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Interference with Dendritic Cell Populations Limits Early Antigen Presentation in Chronic γ-Herpesvirus-68 Infection

Adele M. Mount,* Frederick Masson,* Fiona Kupresanin,* Christopher M. Smith,† Janet S. May,† Nico van Rooijen,‡ Philip G. Stevenson,† and Gabrielle T. Belz*†

A critical factor influencing the ability of the host to mount a robust immune response against a virus depends on the rapid recruitment of dendritic cells (DCs) presenting Ags. From the outset, this step sets the tempo for subsequent activation of virus-specific T cells. Despite this, how induction of the immune response might be modified by pathogens with the capacity to establish persistence is unclear. In this study, we have characterized the in vivo influence of murine γ-herpesvirus K3-mediated interference with MHC class I in DCs that drive the initial adaptive immune response. We observed that γ-herpesvirus could interfere with the very earliest phase of Ag presentation through K3 by directly targeting migratory and lymph node-resident DCs. These results show that a pathogen with the capacity to interfere with early Ag presentation can establish suboptimal conditions for rapid induction of the adaptive immune response and thus favor establishment of viral persistence. The Journal of Immunology, 2010, 185: 3669–3676.

*Dendritic cells (DCs) are involved in a wide range of immune responses ranging from resistance to infection to maintenance of self-tolerance. Importantly, different DC subsets appear to have specialized roles in immune responses, such as the secretion of abundant amounts of type I IFNs in response to viral infections. Among conventional DC (cDC) populations, the CD8α+ DCs play a dominant role in the presentation of Ag in the context of viral infection, particularly to CD8+ T cells (1). CD8α+ DCs also can cross-present exogenous Ags on MHC class I molecules to activate CD8+ T cells (2) so do not necessarily require direct viral infection to initiate the CD8+ T cell response. In contrast, multiple DC subsets including CD8α− cDCs and CD4+ and double-negative (DN) DCs can play significant roles in stimulating CD4+ T cell responses (3, 4). This division of labor between DC subsets appears quite distinct in some viral infections, such as HSV-1 infection, and has led to the notion that DC populations are fundamentally specialized to handle either MHC class I or II pathogen-derived Ags. Despite this, in other infections, such as influenza infection, non-CD8α DC subsets also present abundant amounts of viral Ag to CD8+ T cells, implying that different infections can impact differently on DC populations in driving an immune response (5, 6). Most of our understanding of the induction of CD8+ T cell responses by DC subsets comes from the analysis of lytic infections. Temporal changes in the capacity of different DC subsets to present Ag in persistent infections have not been investigated in detail in vivo but are likely to play a key role in determining the capacity to rapidly induce an effective immune response.

Establishment of persistent infection by viruses such as γ-herpesvirus (γHV) is in part facilitated by immune modulatory proteins. These genes interfere with the expression of a variety of key components of the immune activation apparatus, including MHC class I and costimulatory molecules that are expressed on DCs (e.g., ICAM-1 and B7-2) (7). In the γHV family, the best characterized examples of viral genes that interfere with the expression of MHC class I glycoproteins on the surfaces of cells are Kaposi’s sarcoma-associated herpesvirus K3 and K5 (7) and the murine γHV-68 K3 (MK3) (8). Murine γHV-68 provides a useful model to study the host–pathogen interactions in a physiological setting. After intranasal infection, it establishes an acute lytic infection in the lung that is substantially controlled. Despite this response, the virus subverts the local immune response to establish lifelong persistence. The murine γHV K3 specifically inhibits MHC class I processing and in vivo limits the establishment of latency in spleen (9). This is achieved by directly degrading tapasin and TAP and through its action to ubiquitinate nascent H chains of classical MHC class I molecules, tagging them for proteasomal degradation (8, 10). Despite these effects, however, whether the virus targets particular cells types or tissues in vivo and where MK3 first exerts its action remain unclear. In earlier work, the deletion of MK3 from γHV-68 resulted in enhanced CD8+ T cell responses despite lower viral loads. It seems likely that DCs could be a major target of the effects of MK3 and that this would impact significantly on the development of the immune response if it occurred at an early stage of T cell priming. Such a strategy could result in failure to contain initial infection and facilitate systemic establishment of the virus.

