The Linkage of Innate to Adaptive Immunity via Maturing Dendritic Cells In Vivo Requires CD40 Ligation in Addition to Antigen Presentation and CD80/86 Costimulation

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Abstract

Dendritic cell (DC) maturation is an innate response that leads to adaptive immunity to coadministered proteins. To begin to identify underlying mechanisms in intact lymphoid tissues, we studied α-galactosylceramide. This glycolipid activates innate $V\alpha14^+$ natural killer T cell (NKT) lymphocytes, which drive DC maturation and T cell responses to ovalbumin antigen. Hours after giving glycolipid i.v., tumor necrosis factor (TNF)–α and interferon (IFN)-γ were released primarily by DCs. These cytokines induced rapid surface remodeling of DCs, including increased CD80/86 costimulatory molecules. Surprisingly, DCs from $CD40^{-/-}$ and $CD40L^{-/-}$ mice did not elicit $CD4^+$ and $CD8^+$ T cell immunity, even though the DCs exhibited presented ovalbumin on major histocompatibility complex class I and II products and expressed high levels of CD80/86. Likewise, an injection of TNF-α up-regulated CD80/86 on DCs, but CD40 was required for immunity. CD40 was needed for DC interleukin (IL)-12 production, but $IL-12p40^{-/-}$ mice generated normal ovalbumin-specific responses. Therefore, the link between innate and adaptive immunity via splenic DCs and innate NKT cells has several components under distinct controls: antigen presentation in the steady state, increases in costimulatory molecules dependent on inflammatory cytokines, and a distinct CD40/CD40L signal that functions together with antigen presentation ("signal one") and costimulation ("signal two") to generate functioning $CD4^+$ T helper cell 1 and $CD8^+$ cytolytic T lymphocytes.

Key words: α-galactosylceramide • maturation • CD40 • NKT • TNF-α

Introduction

DCs in lymphoid tissues can initiate antigen-specific adaptive responses: both peripheral tolerance and immunity (for reviews see references 1–3). The administration of a stimulus for maturation switches DC function from tolerance to immunity, including the development of $CD4^+$ T cells of the Th1 type, and active cytolytic $CD8^+$ T cells. Although much of the early work on DC maturation was performed in culture, the process has begun to be studied in vivo, particularly in lymphoid organs (4, 5), which are the tissues involved in the generation of tolerance and immunity. In the steady state, in the absence of overt inflammatory and infectious stimuli, many DCs in lymphoid organs are defined as immature, able to endocytose (6–8), and process antigens to form peptide complexes with MHC class I and II products (8–11), but unable to initiate the differentiation of effector T cells and memory. Instead, DCs in the steady state, or subsets of DCs, elicit different forms of peripheral tolerance, such as deletion (9, 10), anergy (12), and the expansion of regulatory T cells (13). If the antigen-capturing DCs are exposed to a stimulus that leads to their maturation in vivo (5, 9, 10, 14–17), strong T cell immunity develops, especially $CD4^+$ and $CD8^+$ effector T cells capable of IFN-γ production and cytolysis. Thus, the avoidance of tolerance and the initiation of immunity are major correlates of DC maturation; it is important to identify underlying mechanisms particularly in the intact animal.

To begin to identify in vivo mechanisms that drive DC maturation and link innate with adaptive immunity, we

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Abbreviations used in this paper: α-GalCer, α-galactosylceramide; CFSE, carboxyfluorescein succinimidyl ester; MLR, mixed leukocyte reaction.

have dissected the DC response in lymphoid tissues to the synthetic glycolipid, α-galactosylceramide (α-GalCer). This glycolipid is presented by CD1d molecules to the conserved Vα14 T cell receptor on innate NKT cells (18). α-GalCer, in an NKT cell–dependent fashion, acts as an adjuvant for T cell immunity (19) and as an inducer of maturation in splenic DCs (15, 16). The α-GalCer/NKT system is attractive to study the role of different components of DC maturation in vivo. Several cardinal features of maturation are engaged within 4–8 h of a single i.v. dose of α-GalCer. There is a marked up-regulation of CD40, 80, and 86 costimulatory and MHC class II antigen-presenting molecules, identical to that observed with toll-like receptor stimuli in vivo, such as lipopolysaccharide (4) and CpG oligonucleotides (5). The DCs also start to produce large amounts of cytokines such as IFN-γ and IL-12 (15). Importantly, if a small amount of cell-associated antigen is administered together with α-GalCer, the DCs initiate combined CD4$^+$ and CD8$^+$ T cell immunity to that protein. Specifically, a single dose of <1 μg of OVA within dying cells leads to strong immunity, including protection of OVA-transduced tumors (15); this protection persists for at least 2 mo (unpublished data). To prove that maturing DCs are directly responsible for the induction of immunity, DCs can be removed from mice 4–8 h after giving α-GalCer and antigen. When transferred to naive animals, these DCs initiate immunity without further antigen, α-GalCer, or NKT cells (15). An analogous conclusion on the importance of maturing DCs was reached by Shah et al., who adoptively transferred immunity with DCs responding to CpG oligonucleotides (20).

Therefore, the α-GalCer system provides an opportunity to identify mechanisms whereby maturing DCs convert a single low dose of antigen into strong and prolonged CD4$^+$ and CD8$^+$ T cell immunity. Interestingly, NKT lymphocytes rather than microbial stimuli forge the link between innate and adaptive immunity. We will show that different elements in the immunization process are under distinct controls, and that a particularly critical one entails CD40 ligation. It is well known that CD40 acts as a DC maturation stimulus in culture, increasing the expression of CD80 and CD86 (21, 22), enhancing antigen presentation (23, 24), and inducing IL-12 production (25, 26). Also, CD40 is required for DC function in vivo, particularly for CD8$^+$ T cell responses (27–29). Mechanistically, it has been assumed that CD40 ligation triggers DCs to express the two presumed requirements for immunity, antigen presentation or "signal one" and up-regulation of membrane and cytokine costimulators or "signal two." Here, we find that cytokines, independently of CD40 ligation, are responsible for the maturation of DCs when this is assessed by increased expression of CD80/86 in vivo. Nonetheless, CD40 and CD40L are required by DCs to induce both CD4$^+$ and CD8$^+$ T cell immunity even when the DCs are expressing high levels of MHC peptide and costimulatory molecules. At least in the α-GalCer/NKT system, it appears that more is required for DCs to initiate immunity than the combination of signals one and two.

Materials and Methods

Mice. Pathogen-free C57BL/6 (B6), IFN-γ$^{-/-}$, IFN-γR$^{-/-}$, TNF-α$^{-/-}$, and TAP$^{-/-}$ female mice at 6–7 wk were purchased from The Jackson Laboratory. Mice deleted of Jα281 (Jα18) genes were provided by M. Taniguchi (Institute of Physical and Chemical Research, Yokohama, Japan). Mice were maintained under specific pathogen-free conditions and studied in compliance with institutional guidelines.

