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The Dendritic Cell-Specific Chemokine, Dendritic Cell-Derived CC Chemokine 1, Enhances Protective Cell-Mediated Immunity to Murine Malaria

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Cell-mediated immunity plays a crucial role in the control of many infectious diseases, necessitating the need for adjuvants that can augment cellular immune responses elicited by vaccines. It is well established that protection against one such disease, malaria, requires strong CD8+ T cell responses targeted against the liver stages of the causative agent, Plasmodium spp. In this report we show that the dendritic cell-specific chemokine, dendritic cell-derived CC chemokine 1 (DC-CK1), which is produced in humans and acts on naive lymphocytes, can enhance Ag-specific CD8+ T cell responses when coadministered with either irradiated Plasmodium yoelii sporozoites or a recombinant adenovirus expressing the P. yoelii circumsporozoite protein in mice. We further show that these enhanced T cell responses result in increased protection to malaria in immunized mice challenged with live P. yoelii sporozoites, revealing an adjuvant activity for DC-CK1. DC-CK1 appears to act preferentially on naive mouse lymphocytes, and its adjuvant effect requires IL-12, but not IFN-γ or CD40. Overall, our results show for the first time an in vivo role for DC-CK1 in the establishment of primary T cell responses and indicate the potential of this chemokine as an adjuvant for vaccines against malaria as well as other diseases in which cellular immune responses are important. The Journal of Immunology, 2003, 170: 3195–3203.

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4 Abbreviations used in this paper: DC-CK1, dendritic cell-derived CC chemokine 1; AdPyCS, adenovirus expressing the P. yoelii CS protein; CD40L, CD40 ligand; CS, circumsporozoite; IFA, immunofluorescence assay; MCMV, murine CMV; m.o.i., multiplicity of infection; PJ3K, phosphatidylinositol 3-kinase; γ-spz, irradiated sporozoite; WT, wild type.
that undergo maturation (21). In addition, DC-CK1 expression has been detected in both germinal centers and T cell areas of lymph nodes, areas where primary B and T cell responses take place (18, 20). Furthermore, a recent in vivo study has shown that naïve T cells cluster in the vicinity of mononuclear cells, producing DC

CK1 mRNA in portal area lymphoid follicles of livers from patients with chronic hepatitis C (22). Taken together, these data strongly suggest a role for DC-CK1 in the initiation and generation of primary T and B cell responses.

In the present report we demonstrate that human DC-CK1 enhances Ag-specific primary CD8\(^+\) T cell responses when coadministered with malaria vaccines in mice. We further demonstrate that this enhancement of Plasmodium-specific CD8\(^+\) T cell responses results in increased protection from malaria, revealing an adjuvant effect for DC-CK1. We show that DC-CK1 is chemotactic for mouse lymphocytes, and that its adjuvant activity relies on IL-12, but not IFN-\(\gamma\) or CD40. Overall, our results show for the first time a role for DC-CK1 in the induction of a primary T cell response in vivo as well as its possible use as an adjuvant for vaccines where strong CD8\(^+\) T cell responses are required.

Materials and Methods

Animals and parasites

Six- to 8-wk-old female BALB/c mice, purchased from the National Cancer Institute (Bethesda, MD), were used for most experiments. IL-12p40-deficient mice and CD40-deficient mice of BALB/c background were purchased from The Jackson Laboratory (Bar Harbor, ME). IFN-\(\gamma\) receptor-deficient mice with an H-2d background were generated as previously described (23). P. yoelii (17XNL strain) was maintained by alternate cyclic passages in Anopheles stephensi mosquitoes and Swiss-Webster mice as previously described (24). Sporozoites obtained from dissected salivary glands of infected mosquitoes 2 wk after their infective blood meal were used for immunization as well as challenge of the mice.

Construction and screening of recombinant adenosviruses

Recombinant adenosvirus expressing the P. yoelii circumsporozoite (CS) protein (AdpYS89) was constructed by first inserting a PCR fragment containing the open reading frame for aa 1–356 of the CS protein into a CMV expression cassette containing the CMV immediate early promoter, followed by transfer of this cassette into the adenoaviral shuttle vector pHW60 (25). Subsequently, human type 5 adenosviruses were generated in 293 cells (ATCC CRL-1573; American Type Culture Collection, Manassas, VA) by homologous recombination of the constructed shuttle plasmid and plasmid pM17 containing the complete Ad5 \(\Delta E1\Delta E3\) genome (26). Individual viral clones were obtained and analyzed for recombinant gene expression by RT-PCR and for recombinant protein expression by Western blot. Selected AdpYS89-293 cells were infected with AdpYS89 at a multiplicity of infection (m.o.i.) of 10 for 24 h and then assayed, whereas for Western blot, 293 cells were infected with AdpYS89 at an m.o.i. of 200 for 36 h. The clone expressing the most recombinant protein was then purified via large-scale CsCl purification, dialyzed, and frozen in aliquots for use in immunizing animals.

