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A Novel Murine Cytomegalovirus Vaccine Vector Protects against Mycobacterium tuberculosis

Peter C. L. Beverley,*1 Zsolt Ruzsics,†1 Ariann Hey,*1 Claire Hutchings,* Simone Boos,† Beatrice Bolinger,* Emanuele Marchi,* Geraldine O’Hara,* Paul Klemaner,* Ulrich H. Koszinowski,† and Elma Z. Tchilian*

Tuberculosis remains a global health problem so that a more effective vaccine than bacillus Calmette–Guérin is urgently needed. Cytomegaloviruses persist lifelong in vivo and induce powerful immune and increasing (“inflationary”) responses, making them attractive vaccine vectors. We have used an m1–m16-deleted recombinant murine CMV (MCMV) expressing Mycobacterium tuberculosis Ag 85A to show that infection of mice with this recombinant significantly reduces the mycobacterial load after challenge with M. tuberculosis, whereas control empty virus has a lesser effect. Both viruses induce immune responses to H-2d–restricted epitopes of MCMV pp89 and M18 Ags characteristic of infection with other MCMVs. A low frequency of 85A-specific memory cells could be revealed by in vivo or in vitro boosting or after challenge with M. tuberculosis. Kinetic analysis of M. tuberculosis growth in the lungs of CMV-infected mice shows early inhibition of M. tuberculosis growth abolished by treatment with NK-depleting anti-asialo ganglio-N-tetraosylceramide Ab. Microarray analysis of the lungs of naive and CMV-infected mice shows increased IL-21 mRNA in infected mice, whereas in vitro NK assays indicate increased levels of NK activity. These data indicate that activation of NK cells by MCMV provides early nonspecific protection against M. tuberculosis, potentiated by a weak 85A-specific T cell response, and they reinforce the view that the innate immune system plays an important role in both natural and vaccine-induced protection against M. tuberculosis. The Journal of Immunology, 2014, 193: 000–000.

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The online version of this article contains supplemental material. Abbreviations used in this article: Ad85A, adenovirus expressing Ag 85A; ASGM1, asialo ganglio-N-tetraosylceramide; BAC, bacterial artificial chromosome; BCG, bacillus Calmette–Guérin: i.n., intranasally; MCMV, murine CMV; ORF, open reading frame; TB, tuberculosis.

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of the vaccine Ags, properties that may account for its efficacy in protecting against SIV challenge in macaques (16).

The ability to make rCMVs has been facilitated by bacterial artificial chromosome (BAC) technology, and vaccine vectors have been constructed expressing Ags under several different promoters. Furthermore, BAC technology has made it simple to investigate the function of CMV genes and study the effect of removing those known to interfere with immune function to improve the protective efficacy of CMV-based vaccines (17–19).

In the present study, we investigate for our knowledge the first time the ability of a novel recombinant murine CMV (MCMV) vector, in which the first 16 genes of the virus, including some that interfere with expression of MHCI class I having been deleted (17–20), to induce protective immunity against a bacterial pathogen M. tuberculosis. Although MVA85A did not show efficacy in humans (2), recombinant adenviruses expressing M. tuberculosis Ag 85A have been shown to protect in mice (21), guinea pigs (22), and cattle (23), so this well-characterized M. tuberculosis mycolyl transferase was used as a vaccine Ag in our rMCMV, expressed under the control of the human CMV promoter.

We show that this recombinant virus, MCMV85A, induces strong protection against challenge with M. tuberculosis, whereas the control virus, eMCMV, has a weaker, nonspecific effect. We examine the mechanisms of protection.

Materials and Methods

Virus and vector construction

The rMCMV constructs were generated on the Δn1-16-FRT backbone (24), which is derived from pSM3fr (25) and therefore is m129 negative (26). This was modified by insertion of an IRES-controlled mCherry cassette at the 3′ untranslated region of the gene M48.5, allowing fluorescent cell detection in tissue culture (27). The MCMV85A-BAC was generated by insertion of pO6-A5-CMV-TB85A into the Δn1-16-FRT-BAC by Flp-mediated recombination as described (28). pO6-A5-CMV–M. tuberculosis 85A was generated by inserting a PCR-generated fragment of a codon-optimized synthetic 85A open reading frame (ORF) fused to the signal sequence of the human tissue plasminogen activator upstream sequence for better expression in eukaryotic cells (29), into pO6-A5-CMV-gfp by removal of the gfp coding sequence. To detect expression of 85A in vitro, RNA was isolated from 85A-expressing cells using NheI/NotI digestion to replace the gfp coding sequence. The TB85 ORF was amplified using primers NTPA forward (5′-TCCGGCTAGATGGTGCAATGCAATGAAGAGAGGGCT-3′) and 85 reverse (5′-GATCGCGCCGCAGGATCTAGGGGGCGCGGC-3′); the restriction sites used are underlined. The eMCMV-BAC was generated by insertion of pO6-A5-CMV into Δn1-16-FRT-BAC. pO6-A5-CMV was generated from pO6-A5-CMV-gfp by removal of the gfp coding sequence with NheI/NotI. The viruses MCMV85A and eMCMV were reconstituted from the respective BACs after transfection of mouse embryo fibroblasts as previously described (28).