In this study, we systematically investigated how a prototypical persistent virus, murine γHV, influenced the interplay between DCs and T cells during initial T cell priming. We found that one way the virus could diminish induction of the T cell response was to target early Ag presentation in different DCs to dampen rapid induction of the immune response. This early interference is likely to have broad implications for induction of effective pathogen immunity, particularly against persistent infections.
Materials and Methods

Mice
C57BL/6 (B6, H-2b), B6.SJL-1PppcarPep3b/BoyJ (Ly5.1), OT-1 (Ly5.2+), and Ly5.1OT-I mice were bred and maintained in specific pathogen-free conditions at the animal facilities of The Walter and Eliza Hall Institute of Medical Research (Melbourne, Australia). Experiments with all of the mice began when mice were 6–10 wk of age and were approved by and performed in accordance with guidelines of The Walter and Eliza Hall Institute of Medical Research Animal Ethics Committees.

Generation of recombinant γHV viruses

The generation of MHV-68 engineered to express OVA from an intergenic expression cassette under a lytic cycle promoter has been described previously (11). This approach incorporates an ectopic copy of the 500 bp upstream of the MHV-68 M3 open reading frame (ORF) as a strong, ORF50-dependent lytic cycle promoter (12). The full-length OVA-encoding sequence was PCR-cloned between the M3 promoter and a bovine growth hormone poly-A site derived from pcDNA3 (Invitrogen, Carlsbad, CA). The expression construct was then subcloned into the MHV-68 genomic clone (75338–78717) and subcloned with its genomic flanks into pSt76K-SR. This expression cassette was then recombined into the MHV-68 bacterial artificial chromosome (BAC) between the ends of ORF57 and ORF58. Infectious virus was reconstituted from BAC DNA by transfection into BHK-21 cells with Fugene-6 (Roche Diagnostics, Mannheim, Germany) was prepared as described previously (19). Briefly, liposome-encapsulated viruses were added to graded numbers of flow cytometrically sorted DCs in 200 μl RPMI 1640 containing 10% FCS, 50 μM 2-ME, 2 mM L-glutamine, 100 U/ml penicillin, and 100 μg/ml streptomycin in 96-well V-bottom plates (Costar, Corinth, NY). Cultures were analyzed for proliferation after 60 h. Cells were harvested and stained with anti-CD8α-allophycocyanin (33-6-7; BD Pharmingen, San Diego, CA) and resuspended in 150 μl flow cytometry buffer containing 2.5 × 105 blank calibration beads (6 μm; BD Biosciences, San Jose, CA). Samples were analyzed by flow cytometry by PI exclusion until 5 × 105 to 1 × 106 beads were collected.

Ag presentation assays

For in vitro analysis of Ag presentation were grown from bone marrow progenitors of C57BL/6 mice in RPMI 1640 with 10% FCS, 50 μM 2-ME, 100 U/ml penicillin, 100 μg/ml streptomycin, and 7.5 ng/ml GM-CSF (PeproTech, Rocky Hill, NJ). To assay MHICase I-restricted presentation of the H2-Kk-restricted OVA epitope, DCs or peritoneal macrophages (2.5 × 105 cells per well) were infected or not with MHK3-OVA (3 PFU per cell, 4 h) and then incubated with a lactoexpressing OVA-specific T cell hybridoma (9). After 18 h of culture, the cells then were washed in PBS and lysed in PBS containing 5 mM MgCl2, 1% Nonidet P-40, 0.15 mM chloroform and 100 μg/ml chloroform-red-β-galactoside (Merek Biosciences, Nottingham, U.K.) to assay β-galactosidase activity. After 2–4 h, the absorbance at 595 nm was read on a Benchmark microplate reader (Bio-Rad, Hercules, CA).

In some experiments, direct analysis of MHC class I/OVA complexes was detected by incubating FMS-like tyrosine kinase 3 ligand (Flt3L)-stimulated DCs with biotinylated mAb 25-D1 (PharMingen, San Diego, CA) and resuspended in 150 μl flow cytometry buffer containing 2.5 × 105 blank calibration beads (6 μm; BD Biosciences, San Jose, CA). Samples were analyzed by flow cytometry by PI exclusion until 5 × 105 to 1 × 106 beads were collected.