Recombinant adenovirus Adpp89-DC8, homologue to the recombinant vaccinia virus sc-A9/A (27), expresses the H-2L\(^d\)-restricted nonameric CTL epitope from the immediate early protein 1 (IE1/IE89) of the murine CMV (MCMV) inserted into a modified hepatitis B virus HBeAg in which the original signal peptide of the protein was replaced by the signal peptide of the hemagglutinin protein of influenza virus. A PCR fragment encoding this protein was inserted into the same CMV expression cassette noted above, which was then transferred into shuttle vector pMV60. Replication-deficient, human type 5 adenosviruses were generated as described above, and individual clones were screened for recombinant protein expression by Western blot. For this purpose, BALB/c mouse fibroblasts were infected with Adpp89-CD8 at an m.o.i. of 200 for 36 h and then probed with polyclonal rabbit anti-HBe (27) and HRP-labeled goat anti-rabbit IgG (Pierce, Rockford, IL). The clone expressing the most recombinant protein was then purified via large-scale CsCl purification, dialyzed, and frozen in aliquots for use in immunizing animals.

Recombinant adenosvirus AdDC-CK1 was constructed by first PCR cloning cDNA of human DC-CK1 using forward primer 5'-GGGGATCCGTCCTAGAAGGATGATCAGCT-3' and reverse primer 5'-TCACAATCTGATACGGCATCAGTTCCAGGC-3', followed by insertion of the cDNA into the same CMV expression cassette noted above, with the reaction was 95\(^\circ\)C for 1 min.

Quantification of Plasmodium 18S rRNA sequences was performed using a recently developed real-time RT-PCR technique (28). Briefly, total RNA (2 \(\mu\)g) from the livers of mice challenged with 10,000 viable sporozoites 42–44 h earlier was reverse transcribed, and an aliquot of the resulting cDNA (133 ng) was used for real-time RT-PCR amplification of P. yoelii 18S rRNA sequences. This amplification was performed in a GeneAmp 5700 Sequence Detection System (PE Applied Biosystems, Foster City, CA). For this purpose, we used primers 5'-GGGGATCCGTCCTAGAAGGATGATCAGCT-3' and 5'-AACGATCTTTATGATCAGCT-3' (54 nM) and 5'-AAGCATTAAATAGGCGAAATACTCCAT1TAT3' (60 nM) together with the dsDNA-specific dye SYBR Green I incorporated into the PCR reaction buffer (PE Biosystems, Foster City, CA) to detect the PCR product generated. The temperature profile of the reaction was 95\(^\circ\)C for 15 s and annealing/extension at 60\(^\circ\)C for 1 min.

Quantification of epitope-specific CD8\(^+\) T cells by ELISPOT assay

The relative number of CS-specific, IFN-\(\gamma\)-secreting CD8\(^+\) T cells in the spleens of mice receiving different immunization regimens was determined by direct ex vivo ELISPOT assays, as previously described (29). For these assays, we used MHC-compatible A20.2J target cells coated with the CS-derived H-2K\(^d\)-restricted epitope SYVPSAEQI, which is recognized by CS-specific CD8\(^+\) T cells. For quantification of IFN-\(\gamma\)-secreting CD8\(^+\) T cells in the...
cells specific for the CTL epitope of the MCMV immediate early protein 1, we used A20.2J target cells coated with the H-2L\(^d\)-restricted epitope YPHFMPPTNL.

**Indirect IFA**

*P. yoelii* anti-sporozoite Ab titers in the sera of immunized mice were determined using sporozoites air-dried onto multispot glass slides. After 1 h of incubation of these Ag slides with different sera diluted in PBS containing 1% BSA, the slides were washed and incubated with a FITC-labeled goat anti-mouse IgG Ab for another hour (Kirkegaard & Perry Laboratories). After repeated washes, the slides were mounted, and the anti-sporozoite Ab titers were determined as the highest serum dilution producing fluorescence when viewed under an UV microscope.