Reagents. α-GalCer (2S,3S,4R-1-O(α-galactopyranosyl)-2(N-hexacosanoylamino)-1,3,4-octadecanetriol and vehicle were provided by the Pharmaceutical Research Laboratory and diluted in PBS. LPS-free OVA was obtained from the Seikagaku Corp. The following mAbs were obtained from BD Biosciences: FITC-conjugated α-CD4, α-CD8α or PE-conjugated α-CD8α, allophycocyanin-conjugated α-CD11c, biotinylated isotype control, α-CD40, CD80, and CD86. Biotinylated mAbs were detected with streptavidin-allophycocyanin. IFN-γ mAb (R4-6A2) was purified from hybridoma (American Type Culture Collection) supernatants.

Flow Cytometry for DC Surface Markers. Cells were preincubated with 2.4G2 culture medium to block FcγR, washed, incubated with mAb conjugates for 30 min, washed, and analyzed on a FACSCalibur™ flow cytometer (Becton Dickinson).

DC Preparation from Spleen. Using methods described previously (30), splenocytes were released by teasing and treatment with collagenase D (Roche Diagnostics Corp.). For flow cytometry, DC-enriched cells were obtained as a low-density fraction on BSA columns (30). In functional assays, we separated CD11c$^+$ fractions with α-CD11c–coated magnetic beads immediately after collagenase treatment, followed by labeling with α-CD11b–PE and PE-magnetic beads (MACS).

Cytokine Production by DCs. CD11c$^+$ DC enriched, CD11c$^-$ CD11b$^+$ monocyte-enriched, and CD11c$^-$CD11b$^-$ lymphocytes, isolated as aforementioned with magnetic beads 2 h after mice were given i.v. α-GalCer or vehicle, were cultured at 2 × 10^5 cells/well for 24 h in 96-well plates. The supernatants were assayed with the following ELISA kits for cytokines: IFN-γ and IL-12p40 (Opti EIA; BD Biosciences); TNF-α and IL-12p70 (Quantikine; R&D Systems); and IFN-α (PBL Biomedical Labs).

Antigen Uptake and Presentation In Vivo. To measure splenic DC presentation of cell-associated antigens to T cells, we used assays described previously (7, 8) in which mice were injected with 2 × 10^7 OVA-pulsed and osmotically shocked, syngeneic TAP$^{-/-}$ splenocytes (7). Osmotic shock causes cells to die, and these cells are taken up by CD8$^+$ splenic DCs. To monitor OVA presentation, mice were adoptively transferred with carboxyfluorescein succinimidyl ester (CFSE)–labeled, CD8$^+$ (OT-I) and CD4$^+$ (OT-II) OVA-specific TCR transgenic T cells. 3 d later, single cell suspensions of spleen and lymph nodes were taken to monitor T cell proliferation by dilution of CFSE, and T cell expansion was expressed as the number of transgenic T cells in the spleen. OT-I T cells were marked with CD45.1 and OT-II T cells were marked by expression of Vβ5.1/5.2 and Vα2.

Initiation (Priming) of T Cell Immunity. 7 d after cell-associated OVA injection as aforementioned, recipient spleen cells were tested for CD4$^+$ and CD8$^+$ T cell priming. 5 × 10^6 cells were cultured 6 h in 24-well plates ±1 μM OVA$_{257-264}$ peptide (for CD8$^+$ T cells) or 2 μM OVA$_{323-339}$ peptide (for CD4$^+$ T cells) with brefeldin A (BD Biosciences) to accumulate IFN-γ intracellularly. Cells were incubated for 15 min at 4°C with 2.4G2 α-FcγR mAb to block nonspecific staining and with FITC α-CD4 or CD8 for 20 min at room temperature. After Cytofix/Cytoperm Plus™ permeabilization (BD Biosciences), we stained

cells with PE-conjugated α–IFN-γ (XMG1.2) mAb for 15 min at room temperature and analyzed them with a FACSCalibur™ and CELLQuest™ (BD Biosciences) or FlowJo (Tree Star) software. To monitor proliferation by immunized T cells, splenocytes were labeled with 1 μM CFSE for 10 min at 37°C on day 7 and challenged for 3 d in vitro with 500 μg/ml OVA protein to assess successive halving of CFSE/cell. Cytolytic activity of CD8$^+$ T cells in vivo was tested with a 1:1 mix of spleen cells, labeled CSFE^{high}, and pulsed with OVA$_{257-264}$; unpulsed cells were labeled CFSE^{low}. After washing, the cells were coinjected i.v. to immunized B6 mice. 16 h later, we assessed a selective loss of peptide-positive CFSE^{high} cells in spleen by FACS®.

DC Stimulation of the Mixed Leukocyte Reaction (MLR). Spleen CD11c$^+$ DCs were isolated 8 h after administration of α-GalCer or vehicle. Graded numbers of C57BL/6 DCs were irradiated, added to 2×10^5 allogeneic BALB/c or syngeneic (C57BL/6) T cells, and isolated using T cell enrichment columns (R&D Systems) in 96-well flat-bottom plates for 88 h. During the final 16 h, [^{3}H]thymidine (1 μCi/well) was added. In some experiments, DCs were fixed with 0.75% paraformaldehyde (Electron Microscopy Science) for 30 min on ice before coculture with T cells.

Online Supplemental Material. Six figures comprise this paper's online supplemental material. In Fig. S1, cytokine production by splenic DCs after i.v. α-GalCer is shown. Fig. S2 depicts the weak contribution of individual inflammatory cytokines in the α-GalCer–induced remodeling of the DC surface. Fig. S3 shows the role of CD40L in the response to α-GalCer. In Fig. S4, the critical role of a bone marrow–derived cell in presentation of OVA associated with injected TAP$^{-/-}$ splenocytes is indicated. Fig. S5 shows that IL-12p40 is not required to induce OVA-specific immunity by DCs maturing to α-GalCer. Fig. S6 contains a summary diagram of the observed responses to a single i.v. dose of α-GalCer. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20040317/DC1.

