Mucosal HIV-1 Pox Virus Prime-Boost Immunization Induces High-Avidity CD8 + T Cells with Regime-Dependent Cytokine/Granzyme B Profiles

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Mucosal HIV-1 Pox Virus Prime-Boost Immunization Induces High-Avidity CD8+ T Cells with Regime-Dependent Cytokine/Granzyme B Profiles

Charani Ranasinghe, Stephen J. Turner, Craig McArthur, Duncan B. Sutherland, Jee-Hye Kim, Peter C. Doherty, and Ian A. Ramshaw

The quality of virus-specific CD8+ CTL immune responses generated by mucosal and systemic poxvirus prime-boost vaccines were evaluated in terms of T cell avidity and single-cell analysis of effector gene expression. Intranasal (I.N.) immunization regimes generated higher avidity CTL responses specific for HIV KdGag197–205 (amino acid sequence AMQMLKETI; H-2Kd binding) compared with i.m. immunization regime. Single-cell RT-PCR of KdGag197–205-specific mucosal and systemic CTL revealed that the cytokine and granzyme B expression profiles were dependent on both the route and time after immunization. The I.N./i.m.-immunized group elicited elevated number of CTL-expressing granzyme B mRNA from the genitomucosal sites compared with the i.m./i.m. regime. Interestingly, CTL generated after both I.N. or i.m. immunization demonstrated expression of Th2 cytokine IL-4 mRNA that was constitutively expressed over time, although lower numbers were observed after I.N./I.N. immunization. Results suggest that after immunization, Ag-specific CTL expression of IL-4 may be an inherent property of the highly evolved poxvirus vectors. Current observations indicate that the quality of CTL immunity generated after immunization can be influenced by the inherent property of vaccine vectors and route of vaccine delivery. A greater understanding of these factors will be crucial for the development of effective vaccines in the future. The Journal of Immunology, 2007, 178: 2370–2379.

Virus-specific CD8+ CTL play a pivotal role in the control of many acute and chronic viral infections (1–4) including HIV-1 (5–7). Depletion of CD8+ lymphocytes from rhesus macaques during chronic SIV infection can result in a rapid increase in viremia, which can subsequently be controlled by reintroduction of SIV-specific CD8+ T cells (8). The genitoreal mucosa is the primary site of HIV-1 viral entry and predominant site of HIV-1 replication and CD4+ T cell depletion (9). Indeed, significant CD4+ T cell depletion occurs at the mucosa well before that observed in the peripheral circulation. Therefore, vaccines capable of inducing HIV-specific CTL in local mucosa could better control viral replication within local tissue and perhaps prevent systemic dissemination of the virus. Studies have demonstrated that mucosal CTL can control a mucosal viral challenge, whereas systemic CTL are ineffective against mucosal challenge (10).

Currently, a range of vaccine strategies has been tested in various animal models for HIV-1. Many vaccines strategies that co-express molecules to enhance T cell responses to HIV Ags have also been tested (11–14). Although the majority of these vaccines elicit CTL responses, neither initial virus growth nor the establishment of chronic infection is prevented, but a reduction in chronic viral load has been observed (7, 15–19). It is now evident that the route of vaccine delivery plays an important role in the induction of T cell immunity (20). However, there is little information available on the qualitative differences between CTL responses generated by these different vaccines, or delivery routes in terms of CTL avidity or cytokine/granzyme profiles. Although low-avidity CTL are incapable of effector function at low concentrations of Ag, high-avidity CTL are capable of recognizing low concentrations of Ag/peptide and possess an increased functional ability (21, 22). A compelling body of evidence suggest that high-avidity CTL are more effective in viral or tumor clearance compared with low-avidity T cells (23–25). Recently, Belyakov et al. (7) have shown that a mucosal peptide prime/poxvirus boost-immunization regime can generate high-avidity mucosal CTL that are more capable of controlling systemic dissemination of virus in rhesus macaques compared with systemic vaccination. Thus, a much greater understanding of how route of immunization can influence correlation between TCR avidity and protection against HIV-1 will enable the development of better vaccines in the future.

In this study, to determine the quality of immune responses generated by the poxvirus prime-boost vaccines, we have used several poxvirus prime-boost (AE fowlpox virus (FPV)/AE vaccinia virus (VV)) vaccine strategies and compared the levels of mucosal and systemic HIV-specific CD8+ T cell responses generated at early and late stages of secondary response in terms of their T cell avidity. We have also characterized regime-specific cytokine and granzyme B expression profiles of Gag KdGag197–205-positive T cells at a single-cell level to 1) unravel the nature of these T cells and 2) possibly identify traits that are unique to mucosal vaccination.

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1 Abbreviations used in this paper: FPV, fowlpox virus; VV, vaccinia virus; I.N., intranasal; DEPC, diethyl pyrocarbonate; CT, cycle threshold.

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In parallel, we have also evaluated the cytokine profiles generated in the total CD8+ T cell population by RT-PCR and FACS analysis.

Materials and Methods

Recombinant poxvirus vaccines

The AE FPV contained modified AE clade gag, pol, env, rev, and tat genes, and AE VV contained modified gag and pol genes as described elsewhere (26–28).