Adenovirus expressing Ag 85A (Ad85A) is a recombinant human adenovirus type 5 expressing M. tuberculosis Ag85A. The virus was purified using Adenopure columns (Puresyn, Malvern, PA) and used as a positive control vaccine (30).

Infectious virus propagation and quantitation

MCMV85A and eMCMV were propagated and titrated in NIH 3T3 cells (European Cell Culture Collection, Porton Down, U.K.). For propagation, monolayers of NIH 3T3 cells grown in DMEM (Life Technologies, Paisley, U.K.) were infected with eMCMV or MCMV85A and incubated for 4 d. Supernatants were harvested and stored at −80°C.

To detect expression of 85A in vitro, RNA was isolated from 85A-infected NIH 3T3 cells infected with MCMV85A 48 h earlier at a multiplicity of infection of 100.1. Cells were trypanosed, centrifuged, and the pellet was resuspended in 1 ml TRIzol reagent (Life Technologies). RNA was extracted using the RNaseasy kit (Qiagen, Hilden, Germany), DNase treated (DNA-free kit; Ambion/Life Technologies, Carlsbad, CA), and reverse transcribed using a high-capacity cDNA reverse transcription kit (Applied Biosystems/Life Technologies, Foster City, CA) according to the manufactures’ instructions. PCR was performed using forward (5′-CAGGACGACTTCAGCGGC-3′) and reverse (5′-TCCGGCTAGATGGTGCAATGCAATGAAGAGAGGGCT-3′) primers amplifying a 277-bp product of the 85A sequence (nt 134–411).

Virus titers in organs of eMCMV- or MCMV85A-infected mice were determined by plaque assay on NIH 3T3 cells as described (31).

MCMV infection and immunization of mice

All animal work was carried out in accordance with the U.K. Animal (Scientific Procedures) Act 1986 and was approved by the Animal Use Ethical Committee of Oxford University.

Six- to 8-wk-old female BALB/c mice (Harlan Orlac, Blackthorn, U.K.) were infected i.p. or i.v. with 2 × 10⁶ PFU eMCMV or MCMV85A. In some experiments mice were immunized intranasally (i.n.) with 2 × 10⁷ virus particles Ad85A or s.c. with 2 × 10⁷ CFU BCG as described previously (30).

Isolation of lymphocytes from lungs, spleen, and livers

Lungs were perfused with PBS, cut into pieces, and digested with 0.7 mg/ml collagenase type I (Life Technologies) and 30 μg/ml DNase I (Sigma-Aldrich, Dorset, U.K.) for 45 min at 37°C. Digested fragments were crushed through a cell strainer using a syringe plunger, washed, RBCs were removed with lysis buffer (Qiagen) and, after centrifugation, resuspended in HEPES-buffered RPMI 1640 containing 10% FCS and 1% penicillin-streptomycin. Spleens were passed through a cell strainer using a syringe plunger, RBCs were removed with lysis buffer (Qiagen), and the cells were washed. Livers were passed through a cell strainer, the cells washed, and lymphocytes were isolated by gradient centrifugation using Percoll (GE Healthcare, Uppsala, Sweden).

In vitro restimulation of T cells

Splenic lymphocytes from MCMV85A-infected mice were allowed to adhere to plastic for 2 h at 37°C in HEPES-buffered RPMI 1640 containing 10% FCS and 1% penicillin-streptomycin. The nonadherent cells were recovered and mixed 1:1 with naïve spleen cells. The mixture was adjusted to 10⁵ cells/ml and 1 ml was added to 24-well tissue culture plates. Medium or medium containing a pool of 58 peptides (15-mer each) overlapping by 10 aa covering the entire 85A sequence was added in 1 ml to give a final concentration for all peptides of 2 μg/ml. After 4 d culture at 37°C, 1 ml medium was removed and replaced by medium containing 2 ng/ml recombinant human IL-2 (Life Technologies). After a further 3 d the nonadherent cells were recovered from each well, washed, and returned to the same well for overnight culture. The following day the proportion of Ag-specific cytokine-producing cells in the rested cells was determined by flow cytometry after restimulation with 85A peptides, as described below.

NK cell assay

YAC-1 NK-sensitive target cells (32) were labeled with CFSE (Invitrogen) as previously described (30). To 10,000 labeled target cells spleen cells were added at different attacker/target ratios in round-bottom 96-well plates and the plates were centrifuged for 3 min at 1500 rpm before incubation for 16 h at 37°C. The plates were centrifuged again and the supernatant was removed, the cells were resuspended by vortexing, and 50 μl fixable Live/Dead cell stain was added (Molecular Probes). After 20 min at 4°C, 100 μl FACS buffer was added to each well, the plate was centrifuged, the supernatant was removed, cells were resuspended, and 200 μl FACS buffer was added. An aliquot of 100 μl was removed from each well and added to an equal volume of medium containing a known number (~10⁴) of fluorescent microbeads. The ratio of viable target cells to beads was determined by flow cytometry and percentage cytotoxicity calculated by the formula: % cytotoxicity = 1 − [(ratio of viable target cells/beads at each attacker/target ratio)/(ratio of viable cells alone/beads)] × 100.

