accurate assessments of the immune response against the virus, and the lung may not be the perfect proxy for GALT. The present study demonstrates that $CD8^+$ T cells from mucosal tissues are more efficient at preventing viral replication *ex vivo* and provides a unique method for assessing the suppressive capacity of such cells in macaques either infected with or vaccinated against SIV.

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REFERENCES

1. **Almond, N., K. Kent, M. Cranage, E. Rud, B. Clarke, and E. J. Stott.** 1995. Protection by attenuated simian immunodeficiency virus in macaques against challenge with virus-infected cells. Lancet **345:**1342–1344.
2. **Almond, N., J. Rose, R. Sangster, P. Silvera, R. Stebbings, B. Walker, and E. J. Stott.** 1997. Mechanisms of protection induced by attenuated simian immunodeficiency virus. I. Protection cannot be transferred with immune serum. J. Gen. Virol. **78:**1919–1922.
3. **Berry, N., R. Stebbings, D. Ferguson, C. Ham, J. Alden, S. Brown, A. Jenkins, J. Lines, L. Duffy, L. Davis, W. Elsley, M. Page, R. Hull, J. Stott, and N. Almond.** 2008. Resistance to superinfection by a vigorously replicating, uncloned stock of simian immunodeficiency virus (SIVmac251) stimulates replication of a live attenuated virus vaccine (SIVmacC8). J. Gen. Virol. **89:**2240–2251.
4. **Bimber, B. N., B. J. Burwitz, S. O'Connor, A. Detmer, E. Gostick, S. M. Lank, D. A. Price, A. Hughes, and D. O'Connor.** 2009. Ultradeep pyrosequencing detects complex patterns of $CD8^+$ T-lymphocyte escape in simian immunodeficiency virus-infected macaques. J. Virol. **83:**8247–8253.
5. **Brenchley, J. M., K. S. Knox, A. I. Asher, D. A. Price, L. M. Kohli, E. Gostick, B. J. Hill, C. A. Hage, Z. Brahmi, A. Khoruts, H. L. Twigg III, T. W. Schacker, and D. C. Douek.** 2008. High frequencies of polyfunctional HIV-specific T cells are associated with preservation of mucosal CD4 T cells in bronchoalveolar lavage. Mucosal Immunol. **1:**49–58.
6. **Burton, D. R., R. C. Desrosiers, R. W. Doms, W. C. Koff, P. D. Kwong, J. P. Moore, G. J. Nabel, J. Sodroski, I. A. Wilson, and R. T. Wyatt.** 2004. HIV vaccine design and the neutralizing antibody problem. Nat. Immunol. **5:**233–236.
7. **Chung, C., W. Lee, J. T. Loffredo, B. Burwitz, T. C. Friedrich, J. P. Giraldo Vela, G. Napoe, E. G. Rakasz, N. A. Wilson, D. B. Allison, and D. I. Watkins.** 2007. Not all cytokine-producing $CD8^+$ T cells suppress simian immunodeficiency virus replication. J. Virol. **81:**1517–1523.
8. **Connor, R. I., D. C. Montefiori, J. M. Binley, J. P. Moore, S. Bonhoeffer, A. Gettie, E. A. Fenamore, K. E. Sheridan, D. D. Ho, P. J. Dailey, and P. A. Marx.** 1998. Temporal analyses of virus replication, immune responses, and efficacy in rhesus macaques immunized with a live, attenuated simian immunodeficiency virus vaccine. J. Virol. **72:**7501–7509.
9. **Cromwell, M. A., R. S. Veazey, J. D. Altman, K. G. Mansfield, R. Glickman, T. M. Allen, D. I. Watkins, A. A. Lackner, and R. P. Johnson.** 2000. Induction of mucosal homing virus-specific $CD8^+$ T lymphocytes by attenuated simian immunodeficiency virus. J. Virol. **74:**8762–8766.
10. **Daniel, M. D., F. Kirchhoff, S. C. Czajak, P. K. Sehgal, and R. C. Desrosiers.** 1992. Protective effects of a live attenuated SIV vaccine with a deletion in the nef gene. Science **258:**1938–1941.
11. **Dioszeghy, V., K. Benlhassan-Chahour, B. Delache, N. Dereuddre-Bosquet, C. Aubenque, G. Gras, R. Le Grand, and B. Vaslin.** 2006. Changes in soluble factor-mediated $CD8^+$ cell-derived antiviral activity in cynomolgus macaques infected with simian immunodeficiency virus SIVmac251: relationship to biological markers of progression. J. Virol. **80:**236–245.