**Results**

**Coadministration of DC-CK1 enhances Ag-specific T cell responses elicited by vaccines**

CD8\(^+\) T cells secreting IFN-\(\gamma\) have been shown to be the main mediators of protection against the liver stages of murine malaria (8, 13). Given the probable involvement of DC-CK1 in promoting the generation of primary T cell responses, we sought to determine whether exogenously administered DC-CK1 could enhance primary antimalaria T cell responses. For this purpose we used two sources of exogenous DC-CK1: recombinant DC-CK1 protein (rDC-CK1) and a recombinant adenovirus expressing DC-CK1 (AdDC-CK1). Groups of BALB/c mice were immunized with either irradiated sporozoites (\(\gamma\)-spz) or a recombinant adenovirus expressing the CS protein of *P. yoelii* (AdPyCS) in the presence or the absence of different doses of rDC-CK1 or AdDC-CK1. Two weeks after immunization, the number of CS-specific, IFN-\(\gamma\)-secreting CD8\(^+\) T cells was determined by ELISPOT assay.

When mice were injected s.c. with suboptimal doses of either \(\gamma\)-spz or AdPyCS, together with different doses of rDC-CK1, we found that coadministration of 100 ng of rDC-CK1 resulted in the induction of the highest number of CS-specific T cells elicited by either immunogen (Fig. 1, A and B). This dose of chemokine stimulated a 3- to 4-fold increase in the number of CS-specific CD8\(^+\) T cells secreting IFN-\(\gamma\) compared with that of control mice receiving either immunogen alone. This DC-CK1-elicited increase in the CS-specific T cell response was also observed when rDC-CK1 was coadministered with either immunogen i.m., but not when it was given by a different route as the immunogen or at a different time (data not shown).

A similar result was obtained when we injected groups of mice with a suboptimal dose of AdPyCS together with different doses of AdDC-CK1. The number of CS-specific, IFN-\(\gamma\)-secreting CD8\(^+\) T cells elicited upon coadministration of AdPyCS and AdDC-CK1 depended on the dose of AdDC-CK1 coadministered, with a dose 10\(^7\) PFU of AdDC-CK1 resulting in the greatest enhancement of the CS-specific T cell response (Fig. 1C). This dose of AdDC-CK1 resulted in a 3- to 4-fold increase in the number of CS-specific CD8\(^+\) T cells secreting IFN-\(\gamma\) compared with that of control mice receiving AdPyCS alone. This AdDC-CK1-driven increase in the CS-specific CD8\(^+\) T cell response was due to DC-CK1, and not some other nonspecific effect, because mice coinjected with AdPyCS and a control adenovirus expressing the *Escherichia coli* \(\beta\)-galactosidase gene (AdLacZ) showed no increase in the malaria-specific T cell response (Fig. 1D). Interestingly, when AdDC-CK1 was coadministered with a suboptimal dose of \(\gamma\)-spz, no enhancement of the CS-specific T cell response was observed regardless of the dose of AdDC-CK1 given (data not shown).

In addition to the number of IFN-\(\gamma\)-secreting CD8\(^+\) T cells elicited by DC-CK1, we were interested in determining DC-CK1’s effect on the number of CS-specific CD8\(^+\) T cells secreting IL-4.

**FIGURE 1.** DC-CK1 increases the level of Ag-specific CD8\(^+\) T cell responses elicited by malaria vaccines. Groups of three BALB/c mice were immunized s.c. with 2 \times 10\(^4\) \(\gamma\)-spz (A) or 2 \times 10\(^4\) PFU AdPyCS (B) with or without different doses of rDC-CK1 by the same route, 2 \times 10\(^7\) PFU AdPyCS with or without different doses of AdDC-CK1 by the same route (C), or 2 \times 10\(^7\) PFU AdPyCS with or without 10\(^6\) PFU AdDC-CK1 or 10\(^5\) PFU of a control adenovirus, AdLacZ, by the same route (D). Two weeks after immunization, splenic lymphocytes were isolated from all mice, and the relative numbers of IFN-\(\gamma\)-secreting, CS-specific CD8\(^+\) T cells were determined by ELISPOT assay. The results are expressed as the average \(\pm\) SD of replicate cultures. In all figures the data represent one of two or more experiments with similar results.

For this purpose we immunized mice with \(\gamma\)-spz or AdPyCS with or without AdDC-CK1 or AdPC-CK1, and 2 wk later determined the number of CS-specific CD8\(^+\) T cells secreting IL-4 by ELISPOT assay. Coadministration of DC-CK1 with either malaria immunogen resulted in no difference in the number of CS-specific, IL-4-secreting CD8\(^+\) T cells compared with mice receiving either immunogen alone (data not shown). Likewise, when we determined the serum titers of anti-sporozoite Abs via an IFA of air-dried sporozoites, we found that coadministration of DC-CK1 with immunogen failed to increase the sporozoite-specific Ab titers in the sera of malaria-immunized mice (data not shown).