Flow cytometry

Lymphocytes were stimulated in RPMI 1640 containing 10% FCS and 1% penicillin-streptomycin for 6 h with the H-2d-restricted MCMV CD8 peptide epitopes (SPGSRGRIL) from the MCMV M18 (33) or (YPHFMPPTNL) from the pp89 Ag. For Ag 85A, cells were stimulated either with the pool of 58 peptides (15-mer each) or with three H-2d–restricted peptides encoding the N-terminus of CD4 85A (aa 1–16) (TFLTSELPGWLGANHRKVEPT) or CD8 85A, 85B, 85C (MPVGGQSSSF) and 85A, 85B, 85C (YAGAMSGL) epitopes (30, 34, 35) (peptide sequences were synthesized at the Weatherall Institute of Molecular Medicine, Oxford, U.K.). Each peptide was used at 2 μg/ml. After 1 h at 37°C, GolgiPlug (BD Biosciences, Oxford, U.K.) was added according to the manufacturer’s instructions.

Cells were washed and incubated with anti-mouse CD16/CD32 (clone 93) (BD Biosciences, Oxford, U.K.) for 30 min on ice. Cells were washed in FACS buffer and 100 μl was added to each well. The plate was centrifuged, the supernatant was removed, cells were resuspended, and 200 μl FACS buffer was added. An aliquot of 100 μl was removed from each well and added to an equal volume of medium containing a known number (~10⁴) of fluorescent microbeads. The ratio of viable target cells to beads was determined by flow cytometry and percentage cytotoxicity calculated by the formula: % cytotoxicity = 1 − [(ratio of viable target cells/beads at each attacker/target ratio)/(ratio of viable cells alone/beads)] × 100.
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Infection with M. tuberculosis and determination of mycobacterial load

MCMV-infected, immunized, or naive groups of four to seven mice were anesthetized with isoflurane/oxygen and infected i.n. with M. tuberculosis ( Erdman strain) in 40 µl PBS equally divided between both nostrils. Lung CFU were enumerated 24 h after challenge to determine the number of organisms deposited (~200 CFU). Mice were sacrificed at indicated times, the lungs and spleen were homogenized, and mycobacterial load was determined by plating 10-fold serial dilutions of tissue homogenates on Middlebrook 7H11 agar plates (E&O Laboratories, Bonnybridge, U.K.). CFU were counted after 3–4 wk of incubation at 37˚C in 5% CO₂.

We have previously shown that i.n. challenge gives identical results to aerosol challenge with a Henderson apparatus (30).

NK cell depletion

NK cells of naive, eMCMV-infected, or MCMV85A-infected mice were depleted by two i.p. injections of 50 µl anti-asialo ganglio-N-tetraosylceramide (ASGM1) Ab (Alpha Laboratories) or 100 µg normal rabbit Ig (Sigma-Aldrich) as a control 4 d before and on the day of M. tuberculosis challenge.

NK depletion was assessed by staining of lung and spleen cells for NKp46 (29A1.4; bioscience) and DX5 (BD Pharmingen) in addition to CD4, CD8, and Live/Dead marker. Nondepleted mice were used as control.

Manipulation of IL-21 in vivo

Recombinant IL-21Fc or control human IgG1 (75 µg) (R&D Systems) was administered i.p. to eMCMV-infected mice 2 d before and on the day of challenge with M. tuberculosis. Mice were sacrificed 7 d later and M. tuberculosis CFU were enumerated. Recombinant mouse IL-21 (100 ng in PBS) (R&D Systems) or CCL22 (R&D Systems) as control was administered i.n. on the day of M. tuberculosis challenge, mice were sacrificed 7 d later, and M. tuberculosis CFU were enumerated.

Microarrays

Gene expression analysis was performed on purified lung mononuclear cells of four uninfected and four eMCMV-infected mice 15 d postinfection using Agilent whole mouse genome oligonucleotide arrays (Milleniy Biotech). The raw and normalized microarray data are downloadable from the Gene Expression Omnibus database (http://www.ncbi.nlm.nih.gov/geo/), accession number GSE57572.

Microarray data were preprocessed using the R language (http://cran.r-project.org/) and Bioconductor packages (http://www.bioconductor.org/). Array normalization was performed using the “vsn” algorithm and low signal features were filtered out from subsequent analysis. The Limma package was used to infer differentially expressed genes. After p value adjustment, 338 probes were found significant at p < 0.05.

Statistical analysis

Data were analyzed by one-way ANOVA followed by a Tukey multiple comparison test.