12. **Ferre, A. L., P. W. Hunt, J. W. Critchfield, D. H. Young, M. M. Morris, J. C. Garcia, R. B. Pollard, H. F. J. Yee, J. N. Martin, S. G. Deeks, and B. L. Shacklett.** 2009. Mucosal immune responses to HIV-1 in elite controllers: a potential correlate of immune control. Blood **113:**3978–3989.
13. **Gauduin, M. C., R. L. Glickman, R. Means, and R. P. Johnson.** 1998. Inhibition of simian immunodeficiency virus (SIV) replication by $CD8^+$ T lymphocytes from macaques immunized with live attenuated SIV. J. Virol. **72:**6315–6324.
14. **Genesca, M., M. B. McChesney, and C. J. Miller.** 2009. Antiviral $CD8^+$ T cells in the genital tract control viral replication and delay progression to AIDS after vaginal SIV challenge in rhesus macaques immunized with virulence attenuated SHIV 89.6. J. Intern. Med. **265:**67–77.
15. **Genesca, M., P. J. Skinner, K. M. Bost, D. Lu, Y. Wang, T. L. Rourke, A. T. Haase, M. B. McChesney, and C. J. Miller.** 2008. Protective attenuated lentivirus immunization induces SIV-specific T cells in the genital tract of rhesus monkeys. Mucosal Immunol. **1:**219–228.
16. **Genesca, M., P. J. Skinner, J. J. Hong, J. Li, D. Lu, M. B. McChesney, and C. J. Miller.** 2008. With minimal systemic T-cell expansion, $CD8^+$ T Cells mediate protection of rhesus macaques immunized with attenuated simian-human immunodeficiency virus SHIV89.6 from vaginal challenge with simian immunodeficiency virus. J. Virol. **82:**11181–11196.
17. **Hansen, S. G., C. Vieville, N. Whizin, L. Coyne-Johnson, D. C. Siess, D. D. Drummond, A. W. Legasse, M. K. Axthelm, K. Oswald, C. M. Trubey, M. J. Piatak, J. D. Lifson, J. A. Nelson, M. A. Jarvis, and L. J. Picker.** 2009. Effector memory T cell responses are associated with protection of rhesus monkeys from mucosal simian immunodeficiency virus challenge. Nat. Med. **15:**293–299.
18. **Ibarrondo, F. J., P. A. Anton, M. Fuerst, H. L. Ng, J. T. Wong, J. Matud, J. Elliott, R. Shih, M. A. Hausner, C. Price, L. E. Hultin, P. M. Hultin, B. D. Jamieson, and O. O. Yang.** 2005. Parallel human immunodeficiency virus type 1-specific $CD8^+$ T-lymphocyte responses in blood and mucosa during chronic infection. J. Virol. **79:**4289–4297.
19. **Johnson, R. P.** 2002. Mechanisms of protection against simian immunodeficiency virus infection. Vaccine **20:**1985–1987.
20. **Johnson, R. P., and R. C. Desrosiers.** 1998. Protective immunity induced by live attenuated simian immunodeficiency virus. Curr. Opin. Immunol. **10:**436–443.
21. **Johnson, R. P., J. D. Lifson, S. C. Czajak, K. S. Cole, K. H. Manson, R. Glickman, J. Yang, D. C. Montefiori, R. Montelaro, M. S. Wyand, and R. C. Desrosiers.** 1999. Highly attenuated vaccine strains of simian immunodeficiency virus protect against vaginal challenge: inverse relationship of degree of protection with level of attenuation. J. Virol. **73:**4952–4961.
22. **Kader, M., W. M. Hassan, M. Eberly, M. Piatak, J. D. Lifson, M. Roederer, and J. J. Mattapallil.** 2008. Antiretroviral therapy prior to acute viral replication preserves CD4 T cells in the periphery but not in rectal mucosa during acute simian immunodeficiency virus infection. J. Virol. **82:**11467–11471.
23. **Kestler, H. W., III, Y. Li, Y. M. Naidu, C. V. Butler, M. F. Ochs, G. Jaenel, N. W. King, M. D. Daniel, and R. C. Desrosiers.** 1988. Comparison of simian immunodeficiency virus isolates. Nature **331:**619–622.