Results

Cytokine Production by DCs after i.v. Injection of α-GalCer. To account for the rapid maturation of most DCs in the spleens of mice given a single dose of α-GalCer, we assessed the production of inflammatory cytokines because these
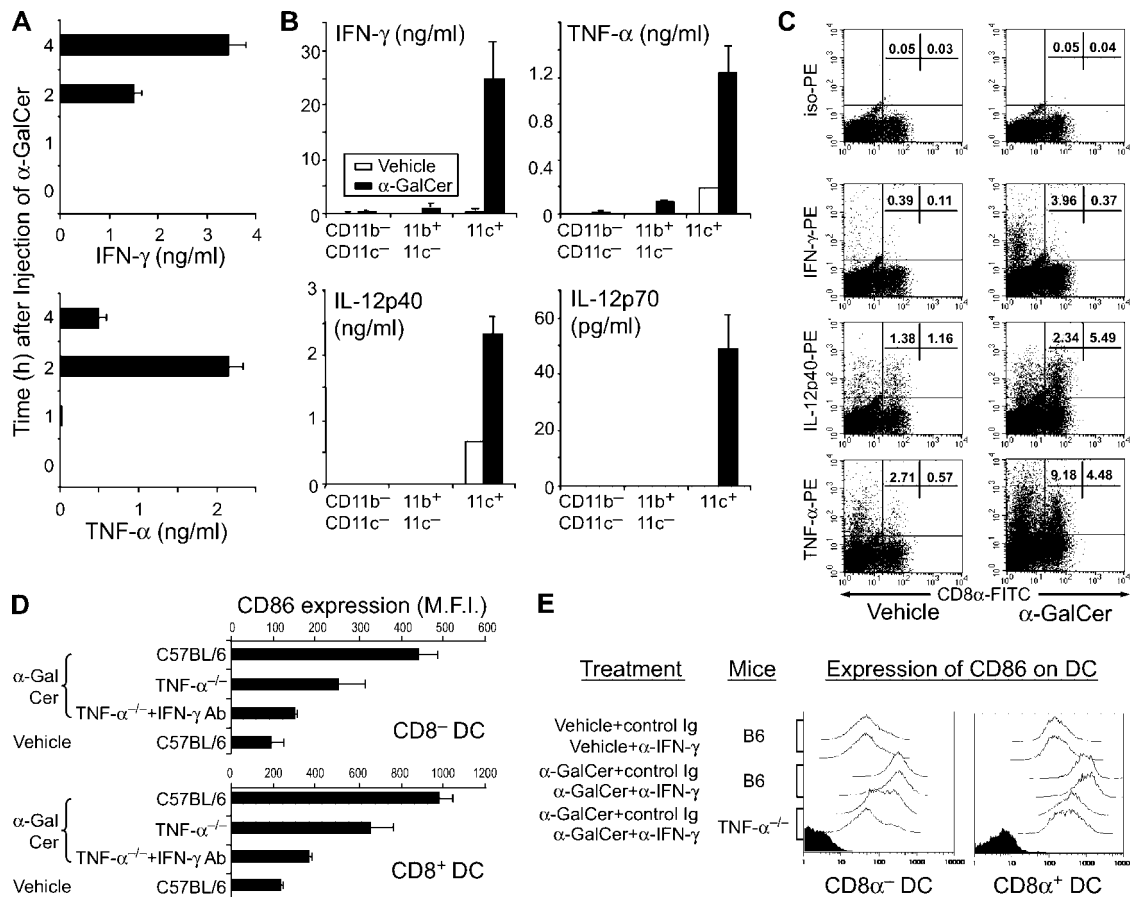
**Figure 1.** Cytokine production by splenic DCs in response to i.v. α-GalCer (A) Serum IFN-γ and TNF-α levels 1, 2, and 4 h after mice received 2 μg α-GalCer i.v.; no cytokines were detected in mice given vehicle only. (B) Production of cytokines by the indicated subsets (x axis) of splenocytes isolated 2 h after vehicle or α-GalCer i.v., which is before the time that NK cells are activated. (C) FACS® for intracellular cytokines produced by splenic CD11c$^+$ DCs taken from mice 2 h after injection of vehicle or α-GalCer and cultured for 4 h in brefeldin A; numbers are the percentage of CD8$^+$ and CD8$^-$ CD11c$^+$ cells producing cytokines. (D and E) Maturation of splenic DCs, as assessed by CD86 expression, after blockade of both TNF-α and IFN-γ. Vehicle or α-GalCer was given to wild-type or TNF-α$^{-/-}$ mice treated with α-IFN-γ antibody or control Ig (300 μg/mouse) 3 h before injection of α-GalCer. Mean values for CD86 expression are shown for three experiments in four groups of mice. All results represent the mean of three or more independent experiments (A, B, and D) or are representative (C and E).

drive DC differentiation (31–33). Both TNF-α and IFN-γ were detected in the serum 2–4 h after α-GalCer, but not in mice given vehicle control (Fig. 1 A). To look for the cellular sources of cytokines, we prepared different cell populations 2, 8, and 24 h after i.v. α–GalCer and cultured the cells without known stimuli for 24 h (in an earlier analysis, we cultured the DCs with anti-CD40 for 72 h; reference 15). IFN-γ, TNF-α, IL-12p40, and IL-12p70 were each released in substantial amounts (ELISA assay), but only by enriched CD11c+ DCs and not by enriched CD11b+ CD11c− macrophages and CD11b− CD11c− lymphocytes (Fig. 1 B). We did not see a contribution of NKT cells in our assays because IL-4 was not detected in four out of four experiments. Also, it is known that IFN-γ–producing NKT cells are evident at 2 h, but not 5 h, after α-GalCer (34). DC cytokine production was also evident by intracellular cytokine staining, permitting analyses of the contribution of CD3− CD11c+ DC subsets (Fig. 1 C). Interestingly, CD8α− DCs were the principal source of IFN-γ and CD8α+ DCs for IL-12p40 as in other studies (35), whereas both subsets made TNF-α (Fig. 1 C). Cytokine production by FACS® was increased if the DCs were assayed after longer culture periods (Fig. S1, available at http://www.jem.org/cgi/content/full/jem.20040317/DC1). IFN-α, which can mature DCs, was not detectably made by splenic CD8α+ or CD8− CD11c+ DCs (unpublished data). Also, when plasmacytoid DCs were sorted at 2, 4, and 6 h after α-GalCer administration, we detected no IFN-α and lower IL-12p70 and p40 (<100 pg/ml) in the supernatants. Thus, nonplasmacytoid DC subsets act in concert to produce inflammatory cytokines and seem to be their major source early after i.v. α-GalCer.

Cytokines Drive Increased Costimulatory Molecules on DCs Maturing in Response to α-GalCer. To determine the consequences of TNF-α and IFN-γ on DC maturation, we analyzed the DC surface from TNF-α−/−, IFN-γ−/−, and IFN-γ R−/− mice 4–8 h after α-GalCer. CD40, CD80, and CD86 increased in the individual knockout mice much like wild type, although there was slightly less up-regulation of CD86 in TNF-α−/− knockouts (Fig. S2, available at http://www.jem.org/cgi/content/full/jem.20040317/DC1). In contrast, when we blocked both cytokines by injecting a neutralizing α-IFN-γ antibody (300 μg/mouse) into TNF-α−/− mice, DC surface maturation was almost completely abrogated (Fig. 1, D and E). Because B cells up-regulate their surface markers in α-GalCer–treated mice (15, 36), we tested if B cells contributed to DC maturation. However, DCs from B cell–deficient JH−/− mice responded comparably to wild-type α-GalCer (unpublished data). Thus, TNF-α and IFN-γ are largely responsible for the changes in the DC surface induced by α-GalCer.