Results

Generation of rMCMV expressing Ag 85A

The rMCMV constructs were generated by insertion into the ∆m1-16-FRT backbone (24) of an IRES-controlled mCherry cassette at the 3’ untranslated region of the M48.5 gene (27). The MCMV85A-BAC was generated by Flp-mediated insertion of p06-A5-CMV-TB85A, carrying a codon-optimized synthetic TB85A ORF under the control of the human CMV immediate early promoter (Supplemental Fig. 1A). The eMCMV-BAC was generated by insertion of the empty vector. MCMV85A and eMCMV were reconstituted from the respective BACs after transfection of mouse embryo fibroblasts (28). The ∆m1-16-FRT–based constructs are derived from pSM3fr (25) and are therefore MCK-2 (m129) negative (26). Additionally, the constructs lack genes m01–m16. This region includes two of the three MCMV genes, m04 and m06, which downregulate MHC class I–mediated Ag presentation, whereas m152 is intact. The replication of ∆m1-16-FRT–derived constructs has been studied extensively in tissue culture where they replicate with wild-type kinetics (24, 27, 36).

Expression of the 85A gene was assessed by RT-PCR analysis of NIH 3T3 cells infected with eMCMV or MCMV85A. Only MCMV85A-infected 3T3 cells generate a PCR product consistent with the expression of 85A RNA in the cells (Supplemental Fig. 1B). To ensure that the rMCMVs had comparable growth characteristics, virus growth was assessed after in vivo infection in the salivary glands, liver, and spleens of mice at 6 d postinfection. Supplemental Fig. 1C shows that eMCMV and MCMV85A replicate comparably, suggesting that the insertion of 85A does not interfere with viral replication in vivo.

MCMV85A protects against pulmonary challenge with M. tuberculosis

To determine the efficacy of eMCMV and MCMV85A in protection against M. tuberculosis challenge, BALB/c mice were infected i.p. with 2 × 10⁶ PFU eMCMV or MCMV85A and 4, 8, 12, or 24 wk later challenged with M. tuberculosis. Mice were also infected i.v. and challenged 4 wk later. Controls were either uninfected or immunized with Ad85A i.n., a highly protective subunit vaccine in this mouse strain, or BCG s.c. (21, 30). The mycobacterial load in the lungs and spleens was determined 5 wk after M. tuberculosis challenge. Although the i.v. route induced better protection at 4 wk after MCMV infection, because MCMV virus stocks produced in vitro are of lower titer it is difficult to give the volumes required for high doses by the i.v. route, so the i.p. route was used for further analysis.

Irrespective of the route of infection, at all times after MCMV85A infection, there is a significant reduction in mycobacterial load in the lungs compared with naive animals. At 4 wk there is significantly greater protection in MCMV85A i.v. infected than in eMCMV i.v. infected animals. At 8 wk the reduction in MCMV85A i.p. infected mice is comparable to that found in Ad85A i.n. immunized animals assayed simultaneously and at 12 wk to BCG. As in Ad85A-immune mice (30), protection is maintained for at least 24 wk in MCMV85A-infected mice (Fig. 1). eMCMV-infected animals almost always show a trend toward a reduction in lung mycobacterial load, but this does not reach statistical significance in the experiments shown. Splenic CFU show similar trends to the lungs (not shown).

These results indicated that MCMV85A induces protection against M. tuberculosis, sustained for at least 24 wk and comparable to that obtained with the most effective subunit vaccine, Ad85A delivered i.n., or BCG, the “gold standard” TB vaccine.

MCMV-specific immune responses

Because it is difficult to detect even wild-type MCMV beyond the first few weeks after infection in vivo in mice (37, 38), we studied the immune response to well-characterized H-2d–restricted MCMV antigenic epitopes to determine whether the attenuated eMCMV or MCMV85A viruses persist in vivo and generate immune responses characteristic of other MCMVs.

The H2-Ld–restricted CD8 T cell response to the immunodominant epitope (amino acid YPHFMPTNL) from the IE1 protein m123/m129 was studied the immune response to well-characterized H-2d–restricted MCMV antigenic epitopes to determine whether the attenuated eMCMV or MCMV85A viruses persist in vivo and generate immune responses characteristic of other MCMVs.

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the lung, ∼1% in the spleen, and 0.5% in the liver (Fig. 2B). There are no significant differences between the frequencies and kinetics of pp89- (Fig. 2A) or M18-specific (Fig. 2B) cells in eMCMV- versus MCMV85A-infected animals.

We also determined the differentiation and activation status of pp89- and M18-specific CD8 T cells, using CD127 and CD62L to define memory subpopulations (Supplemental Fig. 2) and increased KLRG1 and decreased CD27 to define the extent of activation (Supplemental Fig. 3) among the Ag-specific cells of MCMV85A- or eMCMV-infected mice. At 60 d postinfection with MCMV85A, in the lungs ∼61% of pp89-specific cells are effectors compared with 28% of M18-specific cells, whereas 57% of M18-specific and 37% of pp89-specific cells are effector memory. Similar trends are seen for eMCMV at day 60 and for both viruses at day 180 (data not shown). At both time points, pp89-specific cells show increased KLRG1 and decreased CD27 Ag expression (40) compared with M18-specific cells, and also lung and liver Ag-specific cells are more activated than splenic cells (Supplemental Fig. 3).

