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A New Model for CD8⁺ T Cell Memory Inflation Based upon a Recombinant Adenoviral Vector

Beatrice Bolinger,* Stuart Sims,* Geraldine O’Hara,* Catherine de Lara,* Elma Tchilian,* Sonja Firner,† Daniel Engeler,‡ Burkhard Ludewig,§ and Paul Klenerman*

CD8⁺ T cell memory inflation, first described in murine CMV (MCMV) infection, is characterized by the accumulation of high-frequency, functional Ag-specific CD8⁺ T cell pools with an effector-memory phenotype and enrichment in peripheral organs. Although persistence of Ag is considered essential, the rules underpinning memory inflation are still unclear. The MCMV model is, however, complicated by the virus’s low-level persistence and stochastic reactivation. We developed a new model of memory inflation based on a β-galactosidase (βGal)–recombinant adenovirus vector. After i.v. administration in C57BL/6 mice, we observed marked memory inflation in the βGal₄₉₇ epitope, whereas a second epitope, βGal₄₉₇, undergoes classical memory formation. The inflationary T cell responses show kinetics, distribution, phenotype, and functions similar to those seen in MCMV and are reproduced using alternative routes of administration. Memory inflation in this model is dependent on MHC class II. As in MCMV, the only inflating epitope showed immunoproteasome independence. These data define a new model for memory inflation, which is fully replication independent, internally controlled, and reproduces the key immunologic features of the CD8⁺ T cell response. This model provides insight into the mechanisms responsible for memory inflation and, because it is based on a vaccine vector, also is relevant to novel T cell–inducing vaccines in humans. The Journal of Immunology, 2013, 190: 4162–4174.

The induction of potent CD8⁺ T cell responses is an important goal for vaccine strategies against major pathogens and tumors, and defining the induction and maintenance of CD8⁺ T cell populations has been the focus of many studies. Many vaccines and natural infections provoke a strong effector-memory response in the early phase where the Ag is present, but once the nonpersistent vector or pathogen is eliminated, CD8⁺ T cell memory contracts to a “central” memory pool, concentrated in secondary lymphoid organs (1). Much attention has been paid to the situation where Ag is not eliminated and persists at a high level, such as in chronic lymphocytic choriomeningitis virus infection (2, 3). Here CD8⁺ T cell function is lost over time such that memory is functionally impaired or even lost altogether, a phenomenon known as CD8⁺ T cell exhaustion (3). However, exhaustion is not the only outcome of repetitive Ag stimulation. Studies of low-level persistent viruses such as CMV have revealed a “mirror image” response to that seen with exhaustion, where T cell responses may be enhanced numerically over time and maintain strong functionality; this has been termed CD8⁺ T cell memory “inflation” (4). Understanding this phenomenon is relevant not only to disease pathogenesis and the biology of immunologic memory, but it also plays a role in vaccine design, where such populations can be harnessed to provide protection against certain chronic viral infections, such as hepatitis C virus (HCV), HIV, and CMV (5).

CD8⁺ T cell memory inflation was first observed in murine CMV (MCMV) infection (4, 6), and similar findings are observed in human CMV (HCMV) infection. In CD8⁺ T cell memory inflation, responses to a single epitope may become very large and are maintained at high levels throughout life (4, 7, 8). CMV-specific inflating CD8⁺ T cells typically show an extreme of the “effector-memory” phenotype (CD2⁷⁺, CD2₈⁻, CD62L⁻, CD127⁻, and IL-7²⁻) (9). Cells remain functional and respond vigorously to viral rechallenge, providing protection (4). They are located in the spleen and the periphery, particularly in organs such as liver and lung. It is unclear yet what drives the selection of these “inflationary” epitopes, but it has been shown that it is independent of initial immunodominance (10) and viral gene-expression patterns (11). In MCMV, for example, only one of two epitopes from the same protein is associated with an “inflationary” response (12, 13). This suggests factors other than the kinetics of the viral gene expression could be involved; in particular, recent data reveal immunoproteasome independence is associated with inflation and suggest a significant role for Ag processing in epitope selection during memory development (14).

However, in the MCMV model, many questions remain unanswered. The location and the nature of the cells that process and present Ag, and eventually sustain CD8⁺ T cell responses are still elusive. Likewise, it is not known for how long Ag needs to be presented to produce such a sustained CD8⁺ T cell response. It appears that repetitive Ag exposure is an essential factor driving memory inflation, as suggested by analysis of phenotype and activation status (4, 10), and adoptive transfer into naive hosts (9).
Recent work has revealed that ongoing production of infectious MCMV is, however, not an absolute requirement (15, 16). Critically, MCMV is a complex model virologically, with a very large genome containing numerous immunoevasins, long-term low-level persistence, and stochastic reactivation at diverse sites. Thus, a simpler and more tractable system to investigate these questions would be desirable.

The phenomenon of memory inflation is not exclusive to CMVs because it is also observed in other viral infections (17–20). However, it has not been described after immunization with nonreplicating vaccine vectors. Recombinant viral vectors for 

### Materials and Methods

#### Ethics statement

Mouse experiments in Oxford were performed according to U.K. Home Office regulations (project license no. PPL 302235 and 302744), and after review and approval by the local Ethical Review Board at the University of Oxford. Experiments in St. Gallen were performed in accordance with Swiss Kanontal and federal legislations, and were approved by the Veterinary Officer of the Kanton of St. Gallen.