Immunization of mice

Pathogen-free 5- to 6-wk-old female BALB/c (H-2d) mice were obtained from the Animal Breeding Establishment, John Curtin School of Medical Research (JCSMR). All animals were maintained and used in accordance with animal ethics guidelines. Mice (n = 4 or 5) were primed and boosted with 1 × 10^7 PFU rFPV followed by 1 × 10^7 PFU rVV expressing AE clade HIV-1 Ags (under mild methoxyfluorane anesthesia) 2 wk apart using three different immunization regimens: 1) intranasal (I.N./i.m., combined mucosal systemic route; 2) I.N./I.N., purely mucosal; and 3) i.m./I.N., combined mucosal systemic route; 2) I.N./I.N., purely mucosal; and 3) i.m./I.N., combined mucosal systemic route.

To measure systemic and mucosal T cell responses, mice were sacrificed at 7–10 d postimmunization. The spleen and genitorectal lymph nodes were removed, and cell suspensions were prepared in complete RPMI 1640.

IFN-γ ELISPOT assay

HIV-specific T cell responses were measured by IFN-γ capture ELISPOT assay as described elsewhere (20). The cells were stimulated for 20–24 h in the presence of HIV-specific 15-mer overlapping Gag peptide pool supplied by the National Institutes of Health AIDS Research and Reference Reagent Program or the immunodominant H-2Kd binding AMQMLKETI, 9-mer Gag peptide (synthesized at the Bio-Molecular Resource Facility at JCSMR, Canberra, Australia) (29, 30). In these assays, Con A (Sigma-Aldrich) was used as the positive control and unstimulated cells as negative controls. The spot-forming units were counted using an ELISpot BiosReader-4000 (Biosys). Results are expressed as 1 × 10^5 T cells and represent the average of the duplicate or triplicate value. Unstimulated cell counts were subtracted from each sample set before plotting the data.

Tetramer staining and single-cell sorting

Allophycocyanin-conjugated K^B^Gag_{3–20} tetramers were synthesized at the Bio-Molecular Resource Facility at JCSMR. The tetramer staining was performed as described previously (20). Briefly, 2–5 × 10^6 splenocytes or genitorectal lymphocytes were stained with anti-CD8 FITC Ab (BD Pharmingen) and allophycocyanin-conjugated KdGag_{197–205} tetramer.

Single-cell cDNA synthesis and single-cell RT-PCR

The 96-well plates containing the single cells were kept on ice, and 5 μl of cDNA buffer (SensiscRIPT RT kit; Qiagen) containing 0.5 mM dNTP (Qiagen), 125 ng of oligo(dT) (Promega), 2.5 U of RNASin (Promega), 0.5 mM spermidine (Sigma-Aldrich), 0.1% Triton X-100 (Sigma-Aldrich), 100 μg/ml tRNA, and 0.125 μl of Sensitive Reverse Transcriptase (SensiscRIPT RT kit; Qiagen) was added immediately to each cell, and the plates were centrifuged at 2500 rpm for 3 min and incubated at 37°C for 110 min to synthesize the cDNA and stored at −20°C until use (31, 32).

Nested PCR was performed using HotStar Taq Master mix (Qiagen) with 5 pmol of forward and reverse cytokine primers indicated in Table I. The L32 ribosomal protein mRNA (housekeeping mRNA) was used as the positive control to monitor the presence of a cell in each well and the quality of cDNA synthesis. Appropriate positive controls for primes and negative controls were also used at all times. The PCR 1 and PCR 2 were performed, one cycle of 95°C for 15 min, to activate the HotStar Taq (Qiagen), followed by 35 cycles for 95°C 20 s, 55°C 20 s, and 72°C 1 min.

### Table I. Primers used in single-cell-nested PCR

<table>
<thead>
<tr>
<th>Primer</th>
<th>Sense Primer Sequence 5’→3’</th>
<th>Antisense Primer Sequence 5’→3’</th>
</tr>
</thead>
<tbody>
<tr>
<td>IFN-γ 1</td>
<td>AGAAGCGCTACACACTGCTATC</td>
<td>TCCAGAACAGGACCTCTTTTCCG</td>
</tr>
<tr>
<td>IFN-γ 2</td>
<td>GGTTGACCTGCCGAGGAGGA</td>
<td>AAGACGTGTGGACACCCTC</td>
</tr>
<tr>
<td>TNF-α 1</td>
<td>AGGCAAGCGAGATGACAGC</td>
<td>CGGCGATGCCCAAAATTCTAA</td>
</tr>
<tr>
<td>TNF-α 2</td>
<td>TGGGACCTGATGAGCAGCA</td>
<td>TGGGAGATGACAGGACCTTT</td>
</tr>
<tr>
<td>IL-2</td>
<td>CATATCCACCTCTCAGAGG</td>
<td>TGAGGACAGGAGGAAGGA</td>
</tr>
<tr>
<td>IL-2</td>
<td>TGGGACCTGATGAGCAGCA</td>
<td>TGGGAGATGACAGGACCTTT</td>
</tr>
<tr>
<td>IL-4</td>
<td>CAGTCTCAACCCCGAGTT</td>
<td>CGGGGATGACAGGAGGAAGGA</td>
</tr>
<tr>
<td>IL-4</td>
<td>CATATCCACCTCTCAGAGG</td>
<td>TGAGGACAGGAGGAAGGA</td>
</tr>
<tr>
<td>L32</td>
<td>AAGAAGCGCTACACACTGCTATC</td>
<td>TCCAGAACAGGACCTCTTTTCCG</td>
</tr>
</tbody>
</table>

* L32 REV1 was reused in the second round. FWD, Forward; REV, reverse; Gran, granzyme.