The Response of Splenic DCs to Cytokine Administration In Vivo. To further assess the role of cytokines, we gave mice TNF-α and IFN-γ i.v. and examined the DCs 4–8 h later. At sufficiently high doses, we observed an up-regulation of costimulatory molecules, but the increases were smaller than induced by α-GalCer, especially on the CD8+ DC subset (Fig. 2 A, left). TNF-α was primarily active because IFN-γ only had a modest effect and only on CD8+ DCs (Fig. 2 A, right). To test if the cytokine-stimulated DCs were immunogenic, we administered OVA as a protein antigen. Instead of free OVA, where i.v. milligram doses are required for capture by splenic DCs, we used OVA associated with osmotically shocked splenocytes because submicrogram amounts of cell-associated OVA are presented by splenic DCs (7, 8). The injected splenocytes were always from TAP−/− mice, so that the recipient DCs, which capture the injected cells within 30–60 min, were responsible for OVA presentation on MHC class I (7, 8). 7 d later, spleen cells were cultured for 6 h without or with MHC class I and II binding peptides, OVA $_{257-264}$, or OVA $_{323-339}$ in the presence of brefeldin A to
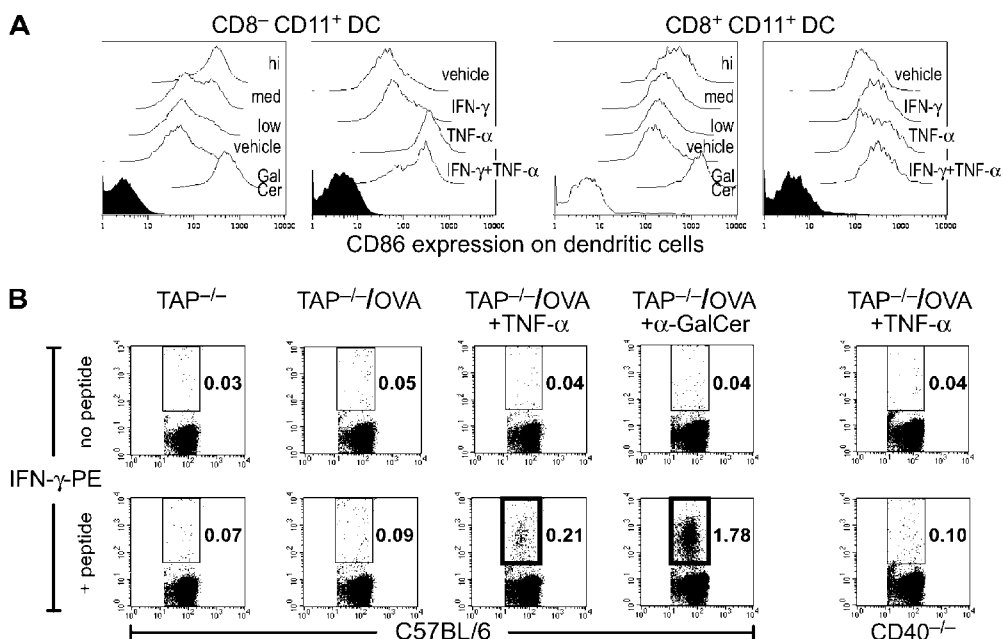
Figure 2. Function of DCs in response to IFN-γ and TNF-α. (A) Up-regulation of CD86 expression on splenic DC subsets 4 h after administration of a single low (20 ng IFN-γ and 2 ng TNF-α/mouse), medium (200 ng IFN-γ and 20 ng TNF-α), or high (2 μg IFN-γ and 200 ng TNF-α) dose of TNF-α (left) or a combination of high dose TNF-α and IFN-γ (right). (B) Induction of some CD8+ T cell immunity when OVA-loaded TAP−/− splenocytes were given to mice followed 2 h later by TNF-α (inset). Immunity was monitored at 7 d by formation of IFN-γ–secreting, OVA-specific CD8+ T cells.

quantify newly formed, IFN-γ–producing CD8^{+} and CD4^{+} "effector" T cells by intracellular cytokine staining.

We found a lack of OVA-specific immunity in mice given TNF-α, IFN-γ, or both cytokines together with OVA-loaded splenocytes (not depicted), in spite of the DC up-regulation of CD80/86 (Fig. 2 A). We were concerned that the TNF-α stimulus may have diminished DC uptake and/or processing of OVA, so we did the experiment another way, giving the OVA 2 h before the TNF-α. At that point, some T cell immunity developed. At 1 wk, ∼0.2% of the CD8^{+} T cells could secrete IFN-γ (Fig. 2 B, inset). However, if we gave OVA-loaded splenocytes followed by TNF-α to CD40^{−/−} mice, a T cell response did not develop (Fig. 2 B), even though CD80/86 costimulatory molecules were elevated comparably to wild-type mice. These data indicated that CD80/86 up-regulation by cytokines did not lead to immunity per se; a CD40-dependent step was needed.

CD40 on Maturing DCs, Activated by CD40L, Is Critical for Immunogenicity Initiated by α-GalCer and NKT Cells. We returned to the basic α-GalCer model and assessed the effects of CD40 ablation on immunogenicity. It is known that activation of NKT cells is intact in CD40^{−/−} mice given α-GalCer, using CD1d/α-GalCer tetramers to identify NKT cells producing IFN-γ and IL-4 (37). However, we noted a major requirement of CD40 for CD8^{+} and CD4^{+} T cell immunity because CD40^{−/−} mice failed to generate responses to the coadministered OVA (Fig. 3 A). Mean values of three such tests are shown in Fig. 3 B. To establish that

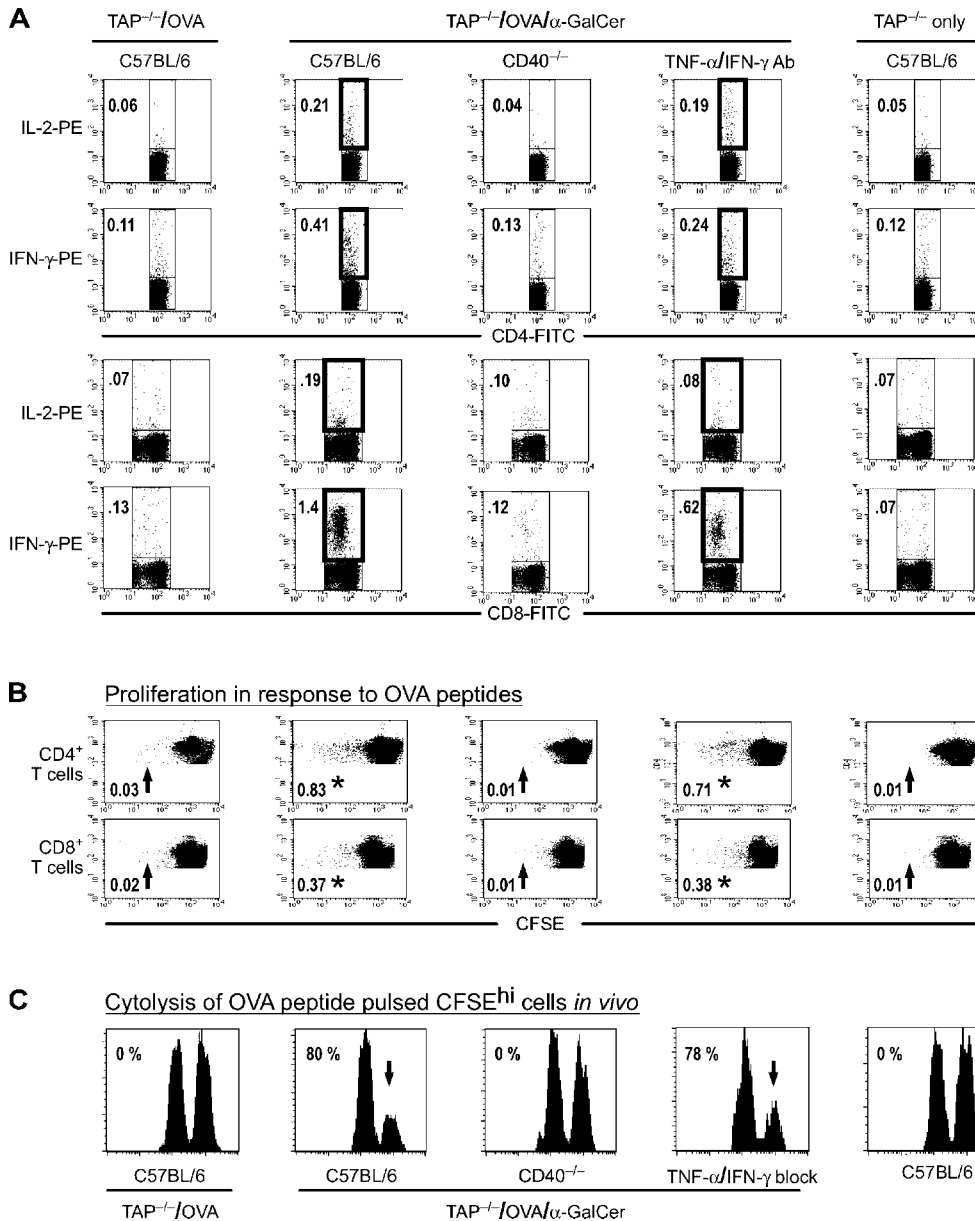CD40 was operating at the level of the DCs, we used CD11c selection to isolate these cells from immunized wild-type and CD40^{−/−} mice and transferred the DCs into naive mice that were not given additional OVA or α-GalCer. CD11c^{+} DCs from α-GalCer–treated mice could initiate immunity when transferred to naive mice as reported previously (15), but DCs from CD40^{−/−} mice were inactive (Fig. 3 C). This implied that CD40L was essential for full DC maturation. In fact, we found a 90% drop in the response to OVA plus α-GalCer in CD40L^{−/−} mice (Fig. S3 A, available at http://www.jem.org/cgi/content/full/jem.20040317/DC1).