Finally, we were interested in determining whether DC-CK1 could enhance T cell responses elicited by vaccines to other microbial infections in which cell-mediated immunity plays an important role. To address this question, we used as an immunogen a recombinant adenovirus expressing a well-characterized, protective, H-2L\(^d\)-restricted CTL epitope of the MCMV pp89 protein (Adpp89-CD8) (30). Groups of mice were immunized s.c. with a suboptimal dose of Adpp89-CD8, with or without coadministration of 100 ng of recombinant DC-CK1 or 10\(^5\) PFU of Ad-DC-CK1, and the number of epitope-specific CD8\(^+\) T cells secreting IFN-\(\gamma\) was determined 2 wk later by ELISPOT assay. As with AdPyCS, both DC-CK1 protein and AdDC-CK1 strongly enhanced the MCMV-specific CD8\(^+\) T cell response elicited by Adpp89-CD8 immunization (Fig. 2). These results indicate that DC-CK1 can enhance T cell responses regardless of the Ags used. It also indicates that DC-CK1’s ability to enhance vaccine-elicited T cell responses is a phenomenon related not only to the H-2K\(^d\)-restricted CD8\(^+\) T cell epitope of the CS protein, but can also be applied to epitopes restricted to other MHC class I molecules.
Coadministration of DC-CK1 enhances protective antimalaria immunity elicited by malaria immunogens

It has been shown that both γ-spz and AdPyCS are capable of conferring sterile immunity to malaria in a significant number of immunized mice subsequently challenged with live sporozoites (31). This sterile immunity was found to be due to the immunogens’ ability to induce strong, specific T cell responses that target and suppress the development of Plasmodium liver stages. Since we found that DC-CK1 enhances malaria-specific CD8$^{+}$ T cell responses induced by γ-spz and AdPyCS, we sought to determine whether DC-CK1 could enhance the levels of antimalarial protection elicited by these two immunogens as well. For this purpose we immunized mice with suboptimal doses of either γ-spz or AdPyCS, with or without coadministration of DC-CK1. Two weeks later these mice along with unimmunized controls were challenged i.v. with 10,000 live sporozoites, and 42–44 h later the livers of the mice were obtained. Total RNA from the livers was then used in a highly sensitive, real-time RT-PCR assay to quantify the amounts of parasite-specific 18S rRNA present in mouse livers. The amounts of parasite-specific rRNA in the livers served as an indication of the degree to which Plasmodium liver stages were able to develop in the differentially immunized mice.

When we immunized mice with a suboptimal dose of γ-spz together with 100 ng of rDC-CK1, we found that the amount of parasite-specific 18S rRNA in the livers was less than that found in mice receiving the immunogen alone (Fig. 3A). This enhanced protection against the development of Plasmodium liver stages was also observed in mice immunized with a suboptimal dose of AdPyCS together with 100 ng of rDC-CK1 (Fig. 3B). These results mirror the aforementioned data showing that DC-CK1 can enhance malaria-specific CD8$^{+}$ T cell responses elicited by γ-spz and AdPyCS, suggesting that such T cell responses are responsible for the inhibited development of Plasmodium liver stages.

Finally, we found that coadministration of a suboptimal dose of AdPyCS along with 10$^6$ PFU of AdDC-CK1 also results in the appearance of less parasite-specific 18S rRNA in the livers of mice compared with those receiving AdPyCS alone (Fig. 3C). Interestingly, coadministration of 10$^7$ or 10$^9$ PFU of AdDC-CK1 with AdPyCS did not result in enhanced protection against malaria liver stages. As shown earlier, these two doses of AdDC-CK1 fail to enhance malaria-specific CD8$^{+}$ T cell responses elicited by AdPyCS. Thus, as with rDC-CK1, the ability of AdDC-CK1 to augment antimalaria protection appears to be due to the enhanced T cell responses stimulated by DC-CK1.