#### Adenoviral vector

Recombinant adenovirus expressing the βgal protein under the control of the HCMV IE1/IE2 promoter-enhancer (MCMV-LacZ RM427) (32) was used. MCMV-LacZ was propagated and titered on NIH 3T3 cells (European Cell Culture Collection, Porton Down, U.K.) and injected i.v. at a dose of 2 × 10^6 PFU.

Recombinant Vaccinia expressing the βgal protein (Vacc-LacZ) (33) was used. UV-LacZ was propagated and titered on BSC-40 cells, and injected i.p. at a dose of 2 × 10^6 PFU.

#### Mice

Male and female C57BL/6 mice were obtained from Harlan (Blackthorn, U.K.). MHC class II (MHC-II) knockout (KO) (34) mice were on the C57BL/6 background. TCR transgenic Bg1 mice that express a TCR recognizing the H2-Kb–restricted βgal96–103 peptide on >95% of their CD8+ T cells have been described previously (35). Bg1 mice have been generated by Dr. Nicholas P. Restifo (National Cancer Institute, Bethesda, MD) and were kindly provided by Dr. Chris Norbury (Penn State Milton S. Hershey College of Medicine, Department of Microbiology and Immunology). Bg1 mice were crossed with C57BL/6-SJL mice expressing the congenic marker Ly5.1 (CD45.1) kindly provided by Dr. Kevin Maloy (Dunn School, University of Oxford, Oxford, U.K.). Transgene expression was monitored by staining of blood cells with anti-β7 by flow cytometry. LMP7 KO mice (36) on the C57BL/6 background were kindly provided by Dr. Marcus Groettrup (Division of Immunology, Department of Biology, University of Constance, Konstanz, Germany). All animals were kept under conventional conditions in individually ventilated cages and fed with normal chow diet. Experiments were carried out with age- and sex-matched animals.

#### Peptides

The βgal96–103 (DAPYTNV) (37), the βgal97–104 (ICPMYAR) (38), and the M45 (HGGNASFI) (39) peptide were purchased from Mimotopes (Melbourne, VIC, Australia).

#### Antibodies


Flow cytometry

For flow cytometry, single-cell suspensions were generated from the indicated organs, and 1 × 10^6 cells were incubated with the indicated mAb at 4°C for 20 min. For PBL samples, erythrocytes were lysed with FACS Lysing Solution (BD Pharmingen). Cells were analyzed by flow cytometry using a BD LSR II flow cytometer and FlowJo software, gated on viable leukocytes using the live/dead fixable near-infrared dead cell stain kit from Invitrogen (Paisley, U.K.).

Isolation of liver and lung lymphocytes

Perfused livers were smashed through a cell strainer (BD), and lymphocytes were purified by a Percoll (GE Healthcare) gradient centrifugation. Lungs were minced with razor blades and incubated in PBS containing 60 U/ml DNase (AppliChem) and 170 U/ml collagenase II (Life Technologies) at 37°C for 45 min. Cell aggregates were dispersed by passing the digest through a cell strainer (BD).

#### Intraacellular cytokine staining

Spleens, livers, and lungs were removed at indicated time points after immunization with 2 × 10^6 PFU Adeno-LacZ. Single-cell suspensions of 2 × 10^6 lymphocytes were incubated for 2 h at 37°C in 150 µl culture medium (RPMI) containing 5% FCS in 96-well, round-bottom plates. The cells were stimulated with PMA (50 ng/ml) and ionomycin (500 ng/ml) as a positive control or left untreated as a negative control. Peptide-specific responses were analyzed after cells were stimulated with 10^-6 M βgal96–103 (DAPYTNV) or βgal97–104 (ICPMYAR) peptide (both from Mimotopes). After 2-h stimulation at 37°C, 50 µl GolgiPlug (1 µl/ml final concentration) from BD Bioscience was added and cells were incubated for another 4 h at 37°C. Cells were fixed with the Fix/Perm solution (BD Biosciences) and stained with PE-conjugated anti-β7 and Cy7-conjugated anti-γ-IFN. Lungs were stained with PE-conjugated anti-β7 and Cy7-conjugated anti-γ-IFN.
Construction of tetrameric MHC-I–peptide complexes

MHC-I monomers complexed with βgal (H-2Kb) were produced as previously described (40) and tetramerized by addition of streptavidin-PE (BD Bioscience) or streptavidin-allophycocyanin (Invitrogen). At the indicated time points postinfection, organs were removed and single-cell suspensions were prepared. Aliquots of 1 × 10^6 cells or 100 μl blood were stained using 50 μl of a solution containing tetrameric class I–peptide complexes at 37°C for 20 min followed by staining with mAbs at 4°C for 20 min. Absolute cell counts were determined by counting leukocytes in an improved Neubauer chamber.

In vivo cytotoxicity

Single-cell suspensions from spleens of C57BL/6 mice were subjected to hypotonic RBC lysis. Before injection, half of the cells were loaded with 10^7 M βgal497 in PBS or 20 μl CellTrace violet in PBS or 0.5 μM CellTrace violet (negative) for 20 min at 37°C. Cells were washed and resuspended in PBS at a concentration of 5 × 10^6 spleenocytes/ml in each group. Recipient B6 mice were injected i.v. with 10^7 βgal497 spleenocytes in 200 μl PBS. Twelve hours later, blood, spleen, liver, and lungs were harvested and single-cell suspension generated. Cells were analyzed by flow cytometry using a BD LSR II flow cytometer and FlowJo software, and gated on viable leukocytes using the live/dead fixable near-infrared dead cell stain kit from Invitrogen. The ratio of killed cells to control cells was calculated to obtain the percentage of specific killing.