24. **Kestler, H. W., III, D. J. Ringler, K. Mori, D. L. Panicali, P. K. Sehgal, M. D. Daniel, and R. C. Desrosiers.** 1991. Importance of the nef gene for maintenance of high virus loads and for development of AIDS. Cell **65:**651–662.
25. **Koff, W. C., P. R. Johnson, D. I. Watkins, D. R. Burton, J. D. Lifson, K. J. Hasenkrug, A. B. McDermott, A. Schultz, T. J. Zamb, R. Boyle, and R. C. Desrosiers.** 2006. HIV vaccine design: insights from live attenuated SIV vaccines. Nat. Immunol. **7:**19–23.
26. **Li, Q., L. Duan, J. D. Estes, Z. M. Ma, T. Rourke, Y. Wang, C. Reilly, J. Carlis, C. J. Miller, and A. T. Haase.** 2005. Peak SIV replication in resting memory $CD4^+$ T cells depletes gut lamina propria $CD4^+$ T cells. Nature **434:**1148–1152.
27. **Loffredo, J. T., B. J. Burwitz, E. G. Rakasz, S. P. Spencer, J. J. Stephany, J. P. Vela, S. R. Martin, J. Reed, S. M. Piaskowski, J. Furlott, K. L. Weisgrau, D. S. Rodrigues, T. Soma, G. Napoe, T. C. Friedrich, N. A. Wilson, E. G. Kallas, and D. I. Watkins.** 2007. The antiviral efficacy of simian immunodeficiency virus-specific $CD8^+$ T cells is unrelated to epitope specificity and is abrogated by viral escape. J. Virol. **81:**2624–2634.
28. **Loffredo, J. T., E. G. Rakasz, J. P. Giraldo, S. P. Spencer, K. K. Grafton, S. R. Martin, G. Napoe, L. J. Yant, N. A. Wilson, and D. I. Watkins.** 2005. Tat_{28-35}SL8-specific $CD8^+$ T lymphocytes are more effective than $Gag_{181-189}$CM9-specific $CD8^+$ T lymphocytes at suppressing simian immunodeficiency virus replication in a functional in vitro assay. J. Virol. **79:**14986–14991.
29. **Mansfield, K., S. M. Lang, M. C. Gauduin, H. B. Sanford, J. D. Lifson, R. P. Johnson, and R. C. Desrosiers.** 2008. Vaccine protection by live, attenuated simian immunodeficiency virus in the absence of high-titer antibody re-

sponses and high-frequency cellular immune responses measurable in the periphery. J. Virol. **82:**4135–4148.
30. **Mattapallil, J. J., D. C. Douek, B. Hill, Y. Nishimura, M. Martin, and M. Roederer.** 2005. Massive infection and loss of memory $CD4^+$ T cells in multiple tissues during acute SIV infection. Nature **434:**1093–1097.
31. **Musey, L., Y. Ding, J. Cao, J. Lee, C. Galloway, A. Yuen, K. R. Jerome, and M. J. McElrath.** 2003. Ontogeny and specificities of mucosal and blood human immunodeficiency virus type 1-specific $CD8^+$ cytotoxic T lymphocytes. J. Virol. **77:**291–300.
32. **Okoye, A., M. Meier-Schellersheim, J. M. Brenchley, S. I. Hagen, J. M. Walker, M. Rohankhedkar, R. Lum, J. B. Edgar, S. L. Planer, A. Legasse, A. W. Sylwester, M. J. Piatak, J. D. Lifson, V. C. Maino, D. L. Sodora, D. C. Douek, M. K. Axthelm, Z. Grossman, and L. J. Picker.** 2007. Progressive $CD4^+$ central memory T cell decline results in $CD4^+$ effector memory insufficiency and overt disease in chronic SIV infection. J. Exp. Med. **204:** 2171–2185.
33. **Picker, L. J., S. I. Hagen, R. Lum, E. F. Reed-Inderbitzin, L. M. Daly, A. W. Sylwester, J. M. Walker, D. C. Siess, M. J. Piatak, C. Wang, D. B. Allison, V. C. Maino, J. D. Lifson, T. Kodama, and M. K. Axthelm.** 2004. Insufficient production and tissue delivery of $CD4^+$ memory T cells in rapidly progressive simian immunodeficiency virus infection. J. Exp. Med. **200:**1299–1314.