DC-CK1 stimulates chemotaxis in murine lymphocytes

To clarify the mechanism by which DC-CK1 exerts its adjuvant activity, we first sought to determine what cell types in mice respond to the chemokine. Although the mouse homologue of DC-CK1 has not yet been identified, a previous study showed that i.p. injection of synthetic human DC-CK1 into mice resulted in the accumulation of CD4$^{+}$ and CD8$^{+}$ T cells in the peritoneal cavity, but not monocytes or granulocytes. Thus, in mice, as in humans, DC-CK1 appears to act preferentially on lymphocytes (32). To confirm this, we performed in vitro chemotaxis assays, which measure the ability of cells to migrate from an upper chamber through a porous membrane into a lower chamber containing chemokine. First, we checked the ability of DC-CK1 to stimulate chemotaxis in unfractionated murine splenocytes. As sources of DC-CK1 we used both rDC-CK1 as well as supernatants from cells infected with AdDC-CK1. Recombinant DC-CK1 protein was able to stimulate chemotaxis in murine splenocytes in a dose-dependent manner. Increasing concentrations of DC-CK1 protein resulted in increasingly larger numbers of splenocytes migrating from the upper chamber into the DC-CK1-filled lower chamber (Fig. 4A). Similarly, supernatants collected from cell cultures infected with AdDC-CK1 also stimulated chemotaxis in murine splenocytes. This activity was due to DC-CK1 present in the supernatant, because supernatants from cells infected with the control adenovirus, AdLacZ, did not induce significant chemotaxis in the same cell population (Fig. 4B). Overall, these data indicate that DC-CK1 can act on mouse cells and stimulate chemotaxis.

To characterize the murine cell types responsive to DC-CK1, we purified various cell populations from unfractionated splenocytes and performed chemotaxis assays to identify the cell types that respond to the chemokine. First, we purified B and T cells by way
CD62L+ cells did respond to the chemokine, suggesting that DC
CK1 does not act exclusively on naive lymphocytes in mice.

DC-CK1 fails to enhance malaria vaccine-elicited CD8+ T cell responses in the absence of IL-12

IFN-γ and IL-12 are two cytokines important in the induction and maintenance of Th1-polarized T cell responses, which are characterized by IFN-γ-producing T cells (33–36). Since DC-CK1 enhances such responses in malaria vaccine-immunized mice in vivo, we wanted to learn whether either one of these molecules is involved in the adjuvant effect of DC-CK1. For this purpose, we immunized mice deficient in either IFN-γ receptor or IL-12p40 along with wild-type (WT) control mice of the same genetic background with AdPyCS with or without rDC-CK1 or AdDC-CK1. Two weeks after immunization we measured the CS-specific, CD8+ T cell response elicited by AdPyCS to the same degree as WT controls, indicating that the adjuvant effect of DC-CK1 is independent of IFN-γ (Fig. 5). In contrast, DC-CK1 failed to enhance the CS-specific CD8+ T cell response elicited by AdPyCS in mice lacking IL-12, but not in WT controls (Fig. 6). This IL-12 dependence was observed in AdPyCS-immunized mice receiving either rDC-CK1 (Fig. 6, A and B) or AdDC-CK1 (Fig. 6, C and D), indicating that the adjuvant activity of DC-CK1 requires IL-12.

It is known that optimal IL-12 production by APCs during the induction of Th1-polarized T cell responses requires engagement of the APC’s CD40 molecules by the CD40 ligand (CD40L) molecules of activated T cells (37–40). To determine whether the adjuvant activity of DC-CK1 requires such signaling, we immunized mice deficient in CD40 along with WT controls with AdPyCS with or without AdDC-CK1, and 2 wk later we measured the CS-specific, CD8+ T cell response by ELISPOT. CD40 knockout mice receiving both AdPyCS and AdDC-CK1 developed a 2- to 3-fold increase in the number of CS-specific, CD8+ T cells secreting IFN-γ (Fig. 6, C and D), indicating that the adjuvant activity of DC-CK1 requires CD40.
IFN-γ compared with knockout mice receiving AdPyCS alone (Fig. 7B). Similarly, WT control mice receiving both AdPyCS and AdDC-CK1 developed a 2- to 3-fold enhancement of the CS-specific, CD8⁺ T cell response compared with WT mice receiving AdPyCS alone (Fig. 7A). Thus, it appears that the IL-12-dependent adjuvant activity of DC-CK1 does not operate through the CD40-CD40L signaling pathway, but, instead, involves other factors.

**Discussion**

In the current report we assessed the ability of the recently discovered human chemokine DC-CK1 to modulate acquired antimalaria immunity in mice. We found that coadministration of DC-CK1, as either a recombinant protein (rDC-CK1) or a recombinant adenovirus (AdDC-CK1), to mice immunized with either a suboptimal dose of γ-spz or a suboptimal dose of a recombinant adenovirus expressing the P. yoelii CS protein (AdPyCS) significantly enhanced protective antimalaria immunity. Significantly, our results provide the first evidence for an in vivo role of DC-CK1 in the generation of primary T cell responses.