We confirmed the data (38) that 2 h after administration of α-GalCer, CD40L increases on some NKT cells (gated as CD3^{+} NKT1.1^{+} lymphocytes), and that this increased CD40L occurred in mice lacking CD40 or subject to cytokine blockade (Fig. S3 B). To test if CD40L on OVA-activated CD4^{+} T cells might play a role in CD8^{+} T cell priming, we used CD4^{−/−} mice. When wild-type mice were given cell-associated OVA and α-GalCer, and 4 h later, DCs from these mice were obtained and transferred to naive CD4^{−/−} mice (thus lacking a CD4^{+} T cell source of CD40L), we observed OVA-specific CD8^{+} T cell priming 1 wk later. These results suggest that an early CD40L–CD40 interaction, presumably from NKT cells interacting with DCs presenting glycolipids, critically allows immunity to be induced by maturing DCs.

We repeated the immunogenicity experiments using more criteria for T cell immunity, and we compared cytokine-
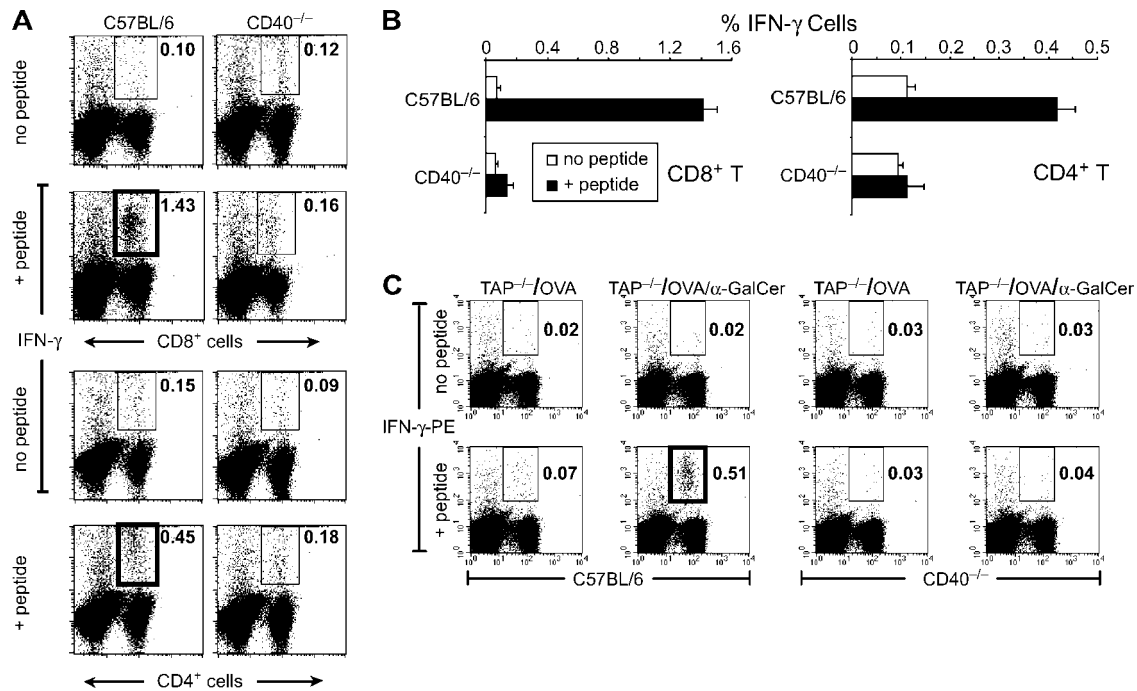
Figure 3. CD40 is required for the immunogenicity of DCs maturing in response to α-GalCer. (A) CD40^{−/−} or wild-type B6 mice were primed with 2×10^7 OVA-loaded TAP^{−/−} spleen cells plus i.v. α-GalCer 7 d later. Spleen cells were evaluated for the production of IFN-γ in response to restimulation by MHC class I (CD8^{+} T)– or MHC class II (CD4^{+} T)–binding OVA peptides. Insets indicate newly formed CD8^{+} and CD4^{+} T cells that produced IFN-γ upon OVA peptide reexposure. (B) As in A, except that the mean values for three experiments are shown. (C) Immunization of naive mice with 10^6 CD11c^{+} DCs taken from wild-type or CD40^{−/−} mice 4 h after administration of α-GalCer together with TAP^{−/−} OVA-loaded splenocytes. Immunity was monitored 7 d later by enumerating OVA-responsive CD4^{+} and CD8^{+} T cells as in A.