Extraction and quantification of LacZ genome copy numbers in tissue

Tissues were homogenized using a MagNA Lyser instrument (Roche Diagnostics). While DNA was isolated using the manufacturer’s Pure PCR Template Preparation Kit (Roche Diagnostics). Real-time quantitative PCR was performed using a LightCycler 480 Real-Time PCR System (Roche Diagnostics) and the LightCycler 480 probes master reaction mix (Roche Diagnostics), according to the manufacturer’s protocol. Data analysis was performed with LightCycler 480 Software (Roche Diagnostics). Oligonucleotides were purchased from Eurofins MWG Operon (Ebersberg, Germany) and oligonucleotide and LacZ probes were compared using the BLAST search engine. Oligonucleotides were used as primers for real-time quantitative PCR: 5'-CGCGGATG- GAAGACCAGC-3' and 5'-CGA AGC GCC CCT GTA AAC-3'. The following oligonucleotides were used as probes: 5'-CAG TCT TGG CGG TTT CGC TAA-3' and 5'-TAC TGC CAG GGC TTT CGT CAG-3'. Probe 1 carried a 3' FAM reporter, and probe 2 was Cy5 labeled at the 5' end. Thermal cycling started with HotStarTaq activation during 15 min at 95°C. Thereafter, 50 cycles of amplification were run consisting of 15 s at 95°C, 20 s at 60°C, and 20 s at 72°C. A negative control, containing reagents only, and serial dilutions of plasmid containing the specific LacZ sequence were included in each run to generate a standard curve. The concentrations of the plasmid dilutions were 280,000, 28,000, 2800, 280, and 28 copies per reaction. LacZ DNA concentration in the unknown samples was calculated using the data from the standard curve. Each sample was measured as a triplicate and the average concentration was used for calculation. Final copy numbers per microgram DNA were calculated.

Extraction of RNA and of LacZ-specific mRNA by quantitative real-time PCR

Organs were homogenized in TRIzol (Sigma-Aldrich, St. Louis, MO) using a MagNA Lyser instrument (Roche Diagnostics). RNA was isolated by isopropanol precipitation, washed with ethanol 70%, and resuspended in diethylpyrocarbonate–water. RNA was DNase treated with DNase I (Invitrogen) and subjected to RT-PCR using 2 μg purified RNA. For RT-PCR, the high-capacity cDNA archive kit from Applied Biosystems (ABI PRISM, Warrington, U.K.) was used according to the specifications of the manufacturer to generate cDNA from RNA samples. Quantitative real-time PCR was performed using a LightCycler 480 Real-Time PCR System (Roche Diagnostics) and the LightCycler 480 probes master reaction mix (Roche Diagnostics) following the manufacturer’s protocol. Data analysis was performed with LightCycler 480 Software (Roche Diagnostics). Oligonucleotides were purchased from Eurofins MWG Operon (Ebersberg, Germany). The following oligonucleotides from LacZ sequences were used as primers for quantitative real-time PCR: 5'-GGCTGGATGAAAGCCAGC-3' and 5'-GAAGCGGCCTGTAAC-3'. The following oligonucleotides were used as probes: 5'-CAGTCTGGCGGCTCG-3' (probe 1). Probe 1 carried a 3' FAM reporter, and probe 2 was Cy5 labeled at the 5' end. Thermal cycling started with HotStarTaq activation during 15 min at 95°C. Thereafter, 50 cycles of amplification were run consisting of 15 s at 95°C, 20 s at 60°C, and 20 s at 72°C. A negative control, containing reagents only, and serial dilutions of plasmid containing the specific LacZ sequence were included in each run to generate a standard curve. The concentrations of the plasmid dilutions were 280,000, 28,000, 2800, 280, and 28 copies per reaction. LacZ mRNA concentration in the unknown samples was calculated using the data from the standard curve. Each sample was measured as a triplicate and the average concentration was used. Final copy numbers were calculated per microgram total RNA.

Adaptive transfer of TCR transgenic T cells

Single-cell suspensions from spleens of Ly5.1+ B6g1 mice were subjected to hypotonic RBC lysis and stained with CFSE (Invitrogen). A maximum concentration of 2.5 × 10^6 cells/ml was incubated in 5 μM CFSE in PBS for 10 min at 37°C. Cells were washed twice with ice-cold PBS and resuspended in PBS at a concentration of 1 × 10^6 spleenocytes/ml. Recipient B6 mice were injected i.v. with 2 × 10^7 B6g1-Ly5.1+ spleenocytes in 200 μl PBS.

Statistical analysis

To evaluate statistically significant differences, we used the unpaired two-tailed Student test. The p values <0.05 were considered statistically significant. Statistical data analysis was performed using GraphPad Prism version 5.0a (GraphPad Software, San Diego, CA).

Results

Epitope-specific CD8+ T cell memory inflation after AdV immunization

Immunization of C57BL/6 mice with the replication-deficient Ad-LacZ induced a strong CD8+ T cell response in blood on day 21 against two distinct βgal epitopes (βgal497 and βgal96). On day 300, βgal497-specific CD8+ T cells had contracted and were detectable at low levels only, whereas the βgal96-specific CD8+ T cell population had increased further (Fig. 1A).

To better define the kinetics of the βgal-specific CD8+ T cell responses induced by Ad-LacZ, we inoculated C57BL/6 mice i.v. with a single dose of Ad-LacZ and tracked longitudinally. Lymphocytes from blood, spleen, liver, lung, and lymph nodes (LNs) were isolated at different time points, and βgal-specific CD8+ T cells were quantified by staining with MHC-I tetramers. βgal96-specific CD8+ T cells showed memory inflation with up to 20% specific cells on day 21, followed by a continued increase over time to 30% on day 100 in blood (Fig. 1B). These cells were further enriched in tissues such as spleen, liver, and lung on day 100 (Fig. 1C). As in blood, in these organs, the βgal96-specific CD8+ T cell population was maintained over time (Fig. 1D).