### Table II. Primers used in real-time PCR

<table>
<thead>
<tr>
<th>Target mRNA</th>
<th>Sense Primer Sequence 5’→3’</th>
<th>Antisense Primer Sequence 5’→3’</th>
</tr>
</thead>
<tbody>
<tr>
<td>IL-2</td>
<td>CTTGGCAACTCCCACGATCT</td>
<td>TCCAGAAGCTGAGCCGAGGA</td>
</tr>
<tr>
<td>IL-4</td>
<td>GGGCTCCTCCACGCAATAT</td>
<td>GGGCGATGATCCTCTCTCATG</td>
</tr>
<tr>
<td>IL-6</td>
<td>GAGCAAGCTACACACTGAGCA</td>
<td>AAGACGTGTGGACACCCTC</td>
</tr>
<tr>
<td>IL-10</td>
<td>AAGAAGCGCTACACACTGCA</td>
<td>CGGCGATGCCCAAAATTCTAA</td>
</tr>
<tr>
<td>IL-13</td>
<td>CAGTCTCAACCCCGAGTT</td>
<td>CGGGGATGACAGGAGGAAGGA</td>
</tr>
<tr>
<td>IL-18</td>
<td>GACTCTTGGCTGACCATAGAGG</td>
<td>CGGCGATGATCCTCTCTCTTCT</td>
</tr>
<tr>
<td>IFN-γ</td>
<td>ATGAAAGCTACACACTGAGCA</td>
<td>AAGACGTGTGGACACCCTC</td>
</tr>
<tr>
<td>TNF-α</td>
<td>CACTCTTCCAAAACTGAGTGAACA</td>
<td>TGGGAGATGACAGGACCTTTTCTG</td>
</tr>
<tr>
<td>L-32</td>
<td>CTTGGGAATGCTGCTCTGAAG</td>
<td>CTTGGGAATGCTGCTCTGAAG</td>
</tr>
</tbody>
</table>
FIGURE 1. Immunization regime-specific systemic T cell responses. Two weeks after poxvirus prime-boost, splenocytes from BALB/c (H-2d) (n = 4 mice/group) were stimulated with 9-mer Gag peptide as described in Materials and Methods and T cell responses were measured by IFN-γ ELISPOT (A). The unstimulated cells from each sample were used as the background control, and this value was subtracted from each sample before plotting the data. The data represent mean + SD of three experiments. Responses between L.N./L.N.–L.N./i.m. (*) and L.N./L.N.–i.m./i.m. (**) were significantly different; p < 0.05. At 14 days prime-boost, the percentage of K^Gag_197–205^-specific CD8^+ T cell response was measured in spleen (B). The y-axis represents the tetramer-positive cells per 10^6 total T cells. The unimmunized animals were used as background controls. The data represent mean ± SE. Immunization regime-specific systemic and mucosal CD8^+ T cell responses were measured over time (C). The percentage of K^Gag_197–205^-positive CD8^+ T cells measured in spleen (black lines) and genitorectal nodes (gray lines) at 3, 7, and 14 days after prime-boost immunization. These data represent a pooled value and are representative of three experiments.

20 s, and one extension cycle of 72°C for 10 min. Results are represented as a percentage of tetramer-positive cells expressing the cytokine or granzyme.

Tetramer dissociation assay

The dissociation assay was performed as described elsewhere (22). Briefly, 2 × 10^6 cells from each sample were aliquoted into a round-bottom 96-well plate and were stained with FITC-CD8^+ and allophycocyanin-Gag K^Gag_197–205 as described previously. The plate was configured to have six time points per sample (0–60 min). A total of 50 μg/ml H-2K^d-competitive Ab (BD Pharmingen) was added to each well to prevent tetramer rebinding, and plates were incubated at 37°C with 5% CO_2. At each time point, aliquots were transferred to ice-cold FACS buffer to stop the reaction, washed, and resuspended in 100 μl of FACS buffer containing 0.5% paraformaldehyde. These samples were analyzed on a

FIGURE 2. Immunization route and T cell avidity. BALB/c (H-2d) mice (n = 4/group) were immunized L.N./L.N. (gray line), L.N./i.m. (black dotted line), and i.m./i.m. (black line), and at 7 (A) and 14 days (B) after AE VV boost the percentage of K^Gag_197–205^-positive CD8^+ splenocyte loss (dissociation) was measured as described in Materials and Methods. The day 7 data represent a pooled value and are representative of three experiments. The day 14 data represent individual animals with mean ± SD. Immunization route-specific systemic and mucosal CD8^+ T cell responses were measured over time (C). The percentage of K^Gag_197–205^-positive CD8^+ T cells measured in spleen (black lines) and genitorectal nodes (gray lines) at 3, 7, and 14 days after prime-boost immunization. These data represent a pooled value and are representative of three experiments.

FIGURE 3. L.N./i.m. regime-specific K^Gag_197–205^-positive spleen and genitorectal node sort profiles. At 14 days following AE VV booster immunization, K^Gag_197–205^-specific spleen (gate R1 = 9.89%), genitorectal (gate R3 = 5.89%) lymph nodes, and K^Gag_197–205^-negative spleen (gate R2), genitorectal (gate R4) lymph nodes were single-cell sorted into Eppendorf 96-well plats, snap frozen immediately to prevent RNA degradation, and stored at −80°C until RT-PCR. Note that first, the single-cell precision was confirmed by sorting single microbeads onto a glass slide and confirming by microscopy, and also resorting the K^Gag_197–205^-specific cells a second time to ensure purity of the cells. (The percentage of K^Gag_197–205^-positive cells is represented as a percentage of total CD8^+ T cells).
FACSCalibur flow cytometer (BD Biosciences) using CellQuest Pro analysis software (BD Biosciences).