The enhancement of protective antimalaria immunity brought about by DC-CK1 administration was due to the generation of increased numbers of IFN-γ-secreting, CD8⁺ T cells specific for malaria Ags. In mice immunized with a suboptimal dose of γ-spz, coadministration of rDC-CK1 enhanced the malaria-specific CD8⁺ T cell response 3- to 4-fold over that of immunized control mice not receiving the chemokine. Likewise, a very similar increase in the malaria-specific CD8⁺ T cell response was found in AdPyCS-immunized mice receiving either rDC-CK1 or AdDC-CK1, indicating that the ability of DC-CK1 to enhance CD8⁺ T cell responses can occur with different immunogens. These enhanced CD8⁺ T cell responses resulted in increased suppression of malaria liver stage development as assayed by real-time RT-PCR. Immunized mice receiving the dose of rDC-CK1 (100 ng) or AdDC-CK1 (10⁸ PFU) that resulted in the biggest increase in CS-specific CD8⁺ T cells exhibited the highest suppression of P. yoelii liver stage development. In the case of AdDC-CK1, only a dose of 10⁸ PFU resulted in an increased CS-specific CD8⁺ T cell response, and only this dose led to enhanced suppression of malaria liver stages: doses of 10⁷ PFU and 10⁶ PFU failed to enhance the CS-specific CD8⁺ T cell response and thus the suppression of malaria liver stages. Given that optimal protective immunity against malaria liver stages requires CD8⁺ T cells, IFN-γ, or both (8–13, 23), it is not surprising that the ability of DC-CK1 to enhance the number of malaria-specific CD8⁺ T cells secreting IFN-γ resulted in increased protection against malaria liver stages. Moreover, protection against malaria liver stages can also be brought about by antisporeozoite Abs (8), but DC-CK1 administration failed to enhance the antisporeozoite humoral response in immunized mice, suggesting further that it was the chemokine’s ability to augment CS-specific CD8⁺ T cell responses that led to the enhanced protection.

The ability of DC-CK1 to enhance Ag-specific CD8⁺ T cell responses was also observed when the chemokine was administered with a recombinant adenovirus expressing the protective CD8⁺ T cell epitope of the MCMV pp89 protein (Adpp89-CD8). Whether as rDC-CK1 or AdDC-CK1, chemokine coadministration with Adpp89-CD8 enhanced the MCMV-specific CD8⁺ T cell response to a degree comparable to that of γ-spz and AdPyCS. This result indicates that the adjuvant activity of DC-CK1 is not specific only for malaria Ags, but works for other pathogens as well.

It is noteworthy that the administration of a high dose of either rDC-CK1 (300 ng) or AdDC-CK1 (10⁹ PFU) with malaria vaccines failed to induce an optimal increase in the CS-specific CD8⁺ T cell response. It is possible that giving too much DC-CK1, as either a recombinant protein or a recombinant adenovirus, results in an overstimulation of T cells, which may lead to inhibitory effects that partially cancel out the stimulatory effects of the chemokine. As discussed below, DC-CK1’s adjuvant activity requires the presence of IL-12. The primary effect of IL-12 on activated T cells is the stimulation of IFN-γ production by these cells (33–36, 40). It is well established that one effect of IFN-γ on activated T cells is enhanced apoptosis (41–43). Thus, too much DC-CK1 may, via IL-12, cause an overproduction of IFN-γ, which could result in enhanced apoptosis of recently activated CS-specific CD8⁺ T cells, thereby lowering the number of such cells elicited by vaccination and canceling out some of the stimulatory effects of the chemokine.

Alternatively, injecting too high a dose of DC-CK1 could result in a diversion of responsive cell types away from the anatomical locales where T cell activation takes place. As discussed below, DC-CK1’s adjuvant effect appears to result from its interaction with naive T cells in the cortical regions of draining lymph nodes. It is possible that injecting too high a dose of DC-CK1, either as a recombinant protein or a recombinant adenovirus, results in a more widespread distribution of the chemokine to parts of the body other than the draining lymph nodes. Such a broader distribution of the chemokine could conceivably result in a diversion of circulating naive T cells to these other sites, preventing them from reaching the appropriate lymph node areas where Ag presentation and T cell activation occur. As a result, fewer numbers of naive, Ag-specific T cells would interact with APCs, thereby counteracting any stimulatory effect the chemokine has on those naive T cells that do.

In the case of rDC-CK1, another possibility is that administration of too high a concentration results in aggregation of the chemokine. Due to their hydrophobic character, chemokines have a tendency to self-aggregate under physiological conditions, especially at higher concentrations, resulting in an inability of the chemokine to interact with its cognate receptor (44). If such a phenomenon is occurring at a disproportionate level with the higher doses of rDC-CK1, it could conceivably result in an effective neutralization of much of the chemokine and, as discussed below, lesser amounts migrating to the appropriate anatomical compartment, where it can interact with responsive cell types.