In contrast with βgal96-specific CD8+ T cells, tetramer staining for βgal497-specific CD8+ T cells revealed only low levels of tetramer+ CD8+ T cells on day 100 in spleen, liver, and lung (Fig. 1C). The initial expansion phase was followed by contraction and classical stable memory at low but detectable levels over time (Fig. 1D). When data were displayed as absolute numbers of Ag-specific T cells per organs, comparable results were obtained (Fig. 1E). On day 200, the total amount of βgal96-specific CD8+ T cells in spleen and liver was >25 times higher than the amount of βgal497-specific CD8+ T cells, whereas in the lung, it was 50 times more, the latter two indicating a major redistribution of βgal96-specific CD8+ T cells to peripheral organs.

Only low frequencies of βgal96- and βgal497-specific CD8+ T cells were found in LNs (inguinal LN; βgal96-specific CD8+ T cells: day 21 = 0.6 ± 0.1%, day 50 = 0.4 ± 0.1%, day 100 = 0.4 ± 0.1%; βgal497-specific CD8+ T cells: day 21 = 0.3 ± 0.1%, day 50 = 0.09 ± 0.03%, day 100 = 0.02 ± 0.01%), whereas βgal96-specific CD8+ T cells did not inflate, as observed in MCMV infection (10, 41). CD8+ T cell memory inflation is not restricted to the i.v. route, but is confined to the vector.

It has been shown previously that the localization of the inoculum of AdVs determines the quality of CD8+ T cell responses (26).
Thus, to identify whether memory inflation in the Ad-LacZ model is restricted to the i.v. route, we evaluated the β-gal-specific CD8+ T cell response after i.v. and i.d. Ad-LacZ injection in blood of C57BL/6 mice. We performed tetramer staining for the inflating (β-gal96) and the noninflating epitope (β-gal497; Fig. 2A). Interestingly, exactly the same pattern for both the β-gal96- and β-gal497-specific CD8+ T cell response is seen after i.v. and i.d. immunization. Although the β-gal96-specific response was significantly reduced after i.d. immunization compared with i.v., CD8+ T cell maintenance was not impaired, and β-gal96-specific CD8+ T cells clearly showed memory inflation in this setting. This is even better illustrated looking at the inflationary potential of the CD8+ T cell responses, by considering the day 100 to day 21 ratio of tetramer+ cells (Fig. 2B). This ratio is used to distinguish responses where
Inflationary potential expressed by the ratio of percentage of tetramer+ 100, which do not inflate, LacZ, and expansion of time points. Mean percentage of tetramer+ cells within the CD8+ compartment is indicated (n = 7; data from two independently performed experiments). (B) Inflationary potential expressed by the ratio of percentage of tetramer+ CD8+ T cells from days 100 to 21 in C57BL/6 mice after i.v. and i.d. immunization for both βgal-specific CD8+ T cells. These characteristics are typical for an Ag-experienced effector-memory CD8+ T cell population.

We next examined the expression of these markers on βgal96-specific inflammatory CD8+ T cells, βgal497-specific, and total CD8+ T cells in blood, spleen, liver, and lung up to day 200 after immunization (Fig. 3B; Supplemental Fig. 1C–F). We demonstrated that βgal96-specific inflammatory CD8+ T cells barely changed their phenotype over time. They displayed a comparable effector-memory phenotype (CD62Llo, CD28lo, IL-7Rα, KLRG1hi, NKG2A/Dhi) from day 21, which is maintained up to day 200 after immunization. In contrast with these data, βgal497-specific CD8+ T cells acquired a divergent phenotype after contraction. This had features of a central memory pool (CD62Lhi, CD27hi, IL-7Rα, KLRG1lo), especially in the spleen and blood. They were also low in expression on NKG2D and NKG2A (Fig. 3B; Supplemental Fig. 1C–F).

Importantly, βgal497-specific CD8+ T cells after i.d. injection displayed an identical effector-memory phenotype on days 21, 50, and 100 in blood as that seen after i.v. immunization (Supplemental Fig. 2C).

We also went on to test the impact of inoculation on induction of memory and phenotype via alternative routes such as s.c. and i.m. We noted that βgal96-specific CD8+ T cells do not inflate numerically after s.c. injection of Ad-LacZ, although a distinction between the kinetics of the βgal497-specific CD8+ T cells and βgal96-specific CD8+ T cells could still be observed. However, the generation of the effector-memory phenotype associated with the βgal96-specific CD8+ T cells was clear in all cases and independent of the route of immunization (Supplemental Fig. 2).
phenotype and the inflationary \(\beta_{\text{gal97}}\)-specific CD8\(^+\) T cell population, with progression toward an effector-memory phenotype, identical to that seen in MCMV infection (4, 9, 10, 16, 41) and independent of the route of injection. Interestingly, this is true for lymphocytes from blood, spleen, liver, and lung, but not from LNs. In LNs, the fraction of \(\beta_{\text{gal96}}\)-specific cells that displayed a \(T_{\text{CM}}\) phenotype was much higher, with >30% (data not shown). This impact through the anatomic site was also reported after MCMV infection (10, 41).