CD8+ T cells were isolated from unimmunized, I.N./i.m., I.N./i.m., and i.m./i.m. immunized mice using the Dynal negative isolation kit (Dynal Biotech) according to the manufacturer’s instructions. Fifty percent of selected cells were stimulated with 15-mer Gag peptide pool for 16–20 h, while others were kept untreated for the same length of time. From these cells mRNA was extracted using Tri-Reagent (Sigma-Aldrich), and cell pellets were resuspended in a final volume of 20 µl DEPC-treated water (Ambion). To each sample, 2U of DNaseI (Roche) and first-strand buffer (Invitrogen Life Technologies) was added and incubated at 37°C for 30 min to degrade any contaminating DNA followed by incubation for 5 min at 75°C to inactivate DNaseI. The concentration of total mRNA was measured using the Nanodrop ND-1000 UV-Vis Spectrophotometer (Nanodrop), and samples were aliquoted and stored at −70°C until required.

cDNA syntheses from primary CD8+ T cells

From each sample 1 µg mRNA was converted into cDNA. To each sample, 2 µl of master mix containing 10 nM dNTPs and 100 µM oligo(dT)s were added, and each sample was made up to a final volume of 15 µl using DEPC-treated H2O and incubated at 37°C for 30 min to remove any secondary structures in the RNA. Samples were cooled on ice for 2 min, and 5 µl of reaction mix containing 2 µl of 0.1 M DTT, 2 µl of 5× first-strand buffer, and 1 µl of SuperScript III (Invitrogen Life Technologies) were added to each sample and incubated at 50°C for 60 min to synthesize the cDNA. Samples were then incubated at 70°C for a further 15 min to denature the superscript, and samples were stored at −70°C.

Real-time PCR

Real-time PCR master mix contained 5 pmols of forward and reverse primers (Proligo; Table II), 10 µl of 2× SYBR Green (Applied Biosystems), and DEPC-treated H2O to a final volume of 20 µl per reaction. A total of 50 ng of cDNA (in a 2 µl volume) from each sample was aliquoted into a Thermo-Fast 96-well detection plate (ABgene), and 18 µl of master mix was added to each well. Real-time PCR was performed as cycle of 50°C, 2 min, 95°C, 10 min followed by 40 cycles of 95°C, 15 s, 60°C, 1 min, using an ABI Prism 7700 Sequence Detection System (PerkinElmer/Applied Biosystems). All reactions were performed in duplicate, and to ensure that single products were obtained after each reaction the melting curves of the primers were also tested by dissociation runs.

The amplification plots obtained for each sample were analyzed using 7700 software, and the corresponding dissociation curves were checked to ensure that each primer pair only yielded one product with one melting point. The fold change in mRNA expression was calculated using the comparative cycle threshold (CT) method using the following formula: fold change = 2−ΔΔCT, where 2 represents a constant reaction efficiency and ΔΔCT is defined as (CTtarget − CTreference/stimulated) − (CTtarget − CTreference/unstimulated). The reference value is equivalent to the CT value of L32 ribosomal protein mRNA, which was the housekeeping mRNA.

Intracellular cytokine staining

A total of 1–2 × 10⁶ lymphocytes was stimulated overnight in the presence of immunodominant H-2Kb binding AMQMLKETI, 9-mer Gag peptide
FIGURE 5. Systemic and mucosal tetramer-specific cytokine profile. BALB/c mice (4–5/group) were immunized I.N./I.N., I.N./i.m., and i.m./i.m. At 3, 7, and 14 days, prime-boost immunization and K\(^{d}\)Gag\(^{197–205}\)-positive single spleen and genitorectal node cells were assessed for their ability (by nested PCR) to produce one or more cytokine(s) at a given time. Data represent the percentage of splenocytes or genitorectal lymphocytes producing IFN-\(\gamma\), TNF-\(\alpha\), IL-4, IL-10, and/or IL-13 cytokines.

and then for a further 4–5 h in the presence of 2 \(\mu\)M monensin, and stained as described previously (20). After stimulation, cells were surface stained with anti-CD8 allophycocyanin or FITC and with anti-CD4 PerCP (BD Pharmingen). These cells were fixed and permeabilized before staining with anti-mouse IFN-\(\gamma\), FITC, TNF-\(\alpha\) PE, IL-2 allophycocyanin or IL-10 FITC (BD Pharmingen). Samples were acquired (60,000–100,000 events) on a four-color FACS Calibur flow cytometer (BD Biosciences), and results were analyzed using CellQuest Pro software (BD Biosciences). Unstimulated cell counts were used as the background control, and where appropriate these values were subtracted from each sample before plotting the data (see Fig. 5).

Statistics and analysis of data
Where appropriate, SE or SD was calculated and \(p\) values were determined using a two-tailed, two sample equal variance Student’s \(t\) test.