34. **Picker, L. J., E. F. Reed-Inderbitzin, S. I. Hagen, J. B. Edgar, S. G. Hansen, A. Legasse, S. Planer, M. J. Piatak, J. D. Lifson, V. C. Maino, M. K. Axthelm, and F. Villinger.** 2006. IL-15 induces CD4 effector memory T cell production and tissue emigration in nonhuman primates. J. Clin. Invest. **116:**1514–1524.
35. **Reynolds, M. R., A. M. Weiler, K. L. Weisgrau, S. M. Piaskowski, J. R. Furlott, J. T. Weinfurter, M. Kaizu, T. Soma, E. J. Leon, C. MacNair, D. P. Leaman, M. B. Zwick, E. Gostick, S. K. Musani, D. A. Price, T. C. Friedrich, E. G. Rakasz, N. A. Wilson, A. B. McDermott, R. Boyle, D. B. Allison, D. R. Burton, W. C. Koff, and D. I. Watkins.** 2008. Macaques vaccinated with live-attenuated SIV control replication of heterologous virus. J. Exp. Med. **205:**2537–2550.
36. **Sacha, J. B., C. Chung, E. G. Rakasz, S. P. Spencer, A. K. Jonas, A. T. Bean, W. Lee, B. J. Burwitz, J. J. Stephany, J. T. Loffredo, D. B. Allison, S. Adnan, A. Hoji, N. A. Wilson, T. C. Friedrich, J. D. Lifson, O. O. Yang, and D. I. Watkins.** 2007. Gag-specific $CD8^+$ T lymphocytes recognize infected cells before AIDS-virus integration and viral protein expression. J. Immunol. **178:**2746–2754.
37. **Saez-Cirion, A., M. Sinet, S. Y. Shin, A. Urrutia, P. Versmisse, C. Lacabaratz, F. Boufassa, V. Avettand-Fenoel, C. Rouzioux, J. F. Delfraissy, F. Barre-Sinoussi, O. Lambotte, A. Venet, and G. Pancino.** 2009. Heterogeneity in HIV suppression by CD8 T cells from HIV controllers: association with Gag-specific CD8 T cell responses. J. Immunol. **182:**7828–7837.
38. **Schmitz, J. E., R. S. Veazey, M. J. Kuroda, D. B. Levy, A. Seth, K. G. Mansfield, C. E. Nickerson, M. A. Lifton, X. Alvarez, A. A. Lackner, and N. L. Letvin.** 2001. Simian immunodeficiency virus (SIV)-specific cytotoxic T lymphocytes in gastrointestinal tissues of chronically SIV-infected rhesus monkeys. Blood **98:**3757–3761.
39. **Sekaly, R. P.** 2008. The failed HIV Merck vaccine study: a step back or a launching point for future vaccine development? J. Exp. Med. **205:**7–12.
40. **Sernicola, L., F. Corrias, M. L. Koanga-Mogtomo, S. Baroncelli, S. Di Fabio, M. T. Maggiorella, R. Belli, Z. Michelini, I. Macchia, A. Cesolini, L. Cioe, P. Verani, and F. Titti.** 1999. Long-lasting protection by live attenuated simian immunodeficiency virus in cynomolgus monkeys: no detection of reactivation after stimulation with a recall antigen. Virology **256:**291–302.
41. **Shacklett, B. L., C. A. Cox, J. K. Sandberg, N. H. Stollman, M. A. Jacobson, and D. F. Nixon.** 2003. Trafficking of human immunodeficiency virus type 1-specific $CD8^+$ T cells to gut-associated lymphoid tissue during chronic infection. J. Virol. **77:**5621–5631.
42. **Shacklett, B. L., O. Yang, M. A. Hausner, J. Elliott, L. Hultin, C. Price, M. Fuerst, J. Matud, P. Hultin, C. Cox, J. Ibarrondo, J. T. Wong, D. F. Nixon, P. A. Anton, and B. D. Jamieson.** 2003. Optimization of methods to assess human mucosal T-cell responses to HIV infection. J. Immunol. Methods **279:**17–31.
43. **Silvera, P., A. Wade-Evans, E. Rud, R. Hull, K. Silvera, R. Sangster, N. Almond, and J. Stott.** 2001. Mechanisms of protection induced by live attenuated simian immunodeficiency virus: III. Viral interference and the role of $CD8^+$ T-cells and beta-chemokines in the inhibition of virus infection of PBMCs in vitro. J. Med. Primatol. **30:**1–13.