\(\beta_{\text{gal95}}\)-specific CD8\(^+\) T cells retain functionality and show rapid acquisition and maintenance of cytotoxicity

We next assessed the functionality of the “inflating” memory population. Intracellular staining for IFN-\(\gamma\) and TNF-\(\alpha\) after peptide stimulation revealed that inflationary \(\beta_{\text{gal95}}\)-specific CD8\(^+\) T cells efficiently secreted effector cytokines (Figs. 4, 5A, 5B). Indeed, both sets of \(\beta_{\text{gal95}}\)-specific memory cells are strong IFN-\(\gamma\) and TNF-\(\alpha\) producers upon stimulation with the cognate peptide. Whereas IFN-\(\gamma\) and TNF-\(\alpha\) secretion on day 21 is comparable for both \(\beta_{\text{gal95}}\)-specific populations, inflationary CD8\(^+\) T cells, especially in peripheral organs, dominated cytokine secretion in the memory phase (Figs. 4, 5A, 5B).

Furthermore, staining for IFN-\(\gamma\), TNF-\(\alpha\), and LAMP-1 revealed that \(\beta_{\text{gal95}}\)-specific inflationary CD8\(^+\) T cells were polyfunctional. On day 100 postimmunization, most of the IFN-\(\gamma\)-\(\gamma\) CD8\(^+\) T cells in spleen, liver, and lung were also positive for LAMP-1, indicating that they had degranulated and released effector molecules. Many IFN-\(\gamma\)-producing, LAMP-1\(^+\) inflationary CD8\(^+\) T cells additionally secreted TNF-\(\alpha\). This pattern of functionality was seen at all time points measured (Fig. 5A, 5B). Overall, if we consider the difference in the amount of \(\beta_{\text{gal96}}\) and \(\beta_{\text{gal97}}\)-specific CD8\(^+\) T cells, calculating the ratio of IFN-\(\gamma\) or TNF-\(\alpha\)-producing cells to tetramer\(^+\) cells, although both populations are clearly functional, \(\beta_{\text{gal97}}\)-specific CD8\(^+\) T cells are stronger IFN-\(\gamma\) and TNF-\(\alpha\) producers on a per-cell basis (data not shown). Furthermore, this ratio also revealed a higher number of IFN-\(\gamma\)- and TNF-\(\alpha\)-producing CD8\(^+\) T cells compared with \(\beta_{\text{gal97}}\)-specific CD8\(^+\) T cells after stimulation with \(\beta_{\text{gal97}}\)-peptide. We suggest that the \(\beta_{\text{gal97}}\)-tetramer may bind specific T cells with a relatively low avidity; hence, the frequency of tetramer-specific CD8\(^+\) T cells might be underestimated compared with the true frequency. Alternatively, there may be binding to distinct MHC molecules. Both alternatives will be assessed further in future studies.

We next assessed the killing capacity of the \(\beta_{\text{gal95}}\)-specific CD8\(^+\) T cells, using an in vivo cytotoxicity assay. \(\beta_{\text{gal97}}\)-peptide–pulsed target cells were efficiently killed in vivo 12 h after adoptive transfer into day 21, 50, and 100 immune mice. This is seen not only in spleen and blood (Fig. 5C), but also in peripheral organs such as liver and lung (Fig. 5D) at all time points, indicating that inflationary CD8\(^+\) T cells retain their cytotoxic capacity. In comparison, \(\beta_{\text{gal97}}\)-peptide–pulsed target cells were killed in a much lower degree, especially if transferred into day 100 mice.

Overall, although \(\beta_{\text{gal95}}\)-specific CD8\(^+\) T cells show evidence of repeated Ag exposure, they are not exhausted and remain functional, even at day 100 after immunization.

Low-level Ag persistence enables CD8\(^+\) T cell memory inflation

Compared with MCMV infection, the Ad-LacZ model is virologically simple. There is no viral replication, which clearly facilitates tracking the virus, and both epitopes are generated from a single gene product.

To establish whether viral genome persists, we performed quantitative real-time PCR. LacZ DNA copy numbers per microgram total DNA were assessed in spleen, liver, lung, and hepatic LNs (hLNs) at different time points after Ad-LacZ immunization. On day 300, viral genome was still found in spleen, liver, and lung, but not in hLNs (Fig. 6A).

Next, we addressed whether the transgene was still expressed at late time points. To do this, first, quantitative real-time PCR for...
LacZ mRNA was performed. LacZ mRNA could only be quantified in liver and draining LNs (hLNs) around day 2 after immunization; thereafter, only low levels of specific mRNA were detected, but below the level of quantification (Fig. 6B).

Although Ag was not detectable on the RNA level, the effector phenotype of inflationary memory T cells strongly suggests continuous transgene exposure, most likely through low-level Ag expression. To test this, we adoptively transferred CFSE-labeled βgal96-specific TCR transgenic CD8+ T cells from Bg1 mice into naive C57BL/6 mice and day 20, 50, and 100 immune recipients. Three days later, proliferation and activation of transferred cells was measured in spleen, liver, hLNs, and lung by staining for CD44 and quantifying CFSE dilution by FACs analysis. Although Ag expression could not be readily detected at day 20 post-immunization at the transcriptional level, TCR transgenic CD8+ T cells vigorously proliferated when transferred into day 20 mice (Fig. 6C, 6D). Even in day 50 and 100 immune mice, adoptively transferred cells became activated and proliferated, although to a lesser extent (Supplemental Fig. 3A). The percentage of proliferated TCR transgenic cells was comparable in day 4, 8, and 14 immune mice. In day 20 immune mice, proliferation was slightly reduced compared with the previous days, and it was further reduced in day 50 and 100 immune mice (Fig. 6D).

Taken together, these results demonstrate that CD8+ T cell memory inflation in this setting is not dependent on viral reactivation and replication; similar findings have been reported for MCMV infection (15, 16).