Results
Evaluating CTL responses generated by mucosal and systemic immunization regimes
The K\(^{d}\)Gag\(^{197–205}\)-specific CTL response was compared following AE FPV prime AE VV boost-immunized mice (\(n = 4–5\)) generated by either systemic (i.m./i.m.), mucosal (I.N./I.N.), and combination mucosal and systemic (I.N./i.m.) regimes14 days following the booster immunization (20). Intramuscular/i.m. and I.N./i.m. immunization regimes induced the highest number of K\(^{d}\)Gag\(^{197–205}\)-specific CTL as measured by IFN-\(\gamma\) ELISPOT assay (Fig. 1A). Interestingly, the highest mucosal responses were also observed with the I.N./i.m. regime (14). Similar results were obtained with tetramer staining (Fig. 1B).

Characterization of genitorectal lymph node and splenic K\(^{d}\)Gag\(^{197–205}\)-specific CD8\(^+\) T cell profiles over time
To assess how these HIV-specific CD8\(^+\) T cells behaved over time, AE FPV/AE VV prime-boosted mice were sacrificed at different time intervals, and the responses to the Gag K\(^{d}\)Gag\(^{197–205}\) were measured. Previously, we have observed peak mucosal T cell responses as early as 3 days following AE VV booster vaccination (20). Hence, we evaluated the total number of tetramer-positive CD8\(^+\) T cells at 3, 7, and 14 days after AE FPV/AE VV immunization (Fig. 1C). An increased proportion of CD8\(^+\) K\(^{d}\)Gag\(^{197–205}\)-specific CTL were found in the spleen compared with the genitorectal lymph nodes, with the greatest numbers being induced at days 7 and 14 with I.N./i.m. immunization (Fig. 1C).

Characterization of cytokine profiles of K\(^{d}\)Gag\(^{197–205}\)-positive genitorectal lymph node and splenic CD8\(^+\) T cells
To assess whether the tetramer-positive cells from the I.N./i.m. and i.m./i.m. regimes were functionally different, we compared the mRNA expression of ex vivo-derived splenic and genitorectal lymph node K\(^{d}\)Gag\(^{197–205}\)-specific CTL (Fig. 3) by single-cell multiplex RT-PCR. We examined these cells at days 3, 7, and 14 time points after AE VV booster immunization. The expression of IFN-\(\gamma\), TNF-\(\alpha\), IL-2, IL-4, and IL-13 mRNA for each single CTL was assayed using a nested PCR strategy (Table I).

At 3 days after prime-boost immunization or early stage of secondary response, K\(^{d}\)Gag\(^{197–205}\)-positive splenic CTL from the I.N./i.m. group elicited a cytokine expression profile IL-4 > IFN-\(\gamma\) > TNF-\(\alpha\) > IL-13 > IL-10 (Fig. 4A), whereas the i.m./i.m. regime showed >30% of the cells expressing the cytokine IFN-\(\gamma\), with a profile of IFN-\(\gamma\) > IL-4 > TNF-\(\alpha\) > IL-10 and no IL-13 (Fig. 4B). At day 3 after AE VV boost, a greater proportion...
of KdGag197–205-specific CTL generated after i.m./i.m. immunization expressed IFN-γ compared with those CTL generated after I.N./i.m. immunization. Expression of IL-13 mRNA was only observed in a small proportion of KdGag197–205-specific CTL derived from the I.N./i.m. immunization (Fig. 4, compare A and B).

By day 7 after secondary boost, similar frequencies of IFN-γ+ KdGag197–205-specific CTL were found after i.m./i.m. (Fig. 4C) and I.N./i.m. immunization (Fig. 4D) for both splenic and genitoreal lymph node populations. In contrast, the number of splenic and genitoreal lymph node-derived CTL producing TNF-α was significantly less after i.m./i.m. immunization compared with the I.N./i.m.-immunized group (Fig. 4, compare C and D). The hierarchy of mRNA expression within KdGag197–205-specific CTL from I.N./i.m. immunization was IFN-γ > IL-4 ≥ TNF-α > IL-10 > IL-13. There was an increase in the frequency of IL-13+ CTL at day 7 compared with day 3 after i.m./i.m. immunization (Fig. 4, compare B and D).

At day 14, similar proportions of KdGag197–205-specific CTL were IFN-γ+ (>80%) for all three immunization regimes. The frequency of TNF-α+ CTL decreased to <1% (compared with >10% at day 7) in the I.N./i.m.-immunized mice with little change in the frequency of TNF-α+ CTL from the i.m./i.m. regime (Fig. 4E). Interestingly, 14 days after booster immunization major differences were observed in the IL-10 mRNA expression in KdGag197–205 splenocytes obtained from the I.N./i.m. group (Fig. 4E), showing an increase in IL-10-producing cells to 45%, compared to 7 days <10% (Fig. 4C) or to the other two immunization regimes (Fig. 4F). Expression of low amounts of IL-10 by CD8+ T cells after I.N./i.m. poxviral prime boosting, but not i.m./i.m. regime, was also confirmed by intracellular cytokine staining and FACS analysis. IL-2 mRNA was not detected in KdGag197–205-specific CTL populations from any of the immunized groups.

Moreover, the expression profile of IL-4 did not alter significantly over time (prime only, 3, 7, or 14 days) in splenocytes and lymphocytes obtained from the I.N./i.m. and i.m./i.m. groups. In contrast, expression of IL-4 in the I.N./L.N. group was relatively low compared with the other two regimes. Data indicate that the poxviral prime-boost immunization can generate tetramer-positive as well as tetramer-negative CD8+ T cells that are able to constitutively express IL-4 mRNA. Whether this expression relates to protein production is yet to be determined.