The kinetics of the pp89 and M18 responses confirm their inflationary and noninflationary nature, respectively. In agreement with previous studies, pp89-specific cells exhibit a more activated phenotype than do M18-specific cells, especially in the lungs and liver. Overall, these data indicated that the two vectors persist in vivo, behave similarly to previously described MCMVs, and induce similar responses to MCMV Ags at the time points tested (39, 41, 42).

Ag 85A-specific responses

We next assessed the response to Ag 85A in the MCMV85A-infected animals. A pool of 58 peptides (15-mer each), covering the whole sequence of 85A protein, was used to stimulate lung, liver, and spleen cells from MCMV85A- or eMCMV-infected mice for 6 h in vitro, and intracellular staining for IFN-γ, TNF-α, and IL-2 was performed but we could not demonstrate convincingly a reproducible, continuing, and statistically significant 85A-specific response at 3, 6, 9, 30, 60, or 180 d postinfection. Neither are cytokine-producing cells from MCMV85A-infected mice demonstrable when individual known dominant H-2d-restricted peptide epitopes of Ag 85A (I-Ed CD499–118, Ld CD870–78, and Kd CD8145-152) (34, 35) are used for stimulation. Furthermore, no T cell response to 85A can be detected by ELISPOT, nor is 85A-specific Ab detectable by ELISA in sera from MCMV85-infected animals (data not shown).

However, because the MCMV85A animals were better protected than eMCMV-infected mice, we reasoned that there must be an 85A-specific response and that it should be possible to reveal this by boosting in vivo or in vitro. Therefore, 4 wk after infection with either eMCMV or MCMV85A, we boosted the animals with Ad85A and examined the immune response 6 d later. At this early time after immunization, eMCMV-infected mice make a very small response to Ag 85A, but the response in MCMV85A-infected mice is much greater (Fig. 3A). Similarly, when spleen cells from MCMV85A are stimulated with 85 peptides in vitro in the presence of uninfected APCs and expanded in IL-2, a population of Ag-specific CD8 T cells can be detected (Fig. 3B).

In BALB/c mice after Ad85A immunization most of the CD8 responding cells react to the dominant 85A70–78 epitope and a smaller proportion to the 85A145–152 epitope. There is also a small but detectable CD4 response to the 85A99–118 epitope (40).
In MCMV85A-infected mice boosted with Ad85A, responses to the CD8 dominant and subdominant epitopes are seen whereas the CD4 response is unchanged (Fig. 3C). In vitro–boosted and IL-2–expanded cells from MCMV85A-immunized animals show similar specificity (data not shown). Data on CD8 IFN-γ and CD4 IL-2–producing cells are shown, as these provide the most sensitive detection of the two subsets.

Overall, these results show that MCMV85A-infected animals have a low frequency of 85A-specific memory CD8 and CD4 cells, which can be revealed by boosting with Ad85A in vivo or with 85A peptides in vitro.

**Mechanism of protection against M. tuberculosis**

In most experiments eMCMV-infected animals show lower CFU than do naive animals, although this seldom reaches statistical significance (see Fig. 1). However, because the 85A-specific response is consistently low and yet protection by MCMV85A is equivalent to BCG and Ad85A i.n., two highly effective vaccines in mice, we wanted to better establish the mechanisms of protective immunity against *M. tuberculosis* in MCMV-infected mice.

As we have previously shown that pulmonary local immune responses can inhibit *M. tuberculosis* growth very early after challenge, whereas systemic immune responses act only later (30), we first determined the kinetics of *M. tuberculosis* growth in the lungs of mice challenged with *M. tuberculosis* 5 wk postinfection with eMCMV or MCMV85A. Groups of mice were sacrificed 7 and 15 d later to determine the mycobacterial load in the lungs (Fig. 4A).

Both eMCMV and MCMV85A animals show a reduction in mycobacterial load at 7 and 15 d after challenge (Fig. 4A). The early reduction of *M. tuberculosis* load in eMCMV mice suggests that MCMV infection on its own induces early acting nonspecific protection against *M. tuberculosis*, potentiated by the specific response to 85A in MCMV85A mice. Because MCMV has been shown to activate NK cells, we used anti-ASGM1 Ab, given 4 d before and on the day of *M. tuberculosis* challenge, to deplete NK cells from naive, eMCMV-infected, or MCMV85A-infected mice. NK depletion alone does not affect *M. tuberculosis* CFU in the lungs of naive mice at 7 d after challenge, whereas it reverses the early protective effect in eMCMV- and MCMV85A-infected mice (Fig. 4B). Staining with DX5 and NKp46 Abs confirms the depletion of NK cells (Fig. 4B). In the experiment shown, a control Ab was not administered but a repeat experiment included control rabbit Ig. Identical results were obtained and control Ig had no effect. Although NK depletion abolishes protection in both eMCMV- and MCMV85A-infected mice, the latter show more effective control of *M. tuberculosis* at both 7 and 15 d (Fig. 4A), suggesting that an Ag-specific response potentiates the NK effect.