Finally, for AdDC-CK1, which only reveals an adjuvant effect when coinjected with AdPyCS, the lack of a dose-dependent enhancement of the CS-specific CD8⁺ T cell response is probably due to in vivo competition of the two viruses for cells that can support infection. In vivo, there is only a limited supply of cells bearing a limited number of receptors necessary for adenovirus
infection. Injecting an excessive amount of AdDC-CK1 relative to AdPyCS would result in a disproportionate infection of cells by AdDC-CK1, and the blocking of optimal AdPyCS infection in vivo. Such interference would lead to less overall expression of the CS protein, which is the antigenic target of the antimalarial immune response, and thus to a lower CS-specific CD8+ T cell response. In contrast, injecting too little AdDC-CK1 with AdPyCS would result in insufficient AdDC-CK1 infection in vivo to ensure adequate production of DC-CK1 protein required for an adjuvant effect. Only when AdPyCS and AdDC-CK1 are injected in the proper proportion will both viruses infect enough cells to bring about adequate production of both Ag and chemokine required for an adjuvant effect. With our fixed suboptimal dose of AdPyCS (2 × 10^7 PFU), such a balance only occurs with a dose of 10^8 PFU AdDC-CK1, not more or less.

In humans, DC-CK1 acts exclusively on naive T and B cells (18–20). Although a murine homologue of DC-CK1 has not yet been identified, a recent study by Guan et al. (32) showed that in response to an i.p. injection of synthetic human DC-CK1 in mice, CD4+ and CD8+ T cells accumulated in the peritoneal cavity, while monocytes and granulocytes did not; B cells were not examined. This result suggests that DC-CK1 acts on similar types of cells in mice as in humans. To test this idea, we performed in vitro chemotaxis assays on mouse splenocytes to determine what types of murine cells respond best to DC-CK1. Our results showed that T and B cells respond equally well to DC-CK1. In addition, our results indicate that T and B cells expressing the naive lymphocyte marker CD62L respond better to DC-CK1 than such cells not expressing this marker (i.e., effector/memory cells). Taken together, these data suggest that in mice, as in humans, DC-CK1 preferentially acts on naive lymphocytes.

The chemotaxis assay results also suggest that the adjuvant activity of DC-CK1 is mediated by events occurring in naive lymphocytes after interaction with the chemokine. Since naive lymphocytes primarily reside in the cortical regions of lymph nodes, and DC-CK1 only displays an adjuvant effect when injected at the same time and place as the immunogen, the question arises as to how a peripherally deposited chemokine such as the DC-CK1 administered in our experiments reaches naive lymphocytes in time to orchestrate an adjuvant effect. An answer to this question comes from a recent study by Gretz et al. (45), who showed that small m.w. molecules originating in the periphery, in particular chemokines, quickly make their way to the cortical regions of local lymph nodes by way of reticular fiber conduits after deposition into the subcapsular sinus via afferent lymphatics. This finding makes possible the idea that DC-CK1 injected into the periphery, as either a recombinant protein bolus or a recombinant adenovirus, immediately drains to the local lymph nodes via afferent lymphatics and then travels to the cortical regions by way of reticular fiber conduits, where it comes into contact with naive T and B cells, resulting in events that lead to adjuvanticity. Interestingly, we found no enhancement of the antisporeozoite Ab response in mice immunized with either γ-spz or AdPyCS with or without DC-CK1, indicating that any action of DC-CK1 on B cells does not result in an enhanced humoral response in vivo. Thus, the DC-CK1-mediated events leading to adjuvanticity probably occur in T cells, which do show enhanced responses in immunized mice receiving the chemokine.