Clodronate liposome treatment

Depletion of inflammatory Gr1+ monocytes was performed according to the protocol previously described (19). Briefly, liposome-encapsulated clodronate (dichloromethylene bisphosphonate was a gift from Roche Diagnostics, Mannheim, Germany) was prepared as described previously (20). To maintain depletion of monocytes throughout the infectious period, 200 μl clodronate-loaded liposomes were administered i.v. commencing 1 d prior to injection and continuing every other day for the duration of the experiment.

Statistical analysis

Statistical comparisons were made on all of the data using the Student two-tailed t test. All of the experiments contained two to five replicates per experimental parameter. Statistically significant comparisons, p ≤ 0.05, are denoted with an asterisk.

Results

Herpesvirus evasion protein MK3 limits maximal Ag presentation and priming of CD8+ T cells early in infection

The activation of T cells during a localized infection occurs in the draining LNs where the bulk of T cell priming to a primary infection is thought to occur (21). In an infection, this represents the first point of contact between cells carrying viral Ag and virus-
specific T cells that are critical to the local control of infection. Murine γHV infection provides a robust model to examine how the interactions between DCs and T cells are affected by a virus encoding a gene known to disrupt Ag presentation. To facilitate detailed tracking of T cell–DC interactions and the influence of MK3 in vivo, we used a γHV encoding OVA (MK3+-OVA) and generated complementary recombinant viruses in which the OVA protein was inserted into the K3 ORF of a γHV-68 BAC (Fig. 1). This approach disrupts the plant homeodomain finger of MK3, rendering MK3 nonfunctional (9).

Persistent viruses, in contrast to acute viruses, commonly infect DCs, and modulation of DC function may offset the opportunity to prime T cells (22). Earlier work has suggested that MK3 was not active in DCs during infection (23). More recent evidence showed that MK3 can operate in DCs, at least in vitro (24), but it is less clear that it is active in vivo. We hypothesized that the enhanced CD8+ T cell response generated in the absence of MK3 (9) occurred by targeting MHC class I molecules in various types of APCs shortly after infection. To test this in an in vivo system in which we could trace Ag-specific presentation, we looked for the capacity of different APC populations to present OVA Ag encoded by competent or MK3-disrupted γHV. DCs and peritoneal macrophages were isolated from mice and then infected in vitro with either MK3+-OVA or ΔMK3-OVA virus (5 PFU per cell). A lacZ-encoding OVA-specific T cell hybridoma was used to detect OVA-specific MHC class I Ag presentation (25). Infection with the ΔMK3-OVA virus was accompanied by a ∼2-fold increase in the level of Ag presentation in both types of APCs (Fig. 2A, upper panel). Similarly, in vitro-generated DCs infected with ΔMK3-OVA showed an increase in both the number and the mean fluorescence intensity of CD11c+ cells expressing the MHC class I Kb/SIINFELK complexes compared with those of MK3+-OVA-infected DCs (Fig. 2A, lower panel). To establish if the effect of MK3 also translated to in vivo-derived DCs and priming of Ag-specific CD8+ T cells, we assessed the capacity of virally infected DCs to drive amplification of naive CD8+ T cells (Fig. 2B). DCs were enriched directly from spleens of naive C57BL/6 mice and then infected with either MK3+-OVA or ΔMK3-OVA viruses. The proliferation of naive OT-I cells was assessed following 60 h of in vitro culture. Increased expansion of OVA-specific T cells was observed when they were stimulated with ΔMK3-OVA-infected DCs, where the MK3 gene has been disrupted, and therefore MHC class I Ag presentation should proceed normally (Fig. 2B). The diminished presentation in MK3+-OVA infection could not be attributed directly to differences in DC death because...
the expression of annexin V in DCs was similar in both infections (data not shown). These data indicate that MK3 is functional in both vitro-derived and purified in vivo DCs and that it can modulate the priming ability of the exposed DCs following in vitro infection.