We therefore analyzed Ag-specific responses of lung cells of eMCMV- and MCMV85A-infected mice 15 d after *M. tuberculosis* challenge. Only the MCMV85A mice show an 85A-specific lung.
CD8 response (Fig. 4C), whereas a pp89-specific response is detected in both eMCMV- and MCMV85A-infected mice. As previously shown by others, all *M. tuberculosis*–challenged mice make a CD4 response to the pool of 85A peptides (34, 35).

**FIGURE 3.** Ag 85A–specific immune responses. (A) Mice were infected with eMCMV or MCMV85A and 4 wk later boosted with $2 \times 10^9$ virus particles Ad85A i.m. Six days later, lung, spleen, and liver cells were isolated and stimulated for 6 h with pooled 85A peptides. (B) Spleen cells from eMCMV- or MCMV85A-infected mice were stimulated in vitro with a pool of 15-mer peptides covering the sequence of Ag 85A, expanded with IL-2, rested, and restimulated with 85A peptides before assaying by intracellular staining and flow cytometry for Ag-specific IFN-γ–producing cells. (C) Lung or spleen cells from MCMV85A-infected mice boosted with Ad85A were stimulated with individual 85A peptides covering the dominant H-2d CD4 and CD8 epitopes. The frequencies of IFN-γ– or IL-2–producing cells were determined by flow cytometry on CD8- and CD4-gated cells. Results are expressed as the means ± SD of three or four mice per group, representative of two independent experiments. Data were analyzed by a one-way ANOVA with a Tukey posttest.
Taken together, these data indicate that MCMV on its own has an early effect on mycobacterial growth, mediated mainly by NK cells, but the low frequency of 85A-specific memory cells present in MCMV85A-infected mice contributes to significantly improved protection.

However, depletion of ASGM1-expressing cells is known to affect more than just NK cells (43, 44), so we sought further evidence for the role of these cells and carried out a microarray comparison of gene expression in the lungs of naive and eMCMV-infected animals (Supplemental Fig. 4). Microarray data were deposited in the Gene Expression Omnibus database (http://www.ncbi.nlm.nih.gov/geo/), accession number GSE57572. IL-21 expression, a cytokine known to be related to NK cell activity, is highly upregulated in eMCMV versus naive mice. Quantitative RT-PCR confirmed the upregulation of IL-21 message (IL-21 mRNA relative to hypoxanthine phosphoribosyltransferase in naive lungs of 0.00036 versus eMCMV lungs of 0.015, \( p = 0.02 \)). We assessed the importance of IL-21 in two ways. First, we administered a soluble rIL-21RFc construct (45) systemically to MCMV-infected mice at the time of \( M. \) tuberculosis challenge to block IL-21 activity, and second, we tested whether rIL-21 administered to the lungs could induce early inhibition of \( M. \) tuberculosis growth. The results of these experiments are shown in Fig. 5. IL-21RFc blocks the early inhibitory effect on \( M. \) tuberculosis growth seen in eMCMV-infected mice (Fig. 5A), whereas IL-21 induces growth inhibition in normal mice (Fig. 5B), suggesting that IL-21 plays an important role in the nonspecific protective effect seen in eMCMV-infected mice, most likely through activation of NK cells (46, 47). In vitro assay of spleen cells from eMCMV mice confirms increased NK killing activity on YAC-1 cells compared with naive mice (Fig. 5C).

**Discussion**

In many species, CMVs establish largely asymptomatic persistent infection, characterized by the accumulation of large numbers of virus-specific T cells (memory inflation) (39). These properties, as well as the fact that infection does not prevent reinfection, make rCMVs attractive vaccine vectors and they have been shown already to induce robust protection against SIV challenge in macaques and Ebola virus or HSV in mice (13–15). In this study,
to our knowledge, we show for the first time that an rMCMV expressing M. tuberculosis Ag 85A confers protection against M. tuberculosis challenge in BALB/c mice. The reduction in mycobacterial load achieved by MCMV85A is comparable to that induced by Ad85A administered i.n. as well as the gold standard vaccine, parenteral BCG (21, 30, 48). Both MCMV85A and Ad85A induce protective immunity maintained for at least 24 wk (Fig. 1) (30).