The heterogeneity of cytokine mRNA expression was determined within single KdGag197–205-specific CTL was evaluated for all immunization regimes at the various time points after AE VV boosting (Fig. 5). The I.N./i.m. group showed increased frequency of

FIGURE 6. Granzyme B profile in tetramer-specific single T cells. BALB/c mice (4–5/group) were immunized I.N./i.m. (A and B) and i.m./i.m. (A). At 7 (A) and 84 (B) days prime-boost immunization, KdGag197–205-positive cells (■ and □ plus tetramer-negative (■) CD8+ splen and genitoreal node cells were single-cell sorted into 96 wells, and cDNA was synthesized as described in Materials and Methods. In each cell, the presence of IFN-γ, IL-4, and granzyme B mRNA transcripts were evaluated using nested PCR (total of 48 cells). Graph (A) represents I.N./i.m. (□), i.m./i.m. (■), and tetramer-negative cells obtained from I.N./i.m. (□). Graph (B) represents I.N./i.m. tetramer-positive splenocytes (■) and genitoreal nodes (□) at 84 days after boost.

FIGURE 7. Real-time PCR of total CD8+ T cells obtained from unimmunized, i.m./i.m., i.m./L.N., and I.N./I.N.-immunized mice. Fourteen days after AE poxvirus prime-boost immunization (n = 4–5 mice/group), negatively isolated CD8+ splenocytes were stimulated with 15-mer AE clade overlapping Gag peptide pool for 16–20 h and mRNA levels were measured by real-time PCR as indicated in Materials and Methods. The graphs represent the fold increases of IFN-γ (A), TNF-α (B), and IL-2 (C) in stimulated compared with unstimulated cells. Data are representative of three experiments.
CTL expressing at least two cytokine mRNAs compared with i.m./i.m. (Fig. 5). Notably, IFN-γ/TNF-α, IFN-γ/IL-10, TNF-α/IL-4, and IL-10/IL-4. These differences were more prominent in the genitoreal node populations than the splenocytes (Fig. 5). There was an increase in the frequency of KdGag197–205-specific CTL expressing multiple cytokine mRNAs by day 14 compared with earlier time points, with a higher frequency of CTL expressing multiple mRNAs in CTL derived from the I.N./i.m. and i.m./i.m. groups compared with the I.N./I.N. group.

Assessment of granzyme B profile in KdGag197–205-specific systemic and mucosal-immunized CTL

The expression of granzyme B mRNA was assessed for KdGag197–205-specific CTL at 7 and 84 days following I.N./i.m. and i.m./i.m. prime-boost immunizations (Fig. 6). The number of tetramer-positive cells producing granzyme B mRNA in the genitoreal lymphocytes from the I.N./i.m.-immunized animals was much higher (71%) than that found in splenocytes (38%) (Fig. 6). In contrast, i.m./i.m. immunization elicited higher granzyme B production in splenocytes (58%) than genitoreal lymphocytes (29%) (Fig. 6). The tetramer-negative population from the I.N./i.m.-immunized animals also showed a small proportion of cells producing granzyme B, where the expression was higher in mucosal cells than splenocytes (18 vs 6%) (Fig. 6a), probably reflect activated CTL with other specificities (i.e., to the vector).

Quantitation of regime-specific cytokine mRNA profiles in CD8+ T cells by real-time PCR

At 14 days following prime-boosting IL-2, IL-4, IL-6, IL-10, IL-13, IL-18, IFN-γ, and TNF-α, mRNA expression patterns were also measured in the “total HIV-specific CD8+ T cell population” after in vitro stimulation for 16–20 h with AMQMLKETI Gag peptide and cytokines IFN-γ and TNF-α were measured by intracellular staining. The FACS plots represent CD8+ T cells (gated on CD8+ T cells) expressing IFN-γ (A) and TNF-α (B). The values in the upper right quadrants indicate the percentage of CD8+ T cells producing IFN-γ or TNF-α, where corresponding unstimulated background value was subtracted. Note that only the i.m./i.m.-unstimulated group is represented to show the general background poststimulation. The y-axis indicate the CD8-allophycocyanin channel and x-axis the IFN-γ-FITC or TNF-α-PE channels. Data are representative of >3 experiments.

Identification of regime-specific cytokine profiles in T cells by intracellular cytokine staining

To determine whether the mRNA expression also correlated with the protein expression profiles, intracellular cytokine staining was performed as described in Materials and Methods. The data indicate that at 14 days, the IFN-γ production in stimulated CD8+ splenocytes was regime specific, showing i.m./i.m. ≥ I.N./i.m. > I.N./I.N. (Fig. 8A) expression profile after 16 h of stimulation with AMQMLKETI Gag peptide. Although the number of cells producing both TNF-α was higher in the I.N./i.m.-immunized group, no significant differences were observed between the other two groups (Fig. 8B). However, after overnight culture, a high background expression of TNF-α in both stimulated and nonstimulated cells was visible compared with the unimmunized group (Fig. 8B). Similar observations were made with TNF-α ELISPOT assays (C. Ranasinghe, unpublished observations), suggesting that the poxvirus regime enhances the overall TNF-α production in these T cells. Interestingly, none of these groups showed CD8+ T cells producing the cytokine IL-2 after overnight stimulation with peptide. This observation was further substantiated by IL-2 ELISPOT assay, which showed extremely low numbers of T cells producing IL-2 upon stimulation with the same peptide pool (C. Ranasinghe, unpublished observations).