Induction of the immune response to murine γHV depends almost exclusively on DCs to activate naive CD8+ T cells (26). Similarly, in the setting of ΔMK3-OVA virus infection, CD11c+ cells were necessary for T cell proliferation for both MK3+OVA and ΔMK3-OVA herpesviruses (Supplemental Fig. 1), demonstrating that this requirement for DCs in T cell priming was not altered in vivo by truncation of the MK3 gene. Analysis of lung viral titers in C57BL/6 mice suggested that viral replication in vivo was similar for the
Deletion of MK3 function uncovers Ag presentation by CD11b+ DCs

Although MK3 transcripts are detected in DCs during the establishment of latency (27), the impact of MK3 on DCs during acute in vivo infection is unclear. Most of our understanding of the function of MK3 is derived from in vitro studies (23, 24). In this setting, lytically infected DCs downregulated CD86 and MHC class I expression, resulting in poor Ag presentation to CD8+ T cells (24). To understand how MK3 induces impairment of CD8+ T cell expansion in vivo, we explored the possibility that Ag presentation by DCs that first traffic from the infected lung and encounter CD8+ T cells was negatively regulated by the expression of MK3. To address this, we isolated DC subsets from the draining mediastinal LN 3 and 5 d after intranasal infection with either MK3+-ova or ΔMK3-OVA. The DCs within the DN subset are composed of multiple subsets (including plasmacytoid DCs, trafficking DCs, and LN-resident DCs), and these populations appear to have distinct functions in other viral infections (5, 6). Mediastinal LN DCs were depleted of plasmacytoid DCs and then divided into lung-derived CD8α+CD11b− trafficking DCs, LN-resident CD8α+CD11b− DCs, and CD8α−/CD11b+ DCs (Supplemental Fig. 2A). In this setting, CD11b− DCs express the αε integrin CD103, whereas CD11b+ DCs lack expression of CD103 (Supplemental Fig. 2B). Purified DCs then were cultured for 60 h with 5 × 10^4 naive CFSE-labeled OT-I cells. With this approach, it became apparent that MK3+-encoded OVA Ag was presented by at least two populations of DCs within the mediastinal LN, namely, CD8α+ DCs and CD8α−CD11b+ DCs (Fig. 3). This sorting regime revealed that, in the absence of MK3, the CD8α−CD11b+ DCs also played a key role in driving the proliferation of naive OVA-specific CD8+ T cells (Fig. 3). Conversely, in the presence of MK3, only very weak Ag presentation was detectable in this population. These data show that MK3 interferes with overall Ag presentation but can specifically interfere with particular subsets, namely, the CD11b+ DCs, resulting in a dampening of the key priming phase of the T cell immune response.

**FIGURE 3.** Fine dissection of DC populations uncovers subset-specific MK3 inhibition of Ag presentation in vivo. Naive C57BL/6 mice were infected with 3 × 10^5 PFU of MK3+-OVA (A, C) or ΔMK3-OVA (B, D). Three and five days postinfection, Ag presentation of different DC subsets was assessed. The mediastinal LNs were isolated at 3 (A, B) and 5 d (C, D) after intranasal infection. CD11c+ DC subsets were purified by flow cytometric sorting into CD8α−CD11b− DCs, CD8α+CD11b− DCs, and CD8α−/CD11b+ DCs (Supplemental Fig. 2A) before culturing titrating numbers of each subset with 5 × 10^4 CFSE-labeled OVA-specific CD8+ T cells for 60 h. A and B show the mean ± SEM of four independent experiments; C and D show one of three similar experiments. E, Mediastinal LNs were pooled from 15–20 mice at each time point, and DC subsets were purified by flow cytometric sorting after depletion of non-DC populations. A total of 5 × 10^7 purified cDCs subsets were cultured with 5 × 10^4 CFSE-labeled OVA-specific CD8+ T cells. Proliferation was analyzed at 60 h of in vitro culture. Data show representative profiles of one of three similar experiments.
MK3 expression impairs recruitment of conventional and inflammatory DCs to the lung-draining LN