A

| | TAP^{-/-}/OVA | TAP^{-/-}/OVA/α-GalCer | | | TAP^{-/-} only |

B Proliferation in response to OVA peptides

C Cytolysis of OVA peptide pulsed CFSE^{hi} cells *in vivo*

Figure 4. Several forms of CD4^+ and CD8^+ T cell priming are blocked in mice lacking CD40, but occur substantially during blockade of TNF-α and IFN-γ (mouse groups defined in the top row of labels). (A) As in Fig. 3 A, mice were immunized with 2×10^7 OVA-loaded TAP^{-/-} spleen cells and i.v. α-GalCer, and 7 d later, antigen (OVA peptide)-responsive, cytokine (IL-2 and IFN-γ)-producing T cells were monitored in spleen and expressed as a percentage of CD4^+ (top) or CD8^+ (bottom) T cells (insets). (B) As in A, but recall proliferative responses (*) were used to monitor T cell priming. CFSE-labeled spleen cells from the different groups of mice were challenged during 3 d of culture with 500 μg/ml OVA protein. (C) As in A, but the development of cytolytic T cells was monitored 7 d after immunization. The groups of mice were given a mixture of CFSE spleen cells, 10^7 each loaded with OVA$_{257-264}$ peptide (high CFSE) or not (low CFSE). 12 h later, killing of antigen-loaded spleen cells was detected (arrow) in wild-type mice and in TNF^{-/-} mice treated with anti–IFN-γ antibody, but not in CD40^{-/-} mice. Data are representative of three individual mice.

blocked and CD40^{-/-} mice in parallel (Fig. 4). First, the CD40^{-/-} mice failed to prime for IL-2 and IFN-γ–producing CD4^+ and CD8^+ T cells (Fig. 4 A, middle), whereas cytokine blockade only had a partial inhibitory effect (Fig. 4 A, insets). Second, the CD40^{-/-} mice failed to prime for T cell proliferative responses in response to OVA restimulation, whereas cytokine blockade had no inhibitory effect (Fig. 4 B; compare arrows with asterisks). We used CFSE dilution to monitor T cell proliferation because this is a more sensitive method than [³H]thymidine uptake and is associated with little or no background (dilution of CFSE in the absence of antigen). Third, CD40^{-/-} mice failed to generate CD8^+ cytolytic effector cells in vivo, whereas cytokine blockade did not detectably alter killer activity relative to control mice (Fig. 4 C, arrows). These results indicate that CD40 ligation is vital for initiating several manifestations of T cell–mediated immunity.

CD40 Is Not Required for the Development of Signal One and Signal Two on DCs Responding to α-GalCer In Vivo. Because CD40 ligation increases MHC class I–peptide complex formation in bone marrow derived DCs (23, 24), we assessed if DCs in CD40^{-/-} mice were able to present OVA. To do this, CFSE-labeled, OVA-specific CD8^+ and CD4^+ TCR transgenic T cells were injected separately. 18 h later, OVA-loaded dying splenocytes were injected i.v. without or with α-GalCer. First, we verified the need for bone marrow–derived cells in the presentation of cell-associated protein because it has been reported that nonhematopoietic, liver sinusoidal endothelial cells were also able to present OVA on MHC class I by a TAP-dependent pathway (39). However, using bone marrow chimeras, we confirmed analogous experiments (40), finding that hematopoietic cells were essential for presentation of TAP^{-/-}
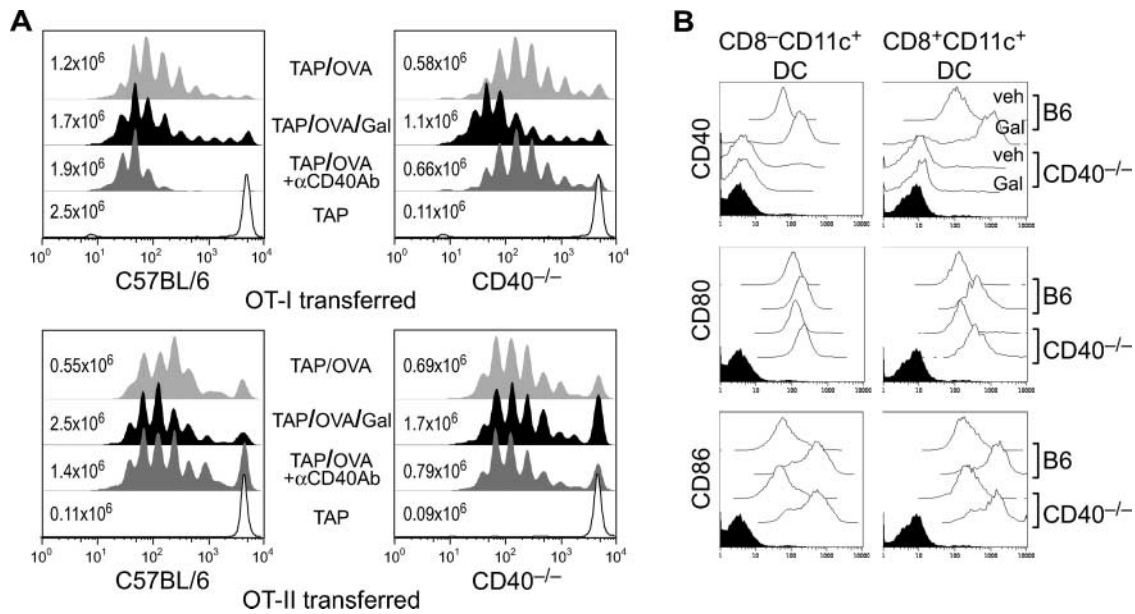
Figure 5. CD40 ablation does not interfere with efficient DC expression of signal one (antigen presentation) and signal two (CD80/86 costimulation). (A) Presentation of cell-associated OVA to OT-I, CD8^{+}, and OT-II, CD4^{+} TCR transgenic T cells in wild-type C57BL/6 or CD40^{−/−} mice in the absence or presence of α-GalCer. Total numbers of transgenic T cells (the mean of two experiments) are shown in each panel. (B) As in Fig. 1 E, 8 h after i.v. α-GalCer to C57BL/6 or CD40^{−/−} mice, the maturation of spleen CD11c^{+} DC subsets was assessed at the level of three surface markers.

OVA splenocytes (Fig. S4, available at http://www.jem.org/cgi/content/full/jem.20040317/DC1), presumably DCs as described previously (8). When we compared presentation of cell-associated OVA to TCR transgenic T cells transferred to wild-type and CD40^{−/−} mice, in the absence or presence of α-GalCer, the proliferation of CD8^{+} and CD4^{+} T cells was identical, as indicated by CFSE dilution and the increase in total T cell numbers in

the spleen (Fig. 5 A). Likewise, we found that CD40^{−/−} (Fig. 5 B) and CD40L^{−/−} (Fig. S3 C) mice still up-regulated CD80 and CD86 comparably to wild type upon challenge with α-GalCer. In addition, CD40^{−/−} mice had similar numbers of splenic DCs relative to wild type, with or without stimulation by α-GalCer. These results indicate that CD40 and CD40L are not required for splenic DCs to present antigen and express CD80 and 86 costimulators;

Table I. *Cytokine Production Requirements for Dendritic Cells from Mice Given α-GalCer*

	Cytokine release from CD11c^{+} splenic DCs			
	IFN-γ	TNF-α	IL-12p40	IL-12p70
	ng/ml	*pg/ml*	*pg/ml*	*pg/ml*
C57BL/6, vehicle	0.7 ± 0.4	119 ± 9.6	693 ± 71	0
α-GalCer treated				
C57BL/6	23 ± 0.8[a]	1,057 ± 77[a]	2,338 ± 124[a]	52 ± 4.1[a]
TNF-α/IFN-γ block	4.0 ± 1.0[b]	0	966 ± 50[b]	0
CD40^{−/−}	13 ± 1.4[a]	306 ± 15[b]	1,074 ± 174[b]	0
CD80/CD86^{−/−}	17 ± 3.5[a]	679 ± 1[b]	1,147 ± 172[b]	27 ± 12[b]
Jα18^{−/−}	0.4 ± 0.2	86 ± 9[c]	772 ± 103[c]	0[c]

2 h after giving mice vehicle or α-GalCer, CD11c^{+} DCs were selected from the spleens and cultured for 24 h. Supernatants were analyzed by ELISA for secretion of the indicated cytokines. Data are representative of four independent experiments. The p-value of the groups relative to the control value was determined by a Student's *t* test.
[a]P < 0.005.
[b]P < 0.05.
[c]No significant difference from C57BL/6 vehicle control (P > 0.05).

i.e., signals one and two in the steady state and during activation with α-GalCer and NKT lymphocytes.