44. **Stebbings, R., N. Berry, J. Stott, R. Hull, B. Walker, J. Lines, W. Elsley, S. Brown, A. Wade-Evans, G. Davis, J. Cowie, M. Sethi, and N. Almond.** 2004. Vaccination with live attenuated simian immunodeficiency virus for 21 days protects against superinfection. Virology **330:**249–260.
45. **Stebbings, R., N. Berry, H. Waldmann, P. Bird, G. Hale, J. Stott, D. North, R. Hull, J. Hall, J. Lines, S. Brown, N. D'Arcy, L. Davis, W. Elsley, C. Edwards, D. Ferguson, J. Allen, and N. Almond.** 2005. $CD8^+$ lymphocytes do not mediate protection against acute superinfection 20 days after vaccination with a live attenuated simian immunodeficiency virus. J. Virol. **79:**12264–12272.
46. **Stebbings, R., J. Stott, N. Almond, R. Hull, J. Lines, P. Silvera, R. Sangster, T. Corcoran, J. Rose, S. Cobbold, F. Gotch, A. McMichael, and B. Walker.** 1998. Mechanisms of protection induced by attenuated simian immunodeficiency virus. II. Lymphocyte depletion does not abrogate protection. AIDS Res. Hum. Retroviruses **14:**1187–1198.
47. **Stebbings, R. J., N. M. Almond, E. J. Stott, N. Berry, A. M. Wade-Evans, R. Hull, J. Lines, P. Silvera, R. Sangster, T. Corcoran, J. Rose, and K. B. Walker.** 2002. Mechanisms of protection induced by attenuated simian immunodeficiency virus. Virology **296:**338–353.
48. **Stone, M., Z. M. Ma, M. Genesca, L. Fritts, S. Blozois, M. B. McChesney, and C. J. Miller.** 2009. Limited dissemination of pathogenic SIV after vaginal challenge of rhesus monkeys immunized with a live, attenuated lentivirus. Virology **392:**260–270.
49. **Titti, F., L. Sernicola, A. Geraci, G. Panzini, S. Di Fabio, R. Belli, F. Monardo, A. Borsetti, M. T. Maggiorella, M. Koanga-Mogtomo, F. Corrias, R. Zamarchi, A. Amadori, L. Chieco-Bianchi, and P. Verani.** 1997. Live attenuated simian immunodeficiency virus prevents super-infection by cloned SIVmac251 in cynomolgus monkeys. J. Gen. Virol. **78:**2529–2539.
50. **Tsukamoto, T., M. Yuasa, H. Yamamoto, M. Kawada, A. Takeda, H. Igarashi, and T. Matano.** 2007. Induction of $CD8^+$ cells able to suppress CCR5-tropic simian immunodeficiency virus SIVmac239 replication by controlled infection of CXCR4-tropic simian-human immunodeficiency virus in vaccinated rhesus macaques. J. Virol. **81:**11640–11649.
51. **Valentine, L. E., S. M. Piaskowski, E. G. Rakasz, N. L. Henry, N. A. Wilson, and D. I. Watkins.** 2008. Recognition of escape variants in ELISPOT does not always predict $CD8^+$ T-cell recognition of simian immunodeficiency virus-infected cells expressing the same variant sequences. J. Virol. **82:**575–581.
52. **Wiseman, R. W., J. A. Wojcechowskyj, J. M. Greene, A. J. Blasky, T. Gopon, T. Soma, T. C. Friedrich, S. L. O'Connor, and D. H. O'Connor.** 2007. Simian immunodeficiency virus SIVmac239 infection of major histocompatibility complex-identical cynomolgus macaques from Mauritius. J. Virol. **81:**349–361.
53. **Wyand, M. S., K. Manson, D. C. Montefiori, J. D. Lifson, R. P. Johnson, and R. C. Desrosiers.** 1999. Protection by live, attenuated simian immunodeficiency virus against heterologous challenge. J. Virol. **73:**8356–8363.
54. **Yang, O. O.** 2009. Assessing the antiviral activity of HIV-1-specific cytotoxic T lymphocytes. Methods Mol. Biol. **485:**407–415.
55. **Yang, O. O., S. A. Kalams, A. Trocha, H. Cao, A. Luster, R. P. Johnson, and B. D. Walker.** 1997. Suppression of human immunodeficiency virus type 1 replication by $CD8^+$ cells: evidence for HLA class I-restricted triggering of cytolytic and noncytolytic mechanisms. J. Virol. **71:**3120–3128.