Recently, inflammatory monocyte-derived DCs (moDCs) have been implicated in Ag presentation during the immune response (28). This subset expresses intermediate levels of the classical DC lectin CD11c together with high levels of the adhesion molecule CD11b and Grl, whereas cDCs can be distinguished from these cells by their high levels of CD11c (Figs. 4, 5) (19). To determine the involvement of inflammatory monocytes in γHV infection, we first compared the number of cDCs and inflammatory moDCs recruited into the mediastinal LN following MK3+-OVA and ΔMK3-OVA infection (Fig. 4). In this setting, we found a reduction in both cDCs and moDCs when MK3 was expressed. This difference was most striking for moDCs and suggested that they could be involved in virus-specific T cell activation (Fig. 4). To test this, we determined the capacity of moDCs isolated from mediastinal LNs of infected mice (Fig. 5A) to induce proliferation of naive OVA-specific CD8+ T cells (Fig. 5B). cDCs were able to effectively activate CFSE-labeled OT-I CD8+ T cells using this approach, whereas moDCs showed no apparent capacity to induce the proliferation of virus-specific CD8+ T cells. To test this further, we used an in vivo model where moDCs are not subjected to ex vivo manipulation prior to determining their functional ability. γHV-infected mice were depleted of moDCs using clodronate-loaded liposomes, then congenically marked OVA-specific CD8+ T cells were adoptively transferred into mice, and their proliferation was assessed (Fig. 5C, 5D). This approach has been used previously to selectively remove moDCs in vivo for assessment of Ag presentation (29). Despite the markedly enhanced recruitment of moDCs that we observed in the absence of MK3 (Fig. 4), the expansion of OVA-specific CD8+ T cells was not significantly different in mice depleted, or left undepleted, of moDCs for either K3+ or K3− γHV infection (Fig. 5D). Thus, we found little evidence for a role for moDCs in early Ag-specific priming of CD8+ T cell responses after γHV infection (Fig. 5B, 5D). The full implications of the alteration of the APC recruitment pattern are yet to be determined, but these data imply that additional factors associated with viral infection can secondarily influence optimal DC recruitment, leading to an impaired or delayed immune response.

**Discussion**

A hallmark of persistent infections is the failure to develop protective immune responses sufficiently rapidly to prevent dissemination of the pathogen throughout the body. In several infections such as HIV (30), hepatitis virus (31) and Mycobacterium tuberculosis (32), there is a significant delay between pathogen infection and induction of the adaptive immune response. This lag period potentially allows uncontrolled spread and/or dissemination of the pathogen. Although high antigenic variability, slow replication, poor immunogenicity, and the capacity of the pathogen to disrupt key recognition elements of the immune system have been causally implicated, the specific mechanisms underpinning this lag period have been poorly elucidated (30).

It is beginning to emerge, however, that pathogens can delay induction of an immune response by sequestration of organisms as a strategy to establish persistence (32). In the case of *M. tuberculosis* infection, although bacteria were present in the lung, initiation of the immune response could not proceed due to a lack of DCs expressing mycobacterial Ags in the mediastinal LN despite normal lung to LN migration by these cells (32).
Previously, γHV MK3 has been shown to interfere with the establishment of viral latency in the spleen, but the cells involved in this process and the tissue site of action in vivo have been unclear (9). We show that in persistent γHV infection this can occur in DCs in the lung-draining LNs. Furthermore, disruption of MHC molecules in DCs by MK3 early postinfection limits amplification of T cells. Indeed, the overall capacity of DCs to present Ag to T cells is a critical parameter to optimize antiviral responses. The effects of MK3 diminished overall Ag presentation but, in addition, appeared to ablate presentation by CD11b+ DCs early in infection and to limit recruitment of moDCs into the immune response. These findings establish a setting for suboptimal induction of early γHV T cell immunity in the lung-draining LN mediated at least in part by MK3 targeting or impairing one or more DC subsets. The broader reliance on non-CD8α DC subsets identified in this study is concordant with other lung infection models where it is now clearer that multiple DC subsets are necessary for full immune induction rather than this being limited to a single DC population (such as CD8α+ DCs) (5, 6, 33).

In the case of MK3-ova infection, although CD8α+ DCs did present significant Ag during the first few days of infection, the effect of MK3 was most striking within the non-CD8α DC subsets where elimination of MK3 uncovered the ability of an additional subset of DCs (the CD8α−/CD11b+ DCs) to present viral Ag. It is possible that efficient early Ag presentation by CD8α+ DCs may be associated with the secreted nature of the surrogate Ag OVA facilitating cross-presentation of Ag. As the virus replicates, however, it is likely that a broader number of DCs are directly infected and thus may be negatively influenced by viral evasins acting to downmodulate the induction and overall magnitude of this early priming response in the regional LN. These effects open the way for a pathogen to largely negate early detection by the immune system while it establishes the foothold that is the basis of persistence.