Discussion

Recently, several studies have indicated that poxvirus prime-boost immunization strategies can generate robust T cell immunity to vaccine Ags in animal models (2, 33). Our recent findings indicate that of the mucosal and systemic immunization regimes tested, the I.N. AE FPV prime i.m. AE VV boosting can generate the highest mucosal and systemic CTL immune responses in BALB/c mice (20). In this study, we have observed that in I.N./i.m. and i.m./i.m.-immunized animals, the level of KdGag197–205-specific systemic T cells peaked at 14 days after the boost, although Ag-specific lymph node CTL responses in the I.N./i.m. and i.m./i.m.-immunized groups considerably differed over time. These
observations further reveal that CTL responses generated by mucosal and systemic immunizations may be fundamentally different. To confirm this hypothesis, we evaluated whether the different immunization regimens induced qualitatively different CTL responses to the same Ag. We first measured the avidity of K\textsuperscript{\textalpha}Gag197–205-specific CTL by tetramer dissociation. Interestingly, our tetramer dissociation data also illustrate that pure mucosal immunization can give rise to tetramer-positive CD\textsuperscript{8} T cells of higher avidity than a pure systemic immunization regime to the same Gag Ag. Although the I.N./i.m. immunization elicited CTL populations with similar avidity to that of I.N./I.N. immunization at the initial stages of immune response, the profile changed to a more intermediary state over time, most likely due to the systemic component of this regime. Therefore, our current data suggests that the vaccine regime (i.e., systemic vs mucosal delivery) can influence not only the magnitude (20) but also the quality of immune response generated, showing a hierarchical T cell avidity profile of I.N./I.N. > I.N./i.m. > i.m./i.m. Regulation of the Ag concentration in vitro has been shown to generate CTLs with distinct functional avidities and viral clearance abilities (21, 34). Moreover, recently it has been documented that anatomical location (i.e., spleen vs mucosa) can play an inductive role in memory T cell differentiation (35). We postulate that the differences in T cell avidity observed could be linked to the 1) mode of Ag uptake and presentation by nasopharynx-associated lymphoid tissue via M (microfold) cells and dendritic cells, 2) initial Ag strength at the priming site, and 3) milieu they induce (34, 36). In summary, the limited Ag dose at the priming site resulted in the selection of high-avidity CTL.

It has been shown that one of the best evaluation methods of recently activated T cells is the detection of cytokines (37). Hence, to test whether the differences in T cell avidity observed in these immunization regimes had any correlation with the cytokines they produced, single-cell cytokine profiling of these CD\textsuperscript{8} T cells were performed. Early after I.N./i.m. immunization, IL-4 mRNA was more prevalent compared with IFN-\gamma mRNA in Ag-specific CTL, and another type 2 cytokine, IL-13, was also detected. In humans, IL-4 and IL-13 genes are located in tandem within a cluster of cytokine genes on the same chromosome (38). Hence, these genes could be regulated by similar transcription factors or common distal promoters, which could explain the detection of both of these Th2 cytokines in HIV-specific tetramer-positive CD\textsuperscript{8} T cells (39). The results also indicated that the cytokine profiles were regime and time dependent, and the IFN-\gamma production in these cells may be controlled by the interplay of IL-4/IL-13 and IL-2 expression. At 14 days, tetramer-positive T cells from the I.N./I.N.-immunized regime expressed low levels of IL-4 and these cells were found to be higher in avidity, although the I.N./i.m. and i.m./i.m.-immunized groups were found to constitutively express IL-4 mRNA (\textlesssim20%) and generated lower avidity T cells compared with the I.N./I.N. group. These observations suggest that the Th2 cytokine milieu (IL-4/IL-13) may impact the avidity of these T cells.

Current results clearly indicate that the tetramer-positive T cell population is heterogeneous for cytokine mRNA profiles. Hence, the IL-4-producing cells could be a subset of CD\textsuperscript{8} T cells that have a unique function, which could be inherent to poxvirus infection. We have also identified a subset of CD\textsuperscript{8} T cells that express IL-4 after a natural mouse-pox infection (C. Ranasinghe and I. A. Ramshaw, unpublished observations). The notion that IL-4 production by Ag-specific CTL is pathogen dependent is supported by the finding that influenza A virus-specific CTL do not express IL-4 (S. Turner, personal communication). Previous studies by our group have shown that an expression of mouse IL-4 by recombinant ectromelia virus generates immune responses that lack virus-specific CTL activity in mice (40). In another study, inhibition of IL-13 expression was shown to enhance protection against viral infection (41). Hence, we postulate that 1) the induction of IL-4/IL-13 expression in CD\textsuperscript{8} T cells could be a mechanism that has evolved by particular viruses such as poxviruses to evade the host immune system (42), and 2) some of the cytokine/chemokine inhibitors encoded by poxviruses (43, 44) may be responsible for diverting CD\textsuperscript{8} T cells to produce IL-4. These factors should be taken into consideration when poxviruses are used as vaccine vectors.