To assess whether the absence of a βgal96-specific inflating response after MCMV-LacZ or Vacc-LacZ infection was due to the lack of Ag presentation, we likewise adoptively transferred CFSE-labeled βgal96-specific TCR transgenic CD8+ T cells from Bg1 mice into day 100 MCMV-LacZ immune and day 21 Vacc-LacZ immune recipients, respectively. In MCMV-LacZ immune recipients, adoptively transferred cells became activated and proliferated compared with naive recipients (Supplemental Fig. 3B). In Vacc-LacZ immune recipients, in contrast, adoptively transferred cells did not proliferate compared with naive recipients (Supplemental Fig. 3C). These results, together with data from Fig. 2C and 2D, suggest that Vacc-LacZ is efficiently cleared on day 21 postinfection; hence, no memory inflation is observed. However, after MCMV-LacZ infection, the βgal96 epitope was still presented on day 100 postinfection, suggesting factors other than pure Ag availability are responsible for the lack of CD8+ T cell memory inflation after MCMV-LacZ infection.

CD4+ T cell help facilitates inflation of memory effector T cells

To further explore the critical requirements for CD8+ T cell memory inflation using this model, we investigated the role of CD4+ T cell help. CD4+ T cells are essential for CD8+ T cell memory induction across a range of immunizations (42) and acute infections (43, 44), although their role in memory inflation after MCMV infection is not fully defined (16, 45).

To establish the role of CD4+ T cells in memory inflation after i.v. Ad-LacZ immunization, we assessed the βgal96-specific CD8+ T cell response on different time points in blood of MHC-II–deficient and wild-type (WT) C57BL/6 mice. In this setting, the generation of tetramer+ CD8+ T cells was clearly dependent on CD4+ T cell help. Only low levels of βgal96-specific CD8+ T cells could be detected on days 21, 50, and 100 after immunization, and the percentage in MHC-II KO mice was significantly reduced at all time points compared with C57BL/6 mice (Fig. 7A). Staining for βgal96-specific CD8+ T cells in spleen, liver, and lung on day 100 revealed similar results, with the tetramer+ population sig-
The main characteristics of CD8+ T cell memory inflation, largely known from studies with MCMV, are: 1) inflating CD8+ T cell populations increase and are maintained at a very high frequency over time; 2) they show an effector-memory phenotype, and they are distributed in peripheral organs, such as liver or lung; and 3) although they show features of repeated exposure to Ag, they are not exhausted and, indeed, retain their functionality over time.
These features are highly relevant to the development of new vaccines eliciting sustained effective T cell memory responses for certain chronic viral infections. Although MCMV is a good model to study CMV infection, there are limitations in examining the mechanisms of memory inflation, because it is a complex system, both virologically with its long-term low-grade persistence, its latency and stochastic reactivation at diverse sites, as well as immunologically, with multiple immunologic mechanisms required to establish and maintain control, and a wide range of CD8+ T cell epitopes. Thus, to further understand the mechanism of CD8+ T cell memory inflation, which is still poorly understood, we developed a simpler and more tractable model using Ad-LacZ. In this study, we showed that Ad-LacZ, a nonreplicating AdV, induced a robust inflating CD8+ T cell population against the βgal96 epitope and a conventional CD8+ memory T cell response to the βgal497 epitope after a single i.v. injection in C57BL/6 mice. CD8+ T cell memory inflation after Ad-LacZ immunization revealed strong resemblance to that seen in MCMV infection, providing us with a novel, robust model for memory inflation that is internally controlled and allows dissection of the mechanism underpinning CD8+ T cell memory inflation. These data further support the idea that memory inflation is a stereotypical pathway of the immunologic memory rather than a unique feature of CMVs, and is consistent with observational data of other viral infections (17–20).

In this study, we demonstrated that βgal96-specific inflating CD8+ T cells were polyfunctional and cytotoxic. Although their effector-memory phenotype is consistent with repeated Ag encounter, they were not exhausted compared with CD8+ T cells in other chronic viral infections (particularly lymphocytic choriomeningitis virus in the mouse, but also HIV, HCV, and hepatitis B virus). We further showed that after i.v. immunization with Ad-LacZ, viral genome was still found at very late time points, and Ag was expressed and presented at very low levels (Fig. 6A–D). These findings imply that long-term maintenance of specific CD8+ T cells after rAdV immunization depends on the very low levels of transcriptionally active AdV genomes. In the context of vaccines, this suggests that persisting low-level Ag might be beneficial, resulting in the maintenance of functional TEM in the periphery, at sites of pathogen entry.

Using different routes of injection, we observed that memory inflation after Ad-LacZ immunization is not restricted to the i.v.