The ability of DC-CK1 to enhance the number of Ag-specific CD8+ T cells secreting IFN-γ depended on the presence of IL-12, but not IFN-γ or CD40. In immunized mice lacking functional IL-12, the enhancement of the CD8+ T cell response elicited by DC-CK1 in WT control mice was abrogated. In contrast, immunized mice lacking either IFN-γ receptor or CD40 displayed no abrogation of the DC-CK1-mediated augmentation of the CD8+ T cell response, indicating that neither IFN-γ nor CD40 signaling is essential for the adjuvant effect of DC-CK1. Since DC-CK1 probably exerts its adjuvant effect after draining to secondary lymphoid organs, the principal cellular sources of the IL-12 needed for the adjuvant activity of DC-CK1 are probably dendritic cells that have migrated from the periphery to the T cell areas of secondary lymphoid organs after Ag uptake. Many studies suggest that IL-12 production by dendritic cells requires CD40-CD40L interaction between dendritic cells and activated T cells (37–40); however, our results indicate that such an interaction is not required for the IL-12-dependent adjuvant effect of DC-CK1. A possible explanation for this CD40 independence comes from a study by Reis e Sousa et al. (46), who showed that in vivo microbial stimulation induces CD40-CD40L-independent IL-12 production by dendritic cells as well as dendritic cell redistribution to T cell areas of secondary lymphoid organs where they initiate primary immune responses. While the microbial stimuli used in this study were of protozoan and bacterial origin, a similar phenomenon could have occurred with the AdPyCS vaccine we used in our knockout mouse experiments. A number of recent studies have shown that infection of murine and human dendritic cells by recombinant, replication-deficient, type 5 adenoviruses results in both dendritic cell maturation and IL-12 production without CD40-CD40L engagement (47–49). Thus, the CD40 independence of DC-CK1’s IL-12-dependent adjuvant activity is probably due to CD40-independent IL-12 production by dendritic cells infected with AdPyCS.

The primary targets of dendritic cell-derived IL-12 are activated T cells. The major action of IL-12 on these cells is the stimulation of a type 1 phenotype characterized by IFN-γ production. In addition to stimulating IFN-γ production, IL-12 promotes the proliferation and survival of activated type 1 T cells (33–36, 40). A recent study by Yoo and colleagues (50) has shown that IL-12 provides proliferation and survival signals to murine T cells through the phosphatidylinositol 3-kinase (PI3K)/Akt signaling pathway, which up-regulates the expression of cell cycle-related molecules such as cyclin D3 and anti-apoptotic molecules such as Bcl-2 and down-regulates proapoptotic molecules such as caspase-3. In addition, the authors show that this signaling pathway is not involved in IFN-γ induction by IL-12. Since DC-CK1 acts on naive T cells, a possible explanation for its IL-12-dependent adjuvant effect is that it renders these cells more sensitive to IL-12-induced proliferation and survival after activation by APCs. While such an increase in sensitivity might occur by way of a DC-CK1-mediated up-regulation of the IL-12R in T cells, it is more likely due to a synergistic interaction of the DC-CK1-mediated signal transduction pathway and the IL-12-mediated signal transduction pathway in T cells. Although DC-CK1’s receptor has not yet been identified in humans or mice, it appears that it, like all chemokines identified to date, signals through a seven-transmembrane domain receptor coupled to a pertussis toxin-sensitive heterotrimeric Gi protein (20, 51, 52). It is known that a number of chemokine receptors, after interaction with their cognate ligand, stimulate both PI3K and Akt via the βγ subunit of their heterotrimeric Gi protein and that both molecules are required for the stimulation of proper chemotaxis as well as the proliferation and prevention of apoptosis in target cells (52, 53). If DC-CK1’s receptor also stimulates PI3K and Akt as part of its signal transduction cascade, then it would necessarily intersect with the IL-12-stimulated cascade. Moreover, naive T cell interaction with DC-CK1 would stimulate these important downstream messengers involved in IL-12 signaling before IL-12 exposure, potentially amplifying the IL-12 signal to the T cells after activation. Since PI3K and Akt are involved in transmitting proliferative and antiapoptotic signals...
to T cells by IL-12, the enhancement of these activities by DC-CK1 signaling would probably result in an augmented clonal expansion of Ag-specific T cells in response to immunization. In addition, because the IL-12-induced PI3K/Akt signaling pathway is not involved in IFN-γ induction, the adjuvant effect of DC-CK1 would not be expected to use IFN-γ, which is consistent with our results. Unfortunately, DC-CK1’s receptor is not known, making a thorough analysis of the signaling pathways involved in its adjuvant effect difficult. Whatever the mechanism, the permissive effect of DC-CK1 on IL-12 signaling is intriguing in light of much recent evidence indicating a down-regulatory effect of G protein-coupled receptor signaling on IL-12 production and signaling (54–57).

Overall, our report indicates the potential of DC-CK1 as a vaccine adjuvant for diseases in which strong cellular immune responses are needed. In addition, it adds to the relatively small number of studies showing the promise of chemokines as vaccine adjuvants (58, 59). More importantly, we provide the first evidence that DC-CK1, a chemokine produced by dendritic cells, active on naïve lymphocytes, and presumably involved in the orchestration of adaptive immune responses, actually participates in the induction of primary T cell responses in vivo. Furthermore, we show that this participation is IL-12 dependent, thereby shedding new light on the role of chemokines in regulating T cell differentiation.

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References