An additional unexpected finding of this study was the alteration in recruitment of inflammatory moDCs detected in the mediastinal LN. The precise role played by moDCs in infection is currently unclear, although they have been implicated as main producers of TNF-α and inducible nitric oxide synthase and may play a role in Ag presentation (28, 29). In MK3-ova infection, moDCs do not effectively present MHC class I viral Ag and thus do not appear to be directly involved in the early phase of the induction of the CD8+ T cell response. It has been proposed that moDCs may be principally involved in modulating the innate immune response during inflammation and thus play essential functions during infection.
although the precise nature of this remains to be elucidated. Despite this, the fact that Ag presentation of DC subsets and recruitment of moDCs are both modulated by the action of MK3 during MK3–OVA infection highlights the multiple pathways that may be influenced by such an evasion gene. This opens the possibility that in persistent infections differential effects on DC subsets by the virus itself may facilitate the establishment of persistence by allowing it to sneak through the frontline defense in the LN early in infection (34).

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Disclosures
The authors have no financial conflicts of interest.

References
Supplementary Data:

Interference with Dendritic Cell Populations Limits Early Antigen Presentation in Chronic γHerpesvirus-68 Infection

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**Supplementary Figure 1.** Conditional depletion of CD11c<sup>high</sup> cells abrogates CD8<sup>+</sup> T cell proliferation. A, Bone marrow chimeras were generated by reconstituting lethally irradiated C57BL/6 mice with CD11cDTR bone marrow and allowed 6-8 weeks for their haemopoietic compartment to reconstitute. Mice were then depleted of CD11c<sup>high</sup> cells using an i.p. injection of 100mg Diptheria toxin (DTx) one day prior to infection. 1 x 10<sup>6</sup> purified CFSE-labeled congenic Ly5.1.OT-I CD8<sup>+</sup> T cells were adoptively transferred into mice and they were then infected with either MK3<sup>+</sup>-OVA or MK3<sup>-</sup>-OVA. After five days, the draining mediastinal LN was harvested and the proliferation of Ly5.1.OT-I CD8<sup>+</sup> T cells was assessed by loss of CFSE staining. Data are pooled from two independent experiments with six to seven mice per group and show the mean ± SEM. n.d., not detected. B, Efficiency of DTx depletion was assessed by enrichment of DNase/collagenase digested, nycodenz density gradient enriched and staining recovered cells with anti-CD11c. The presence of CD11c<sup>+</sup> DC in control (left panel) and DTx treated mice (right panel) was assessed by coexpression of CD11c and GFP by flow cytometry. DTx was given at -1 and +2 days of infection to maintain depletion over the course of the experiment.

**Supplementary Figure 2.** Sorting strategy for mediastinal LN DCs following i.n. γ-HV infection. A, Flow cytometric gating strategy for analysis of DCs isolated from mediastinal LN following DNase/collagenase digestion and staining for surface expression of CD11c, CD11b, CD8α and CD45RA. Profile is gated on CD11c<sup>+</sup>CD45RA<sup>-</sup> conventional DCs thereby excluding CD45RA<sup>+</sup> pDCs. Cells were purified to > 98% by high a speed flow cytometric sorting. B, Flow cytometric analysis of CD103 expression on CD11b<sup>+</sup> and CD11b<sup>-</sup> DC subsets from mediastinal LNs on day 5 after intranasal infection with MK3<sup>+</sup>-OVA (upper panels) or ΔMK3-
OVA (lower panels). Data are representative of similar profiles analysed from individual mice.
Supplementary Figure 1

**A**

![Bar Chart]

- **x-axis:** MK3^+ OVA, MK3^+ OVA DTx, ΔMK3-OVA, ΔMK3-OVA DTx
- **y-axis:** Number of CFSE<sub>low</sub> OT-1 cells (x 10<sup>5</sup>)
- Legend: n.d., *p < 0.05

**B**

![Flow Cytometry Graphs]

- **Legend:** CD11c
- **Data:** MK3^+ OVA, MK3^+ OVA DTx

*Note: The diagram includes statistical significance indicated by an asterisk.*
Supplementary Figure 2

A

- a. CD8α+ DC
- b. CD8α-CD11b- DC
- c. CD8α+/−CD11b+ DC

B

- CD11b+ DC
- CD11b- DC

CD103

MK3−-OVA

Relative cell number

MK3+-OVA

Relative cell number