Surprisingly, an immune response to Ag 85A was not detectable ex vivo in MCMV85A-infected mice and could be demonstrated only after in vivo boosting with Ad85A, following M. tuberculosis challenge or after in vitro stimulation in the presence of uninfected APCs, indicating that the MCMV85A-infected animals do have 85A-specific memory cells, but at a frequency not reliably detectable by intracellular cytokine staining. We considered several explanations for the low response to 85A. The first was that these vectors do not productively infect mice or persist in vivo. However, the vectors replicate in vitro similarly to wild-type MCMV (24, 27, 49) and they are capable of productive infection in vivo. Furthermore, they induce typical inflammatory and noninflammatory responses against pp89 and M18 epitopes. Because tissue culture grown MCMV is difficult to detect in vivo after the first few weeks of infection in immunocompetent mice (37) (so called “molecular latency”), virus can often only be revealed by transfer of tissues to SCID recipients. Therefore, persisting and inflating immune responses are commonly taken to indicate persistent infection (reviewed in Ref. 38), indicating that eMCMV and MCMV85A persist in vivo, as do similar attenuated MCMVs (49, 50). Another explanation for the low frequency of the 85A response might be antigenic competition between the dominant CD8 Ld-restricted 85A70–78 epitope and the Ld-restricted inflationary pp89 epitope. MCMV85A lacks the first 16 genes of the MCMV genome, including the m04 and m06 genes responsible for downregulation of MHC class I (17–20), so that presentation of MHC class
I–restricted epitopes should not be inhibited in MCMV85A-infected cells because of the abundance of class I. However, mL152, which is intact in this backbone, can downregulate D1 and L3 (19) and might potentiate competition, although both pp89 and 85A should be expressed with immediate early kinetics and should therefore be less sensitive to interference by the early gene mL152 (38). Nevertheless, the possibility of antigenic competition for L3 is supported by data on the response to another L3-restricted epitope, M83/pp105, which is also maintained at a very low frequency, close to the limit of detection of intracellular cytokine staining (39). Thus, it may be that the pp89 epitope outcompetes other L3-restricted epitopes irrespective of the abundance of MHC class I, either because it has higher affinity for L3 or through other undetermined viral mechanisms.

The CD8 response in MCMV85A-infected animals, detected after boosting with Ad85A in vivo or with 85A peptides in vitro, is directed to MHC class I–restricted epitopes previously reported in animals immunized with Ad85A, 85A protein, or peptides (34, 35). There is no evidence for the unconventional MHC class II–restricted CD8 responses generated by recombinant rhesus monkey CMV vectors, but clearly these responses require expression of a particular set of CMV genes (16), which may not be present in MCMV85A.

Irrespective of the reason for the very low 85A-specific response in the MCMV85A-infected animals, the data illustrate an important principle, that it may not be necessary to induce a large Ag-specific population to obtain effective protection. This is in agreement with a recent study using an rMCMV virus containing an HSV-1 epitope, which showed that it is not necessary to induce a powerful, largely CD8, local immune response in MCMV85A-infected animals, the data illustrate an inflationary CD8 response for protection (13).

Our data indicate that in addition to the specificity and magnitude of the adaptive response, other factors may be critical for effective protection against M. tuberculosis. It is clear that MCMV itself has a nonspecific protective effect against M. tuberculosis, as has already been shown for Listeria monocytogenes for both MCMV (51) (P. Klenerman and G. O’Hara, personal communication) and murine gammaherpesvirus 68 (52). However, this effect, attributed to IFN-γ production and macrophage activation, has been reported to wane between 3 and 6 mo after virus infection (53), whereas there was still a trend toward a decreased mycobacterial load in eMCMV-infected mice at 24 wk (Fig. 1). It will be interesting to examine protection induced by both eMCMV and MCMV85A at even later time points after infection. Furthermore, although we have not excluded an effect of macrophage activation, this is largely dependent on MCK-2 in vivo, which is deficient in the Δm1-16-FRT backbone (54).

MCMV infection is known to efficiently activate NK cells, although the magnitude of this effect varies substantially depending on the host strain and virus variant (55, 56). Our microarray data indicate that the IL-21 message is upregulated in eMCMV-infected BALB/c mice, and we chose to investigate this gene further because it is known that a prominent effect of this highly pleiotropic member of the common γ-chain cytokine family is NK cell activation (57). Furthermore, pathway analysis showed that several genes related to IL-21 function are also highly upregulated (AICDA, RGS13, IL-10, MADCAM1). NK cell activation was confirmed by the increased NK cytotoxicity of cells from eMCMV mice. The importance of IL-21 and NK cells is supported by the in vivo experiments with IL-21RFc and IL-21, as well as the abolition of nonspecific protection by administration of anti-ASGM1 Ab. Interestingly, a plasmid expressing M. tuberculosis Ags 85A and ESAT-6 with IL-21 has been shown to give increased immune responses to the M. tuberculosis Ags, higher NK activity, and better protection against M. tuberculosis, compared with a plasmid without IL-21 (58).

In addition to the nonspecific effect, the 85A-specific cells induced by MCMV85A and recruited to or expanded in the lungs after M. tuberculosis challenge must play a role in protection (Fig. 4C) because MCMV85A consistently provides better protection than eMCMV, although whether the activated NK cells play a role in the activation of the Ag-specific CD8 cells remains to be determined.

As is the case with MCMV85A, BCG, the gold standard TB vaccine, is known to activate the innate immune system as well as induce an adaptive response (59). Furthermore, BCG induces a state of “trained immunity” in macrophages, persisting for several months and conferring increased nonspecific protection against other infections (8, 60), and recently cytokine responses of NK cells were identified as an effector mechanism induced by BCG (61).