**FIGURE 6.** Low-level Ag persistence in Ad-LacZ–immunized B6 mice. (A) Viral genome distribution after immunization with Ad-LacZ. LacZ DNA copy numbers per microgram total DNA were determined with quantitative real-time PCR on different time points after immunization in liver, lung, spleen, and hLNs. Values <10 copies are detectable but not quantifiable. Pooled data from two independent experiments for each time point are shown (mean ± SEM; liver: n = 3–12; spleen: n = 3–12; lung: n = 3–8; hLN: n = 3–6). (B) βgal expression after immunization with Ad-LacZ. LacZ mRNA copy numbers per microgram total mRNA were determined with quantitative real-time PCR at different time points after immunization in liver, lung, spleen, and hLNs. mRNA copy numbers <10 are detectable but not quantifiable. Pooled data from two independent experiments for each time point are shown (mean ± SEM; liver: n = 3–7; spleen: n = 3–7; lung: n = 3–6; hLN: n = 3–4). (C) Low-level Ag persistence after i.v. immunization of B6 mice with Ad-LacZ. CFSE-labeled, βgal96-specific, Ly5.1+ TCR-transgenic CD8+ T cells from Bg1 mice transferred on day 20 after Ad-LacZ immunization proliferated in spleen, hLNs, and lung 3 d after transfer. Numbers indicate the percentage of proliferated Ly5.1+ CD8+ T cells that are donor derived. Pooled data from two independent experiments for each time point are shown (± SEM; spleen: n = 4; liver: n = 4; hLN: n = 4; lung: n = 4). (D) Percentage of proliferated Ly5.1+ TCR-transgenic CD8+ T cells in spleen analyzed 3 d after adoptive transfer in mice previously immunized with Ad-LacZ on different time points (days 4, 8, 14, 20, 50, and 100). Mean percentage (± SEM; n = 3–5) is indicated.
route, but is also seen after i.d. immunization. s.c. immunization induced a variant pattern of a βgal96-specific CD8+ T cell response, which was reduced in magnitude and did not increase, but was nevertheless sustained over time (Fig. 2, Supplemental Fig. 2). Importantly, although only i.v., i.d., and i.m. routes gave strictly defined infiltration, in terms of increasing frequencies of βgal96-specific cells (day 100/21 ratio > 1), an identical effector-memory phenotype was observed in all cases, that is, after i.v., i.d., s.c., and i.m. immunization. This illustrates that although the magnitude and kinetics of the βgal96-specific CD8+ T cell memory response are dependent on the route of immunization, the phenotype is not (Fig. 2, Supplemental Fig. 2). Two factors are likely to influence these phenomena: first, Ag dose; and second, Ag distribution, the latter reflected in the APCs involved in priming and in memory maintenance. Previous work by other groups (26, 27) demonstrated that the route and dose of adenovirus-based vaccine delivery impacts on distribution of the virus, and thus expansion and trafficking of vaccine-elicited CD8+ T cells. In such experiments, differences in Ag dissemination would readily account for the reduced overall magnitude of the CD8+ T cell response with the non-i.v. compared with the i.v. routes. The distinctive phenotype of inflating populations is, however, shared between populations regardless of the route or magnitude; likewise, regardless of route, there are marked differences in phenotype between the inflating and noninflating epitopes, which emerge over time. The nature of the APCs involved in Ag presentation during the memory phase is discussed further later, but it therefore appears that this APC must be accessible to the inflating memory pool regardless of the route of immunization.

In this study, we also showed that the βgal96-specific CD8+ T cell response was significantly reduced in MHC-II-deficient mice. However, unlike the situation with different routes, βgal96-specific CD8+ T cells in MHC-II KO mice also displayed an altered phenotype compared with the standard i.v. inoculation in...
WT mice; overall, this could be summarized as skewed toward a T\textsubscript{CM} phenotype rather than the T\textsubscript{EM} phenotype typically seen (data not shown). Interestingly, although CD\textsuperscript{8} T cell expansion was significantly reduced, on day 100 after immunization, \(\beta\text{gal}_{\text{ag}}\)-specific CD\textsuperscript{8} T cells were nevertheless still present in blood, liver, lung, and spleen (Fig. 7A, 7B). Thus, CD\textsuperscript{4} T cell help is clearly essential both for the initial priming of \(\beta\text{gal}_{\text{ag}}\)-specific CD\textsuperscript{8} T cells and the evolution of an effector-memory phenotype. However, for the maintenance of these cells in the memory phase, CD\textsuperscript{4} T cell help might be dispensable. This theory is supported by findings exploiting other rAdVs (42, 46). CD\textsuperscript{4} T cell help is likely required during memory inflation in MCMV infection, although the situation is more complex (16, 45). In a model where MCMV reactivation was controlled by injection of an antiviral drug, CD\textsuperscript{4} T cell help appears necessary; if viral reactivation is not controlled, CD\textsuperscript{4} T cell help can partially be compensated and less impact on memory inflation was observed (16). Overall, in a setting without viral replication, memory inflation is dependent on CD\textsuperscript{4} T cell help; however, further experiments are required to determine at what stage such help is critical.

We demonstrated that CD\textsuperscript{8} T cell memory inflation in this system was not dependent on viral reactivation and replication (Fig. 6). Similar findings were reported for MCMV infection (15, 16), although the levels of inflation seen in these studies were relatively limited. In our model, substantial memory inflation and conventional memory are both induced with a widely used non-replicating AdV. Prolonged CD\textsuperscript{8} T cell responses for several weeks after adenoaviral vector immunization has been described previously, followed by contraction (21, 25, 29–31, 46, 47), although robust CD\textsuperscript{8} T cell memory inflation sustained over many months has not been observed. Previous studies have indicated that prolonged CD\textsuperscript{8} T cell responses depended on low levels of Ag (30, 31). Interestingly, in such models, specific CD\textsuperscript{8} T cells become Ag independent, as shown using a doxycycline-regulated AdV transgenic for SIINFEKL (30).