Inflammatory Cytokines and CD40 Ligation in Concert Lead to IL-12 p70 Release. We considered the possibility that the need for CD40 in adaptive immunity reflected its role in the production of IL-12 (41). In fact, IL-12p40 and p70 release from CD11c$^+$ splenic DCs was greatly reduced when either inflammatory cytokines (TNF-α, IFN-γ) or CD40 were nullified. In wild-type mice, α-GalCer increased IL-12p40 threefold and induced the active IL-12p70 heterodimer de novo, whereas the cytokine-blocked and CD40$^{-/-}$ mice only increased IL-12p40 by 50% and did not produce any IL-12p70 (Table I, compare second with third and fourth rows). In contrast, substantial production of cytokines including IL-12p70 took place in CD80/86$^{-/-}$ mice. We also verified that NKT cells were needed for α-GalCer to induce cytokine production by DCs (Table I, compare second and bottom rows). We tested if IL-12p40 contributed to immunity in response to α-GalCer plus OVA. However, IL-12p40$^{-/-}$ mice were fully competent to initiate immunity, both cytokine-producing CD8$^+$ and CD4$^+$ effectors and cytolytic T cells (Fig. S5, available at http://www.jem.org/cgi/content/full/jem.20040317/DC1). Together, these data and the results in Fig. 2 indicate that some features of DC maturation in response to α-GalCer are dependent on the production of TNF-α and IFN-γ (i.e., the up-regulation of costimula-

tory molecules [Fig. 1] and production of IL-12p70 [Table I]), but neither leads directly to T cell–mediated immunity.

The Need for CD80 and CD86 Costimulatory Molecules. Although our data showed that the marked CD80/86 up-regulation during DC maturation did not initiate immunity independently, we wanted to know if these costimulators were required, perhaps at the lower but significant levels observed on DCs in lymphoid tissues. Therefore, we extended our studies to CD80/86$^{-/-}$ mice. Interestingly, DCs from these mice, such as CD40$^{-/-}$ mice, could remodel their surface in response to α-GalCer, as shown by the up-regulation of the endocytic receptor DEC-205 (CD205) and down-regulation of the IFN-γ receptor (CD119; Fig. 6 A, gray). Nevertheless, CD80/86$^{-/-}$ mice were unable to initiate an immune response to α-GalCer and OVA (Fig. 6 B). Therefore, the immunogenic properties of DCs maturing to α-GalCer requires at least basal levels of CD80 and CD86.