Kelso and Groves (45) have demonstrated that under type 2 polarizing conditions in an in vitro culture system, CD\textsuperscript{8} T cells are able to express IL-4. Recently, they have shown that these IL-4-producing T cells can be subdivided into CD\textsuperscript{8}\textsuperscript{high} and CD\textsuperscript{8}\textsuperscript{low} populations according to the type 1 or 2 cytokine milieu and the weak or strong Ag pressure they encounter, respectively, during development (46). Compared with the CD\textsuperscript{8}\textsuperscript{high} T cells, the CD\textsuperscript{8}\textsuperscript{low} T cells also elicited a reduced cytokytic activity (47). IL-4-producing CD\textsuperscript{8} T cell subsets that show reduced CTL activity was also reported in HIV-1-infected individuals (48). In this study following the first I.N. or i.m. AE-FPV encounter, the primary tetramer-positive CD\textsuperscript{8} T cells were found to produce IL-4 or/and IFN-\gamma (data not shown). These findings further substantiate the fact that naive CD\textsuperscript{8} T cells can undergo changes to suit the environment and hence steer subsets of cells to coexpress type 2 cytokines, in contrast to the well-accepted CD\textsuperscript{8} polarization theory.

Tetramer-positive T cells obtained from all three immunization regimes showed a lack of cytokine IL-2 mRNA transcripts. Nevertheless, when total CD\textsuperscript{8} T cells from immunized animals were stimulated with the full-length Gag 15-mer overlapping peptide pool (which also contained the immunodominant AMQMLKETIGag sequence) for 16–20 h, enhancement of IL-2 mRNA was detected in a regime-dependent manner; I.N./I.N. > I.N./i.m. > i.m./i.m. However, IL-2 protein was undetected at this time point. It has been recognized that kinetics of IL-2 expression upon external stimuli is relatively different to other cytokines such as IFN-\gamma (F. Shannon, personal communication). Our recent observations also reveal that after 15-mer overlapping Gag peptide pool stimulation, much higher levels of IL-2 and TNF-\alpha mRNA can be detected at 2–3 h compared with 16–20 h (C. Ranasinghe unpublished data). This again supports the notion that cytokine expression should be evaluated in a time-dependent manner because kinetics are known to depend upon the length, strength, and dose of Ag exposure (37, 49) plus the number of cells producing the cytokine (50). Intriguingly, the expression of IL-2 has also been implicated in T cell avidity. It has been shown that low Ag exposure favor IL-2 expression by high-avidity CD\textsuperscript{8} T cells (22), whereas high Ag dose was associated with CD\textsuperscript{8}\textsuperscript{low} T cells that expressed IL-4 (46). We observed little IL-2 production by Ag-specific CTL after various immunization regimes and increased IL-4 production. Given the fact that high Ag load induces low-avidity CTL, we postulate that the systemic delivery (i.m./i.m.) of recombinant poxvirus may possibly create a high Ag milieu in vivo, thus skewing the relative immune response toward low avidity CD\textsuperscript{8} cell subsets expressing IL-4 over IL-2 compared with mucosal delivery.

According to the immunization regimes tested, the number of tetramer-positive cells producing granzyme B differed in the mucosal and systemic compartments. The genitocutaneous cells from I.N./i.m. immunization mice showed twice the number of cells producing granzyme B compared with mice immunized by the pure systemic immunization regime, whereas i.m./i.m.-immunized animals elicited higher proportions of splenocytes producing granzyme B. Previously, we have also shown that i.m. recombinant
DNA prime/intrarectal rFPV boosting can significantly reduce plasma viremia against a pathogenic vaginal SHIV(SF162P3) challenge compared with i.m. recombinant DNA/i.m. rFPV immunization regime (19). Recently, Belyakov et al. (7) have also shown that mucosal immunization can protect rhesus macaques from a pathogenic intrarectal SHIV-ku2 challenge. The current observations further substantiate that the mucosal immunization can induce higher numbers of iliac lymph node cytotoxic CD8+ T cells compared with a systemic immunization and this may be reflective of their capacity to resist virus challenge at this site. Interestingly, only a small number of CD8+ T cells are detected in the present study because the presence of IL-4 is thought to produce CD8+ T cells of reduced cytolytic activity (52). Hence, the low or lack of IL-2 and the presence of IL-4 in these tetramer-positive cells or 2) differential expression kinetics of perforin compared with granzymes could also account for the low perforin expression profile in these cells. The fraction of tetramer-negative CD8+ T cells producing granzyme B and/or TNF-γ is not unexpected because this population is also able to present other HIV-specific CTL with specificities to other Gag/Pol epitopes or to vector, even though the Gag-specific tetramer tested (AMQMLKETI) is known to be the dominant BALB/c (H-2b) tetramer (29).

A larger proportion of K5Gag197-205-specific splenic CTL generated 14 days following i.n./i.m. immunization, expressed IL-10 mRNA that was also confirmed by FACS analysis. Although i.n./i.n.-specific cells did not show any IL-10 mRNA expression, these cells following Gag peptide stimulation were able to express IL-10 protein (data not shown). In contrast, neither IL-10 mRNA nor protein were detected in CD8+ T cells obtained from i.m./i.m.-immunized mice. These observations suggest that the IL-10 expression is most likely related to the mucosal delivery of rFPV, which merits further investigation.

In summary, current observations suggest that 1) route of delivery, 2) uptake and mechanisms of Ag presentation at these sites and their environment, 3) initial Ag dose and animal encounters in vivo, and 4) the inherent qualities of vaccine vectors and cytokines/serine proteases they induce can greatly influence the quality of immune responses generated by a vaccine. Hence, deciphering the molecular mechanisms governing these properties may enable the better design of HIV-1 vaccines in the future.

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References