We further exploited the model to analyze the dependence of memory inflation after Ad-LacZ immunization on processing via immunoproteasomes. Immunization of LMP\textsuperscript{7} KO mice revealed a comparable \(\beta\text{gal}_{\text{ag}}\)-specific CD\textsuperscript{8} T cell response with that seen in WT mice. In contrast, the noninflating \(\beta\text{gal}_{\text{ag}}\)-specific response was completely abolished in LMP\textsuperscript{7} KO mice (Fig. 7D–G). Interestingly, identical findings regarding immunoproteasome dependency were observed after MCMV infection (14). Clearly, in both settings, processing of inflating epitopes was not dependent on immunoproteasomes (Fig. 7D, 7E) (14). Because of the non-inflammatory environment in the Ad-LacZ model, as well as in MCMV latency, these combined data strongly suggest that processing of inflating epitopes depends on constitutively expressed proteasomes. Constitutively expressed proteasomes can be found in hematopoietic APCs, as well as in nonhematopoietic APCs. Recent data from studies with MCMV demonstrated that hematopoietic APCs primed MCMV-specific CD\textsuperscript{8} T cells but were not sufficient for driving memory inflation (48), and that nonhematopoietic cells, likely in the LNs, were responsible for driving memory inflation in MCMV infection (41). Similar data were obtained with an rAdV (29). Thus, our data from LMP\textsuperscript{7} KO mice support the theory of APCs from a nonhematopoietic origin being responsible for prolonged Ag presentation resulting in memory inflation.

Which nonhematopoietic APCs might be responsible, and where, remains to be defined. It has been shown that the major reservoir of MCMV latent genomes are cells of nonhematopoietic origin such as sinusoidal lining cells of the spleen (49), liver sinusoidal endothelial cells (50), or CD11b \(^+\) CX3CR1 \(^+\) nonhematopoietic cells in the lung (51). After i.v. Ad-LacZ immunization, most of the viral genome is found in spleen, liver, and lung. We directly tested the role of splenic Ag by repeating the experiments in splenectomized mice, and found no effect of splenectomy (Supplemental Fig. 4). Because memory inflation is not impaired in the absence of a spleen, this suggests the liver and/or the lung are the main sites of Ag presentation. Our quantitative real-time PCR results for LacZ DNA, as well as the proliferation behavior of adoptively transferred TCR transgenic CD\textsuperscript{8} T cells, further support this idea. In this study, directly infected endothelial cells or stromal cells could be potential APCs because evidence suggests direct presentation during memory inflation (41). However, whether this is true after i.v. Ad-LacZ immunization still requires investigation. Regardless of the cell type, it remains unclear how Ag-expressing cells can persist in the presence of specific CD\textsuperscript{8} T cell immunity, although potentially such pools may simply decline very slowly.

The observation that \(\beta\text{gal}_{\text{ag}}\)-specific CD\textsuperscript{8} T cells are not exhausted and located at a high frequency in peripheral organs renders them to a very desirable cell population for T cell–inducing vaccines. In this context, effector-memory T cells have been shown to respond rapidly to invasive and proliferating pathogens, and were highly protective in epithelial challenges (5). The very high frequencies of specific effector cells at the site of infection might compensate for the reduced proliferative and functional capacity of T\textsubscript{EM} compared with T\textsubscript{CM} (52, 53). Specifically, for chronic hepatitis B virus and HCV infection and Mycobacterium tuberculosis, where a high number of functional CD\textsuperscript{8} T cells in the liver or lung is required to eliminate the pathogen, such a vaccine strategy would be of major importance. Interestingly, recent studies using i.m. vaccination with recombinant adenoaviral vector to induce T cell responses against HCV revealed a distinct phenotype with sustained development of effector-memory CD\textsuperscript{8} T cell populations (CD45RA\(^{-}\), CCR7\(^–\)) (21), showing some of these features of this phenomenon may be already embedded in current vaccine programs.

To further exploit this, however, we should first identify and then target the APC population(s) responsible for Ag processing and presentation during the memory phase. Dendritic cell–based strategies may, in theory, run the risk for selecting CD\textsuperscript{8} T cell populations, which, after the first phase, contract to a low-level memory population of a T\textsubscript{CM} phenotype. Second, we should further dissect the molecular mechanisms underpinning the evolution of inflationary CD\textsuperscript{8} T cell responses to promote this pathway of memory development. Third, we should optimize methods to identify and/or generate inflating epitopes from longer proteins. Clearly, memory inflation depends not only on the processing of the peptide, but also other features of the vector. But given the data on immunoproteasome independence, defining the rules governing the relevant cleavage of inflating versus noninflating peptides should be a priority for future vaccine design. Inflating/immunoproteasome-independent epitopes and noninflating/immunoproteasome-dependent epitopes could both be included to induce long-lived and functional CD\textsuperscript{8} T cell effector and central memory populations.

Overall, we propose that although MCMV infection and Ad-LacZ immunization are two completely distinct settings, the mechanism for CD\textsuperscript{8} T cell memory inflation is comparable in the two models. Together with findings from studies with other rAdV and from MCMV infection, we suggest that CD\textsuperscript{8} T cell memory inflation is a distinct, evolutionarily conserved, stereotypical memory response, observed after different routes of exposure to diverse vectors. This response depends at least initially on CD4\textsuperscript{+} T cell help and may depend on presentation of Ag during the memory phase by unconventional (non–dendritic cell) APCs lacking immunoproteasomes. rAdVs are well characterized and generally easy to manipulate. They transduce a variety of cells, but the vector genome does not
integrate, and their safety is well established (25). In contrast, CMV would need substantial further work on its use as a vector regarding the safety and efficiency profile. Therefore, the Ad-LacZ model not only facilitates further studies on CD8+ T cell memory inflation, but also enables direct implications, because of adenoviruses’ wide potential as vaccine vectors. This convergence of a window on an emerging and tractable area of immunobiology with a technology that forms the basis for many major vaccine programs means the model presented in this article should be of general value and the implications of the results obtained of broad relevance in future studies.

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