Although the relative importance of innate and adaptive responses in BCG-induced protective immunity remains to be determined, in the case of MCMV85A, innate immunity appears to play an important role, although clearly potentiated by a weak adaptive response. However, even when a much more powerful and readily detectable adaptive response is induced, correct innate signaling remains crucial, as shown in experiments in which Ad85A and VSV85A were delivered to the lungs. Both vectors induce powerful, largely CD8, local immune responses, but whereas Ad85A is protective against M. tuberculosis, VSV85A is not, an outcome ascribed to a critical difference in the balance between IL-12 and type I IFN induced by the two vaccines (9).

To our knowledge, we have demonstrated specific anti-M. tuberculosis protection for the first time using novel MCMV vectors. Surprisingly, a small Ag-specific response may be highly effective in synergy with the correct innate activation in this case involving IL-21 and NK cells. There is clearly great scope for improving further the efficacy of CMV vectors (16, 51). New approaches are certainly required, because so far no vaccine against pathogens, for which T cells are the protective mechanism, has been successful, and the strategy of attempting to induce ever greater adaptive T cell responses has so far failed (2). Our data support the view that it is essential to induce correct innate as well as adaptive responses.

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Disclosures

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References


Figure S1. Generation of eMCMV and MCMV85A

(A) Schematic representation of the genetic engineering of the MCMV constructs. The upper schema shows the wt recombinant MCMV genome (wt MCMV): Gene blocks (I-VII, including genes M45-M116) that are conserved among all herpesviruses are located in the center of the genome (black boxes with Roman numerals). Within these gene blocks other genes are interspersed which show only a small degree of conservation. Additional gene clusters towards the ends of the genome are conserved in cytomegaloviruses (gray boxes, C1, C2 and C3; representing M23-M44, m106-m108 and m117-m131 respectively), and finally the terminal gene clusters (light gray boxes, M1 and M2 + M3 corresponding to m01-m22 and m132-m170) represent genes that are species specific. The BAC cassette (white box) is inserted into the right terminal species-specific gene cluster, splicing it artificially to M2 and M3, which remain functionally intact. In the vector backbone (Δm1-m16-FRT) used in this study and shown in the second schema, the terminal part of M1 including the genes m01 to m16 is deleted and an FRT site is inserted (gray arrowhead). Into this position expression cassettes are inserted by site-specific recombination. The expression cassette for MCMV85A (shown in the third schema) includes the Mtb 85A antigen (black box, TB85A) expressed under the control of the human CMV immediate early promoter and the BGH poly-adenylation signal. The control construct eMCMV depicted at the bottom contains only the empty transcription unit including the promoter and poly-adenylation signal. The control construct eMCMV depicted at the bottom contains only the empty transcription unit including the promoter and poly-adenylation signal. The vector backbone carries a mutant allele of m129 (m129mut) and wild type m157 allele (m157wt).

(B) RT-PCR of 3T3 cells infected with MCMV85A. RNA was isolated from 3T3 cells infected with eMCMV or MCMV85A 48 hours after infection, reverse transcribed and amplified with 85A specific primers. The arrow indicates the 300bp marker. A strong 277bp 85A specific band is present in MCMV85A infected cells. (C) Virus titre. Mice were infected with 10^6 PFU eMCMV or MCMV85A and 6 days later MCMV titres were determined in salivary gland, liver and spleen. Each symbol represents one mouse. Empty circles indicate eMCMV and filled MCMV85A. Representative of two experiments.
Figure S2. Memory T cell subsets of pp89 and M18 specific cells in eMCMV or MCMV85A infected mice at d60

BALB/c mice were infected with 2 x 10^6 PFU eMCMV or MCMV85A I.P., and sacrificed 60 days post infection. The proportion of pp89 or M18 central (CD62L+ CD127+), effector memory (CD62L- CD127+) or effector (CD62L- CD127-) antigen specific CD8 T cells in lungs, liver and spleen of each mouse, was determined by surface and intracellular immunofluorescence staining and flow cytometric analysis. The gates used are shown in the FACS plot. Results are expressed as the proportion of CD8 IFNγ cells with each phenotype and show the mean and SD of 3 mice.
BALB/c mice were infected with 2 x 10^6 PFU eMCMV or MCMV85A I.P. and sacrificed 60 days post infection. The proportion of pp89 or M18 antigen specific CD8 T cells was determined by surface and intracellular immunofluorescence staining and flow cytometric analysis after 6 hours stimulation of lung, spleen or liver cells with the pp89 or M18 peptides. Results are expressed as the proportion of pp89 or M18 specific CD8+ IFNγ+ KLRG1+ (A) or CD8+ IFNγ+ CD27- cells (B). Cells from 3 mice were assayed separately. Error bars show SD.
Figure S4. Microarray heat maps.

A. The heat map shows the top 100 most significant genes that are 2 fold up- or down-regulated, ranked by p value and expression level, mean centralized and divided by standard deviation (by row) (Z-score scaling). B. The top 22 most significant 3 fold up- or down-regulated genes are shown. Arrows indicate IL-21. Lung mononuclear cells of 4 naive (n) and 4 eMCMV infected mice (eM) were analyzed.