Stimulation of the MLR by Maturing DCs Also Requires Both Cytokines and CD40. Another assay for the capacity of maturing DCs to activate resting T cells is MLR stimulation. Splenic DCs from α-GalCer–treated mice have greatly increased MLR stimulatory activity (15). CD11c$^+$ DCs from IFN-γ$^{-/-}$ mice were comparable MLR stimulators to those from α-GalCer treated wild-type mice, whereas the DCs from TNF-α$^{-/-}$ mice were slightly less active (Fig. 7 A, left). Because DCs could undergo additional maturation during the MLR assay itself, we tested cells that were inhibited by
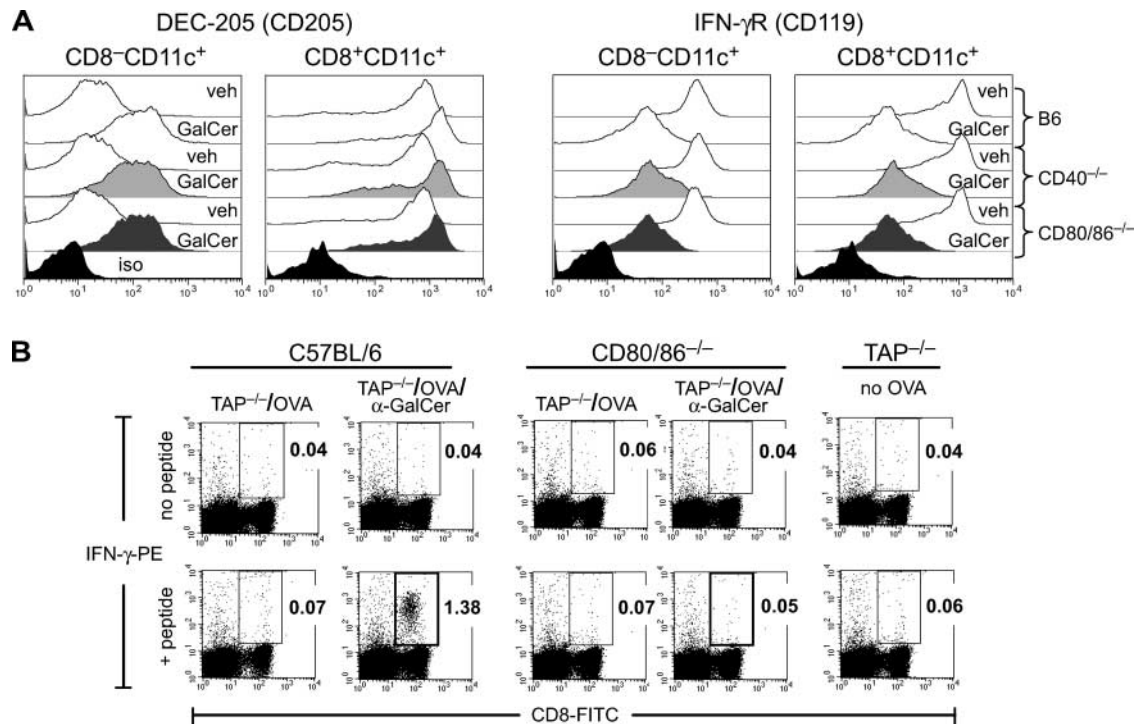
Figure 6. Requirement for CD80/86 for the adjuvant action of α-GalCer. (A) As in Fig. 1 E, 8 h after i.v. administration of α-GalCer to C57BL/6, CD40$^{-/-}$, or CD80/86$^{-/-}$ mice, the maturation of spleen CD11c$^+$ DC subsets was assessed at the level of surface markers using α-CD205 and α-CD119 antibodies. (B) As in Fig. 3, CD80/86$^{-/-}$ or wild-type B6 mice were primed with a combination of 2 × 10^7 OVA-loaded TAP$^{-/-}$ spleen cells and i.v. α-GalCer. 7 d later, spleen cells were evaluated for the production of IFN-γ in response to restimulation by MHC class I (CD8$^+$ T cells)– or MHC class II (CD4$^+$ T cells)–binding OVA peptides. The results (insets) expressed as the percentage of CD4$^+$ or CD8$^+$ T cells producing IFN-γ, are representative of four individual mice.
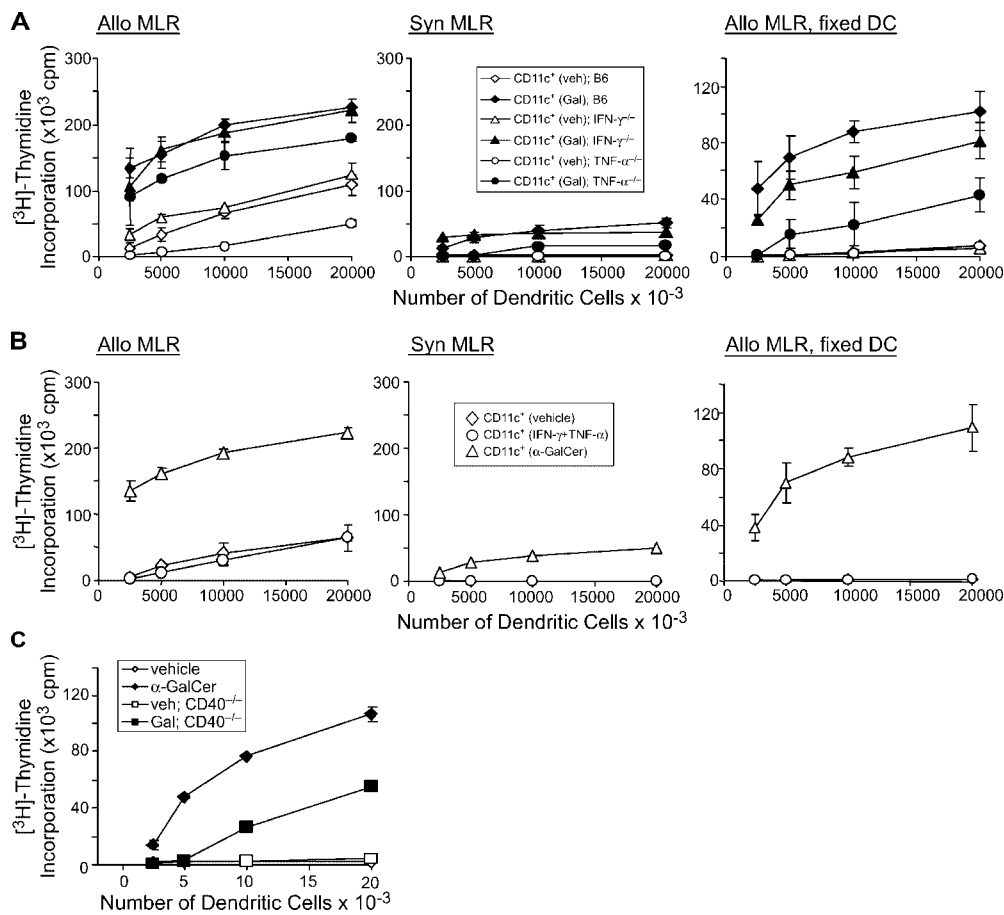
Figure 7. Cytokine and CD40 requirements for increased MLR stimulatory activity. (A) 8 h after i.v. administration of α-GalCer, CD11c^{+} DCs were used to stimulate T cell proliferation (y axis) in the MLR. Graded numbers of spleen DCs from wild-type B6, TNF-α^{−/−}, or IFN-γ^{−/−} mice were irradiated (30 Gy) and added for 3 d in flat bottomed 96-well plates to 2 × 10^{5} allogeneic BALB/c T cells (Allo MLR, left) and C57BL/6 T cells (Syn MLR, middle). To block DC maturation in the T cell coculture, the DCs were fixed with paraformaldehyde for 30 min and irradiated followed by the addition to allogeneic T cells (right). T cell proliferation was measured by [³H]thymidine incorporation; representative results of three independent experiments are shown. (B) As in A, DCs from mice given TNF-α and IFN-γ i.v. were fixed with paraformaldehyde for 30 min and irradiated followed by the addition of allogeneic T cells, and [³H]thymidine uptake was measured at 88–96 h. (C) As in A, DCs from α-GalCer–treated wild-type and CD40^{−/−} mice were fixed, irradiated, and used to stimulate the MLR.

paraformaldehyde fixation immediately upon isolation. The splenic CD11c^{+} DCs from TNF-α^{−/−} mice now showed less MLR stimulatory activity (P < 0.05; Fig. 7 A, right). When DCs were examined from TNF-α^{−/−} mice that also received α-IFN-γ antibody, there was no further reduction in MLR stimulation in response to α-GalCer (unpublished data). In contrast, when we tested DCs from mice injected with TNF-α and/or IFN-γ, no MLR stimulation was observed, in contrast with the strong MLR induced by DCs from α-GalCer–treated mice (Fig. 7 B). This implied that other factors, in addition to cytokines and CD80/86 up-regulation, were required for increased MLR stimulation by DCs. Again, CD40 was playing a role because MLR stimulation was reduced in its absence (Fig. 7 C). Therefore, the induction of immunity by DCs, as assessed by stimulation of the MLR, also requires cytokines and CD40 in concert.

Discussion

The α-GalCer Model for DC Maturation In Vivo. α-GalCer was discovered to be an adjuvant for protective T cell immunity with an important antigen, irradiated malaria sporozoites (19). The antigenic system we chose to study involved a single intravenous injection of OVA-loaded dying splenocytes (7, 8). These were rapidly captured (uptake was evident within 30 min) and presented by a subset of CD8α[+] splenic DCs in vivo, the consequence of which is tolerance in the

steady state (8). We used OVA-loaded dying cells to model the handling by DCs of dying cells from self tissues, tumors, and infections. When given together with α-GalCer, uptake of a single submicrogram dose of cell-associated OVA elicits combined CD4^{+} and CD8^{+} T cell immunity (15, 16), which is long lived and imparts resistance to OVA-transduced tumors for at least 2 mo (unpublished data). To do this, α-GalCer activates innate NKT lymphocytes that are responsible for most of the major features of DC maturation, such as remodeling of the DC surface to express high levels of CD80 and CD86 costimulators and the production of numerous cytokines (Table I and references 15, 16). These consequences of innate NKT lymphocyte responses to α-GalCer parallel what takes place with several microbial ligands for toll-like receptors in vivo (4, 5, 42, 43).

Previous studies with ex vivo–derived and antigen-loaded DCs showed that mature DCs were more immunogenic (32, 44). Likewise, immunity is induced in vivo by administering antigen together with maturation stimuli such as microbial products (5), infection (14), and agonistic α-CD40 antibodies (9, 10, 17). Here, we have used the α-GalCer/NKT model to begin to dissect the components of maturation responsible for the induction of effective T cell–mediated immunity. In contrast, much of the literature on DC maturation from its very beginnings (45–48) has involved surrogate criteria, especially a marked up-regulation of costimulatory molecules and production of cytokines.

Distinct Controls for the Components of DC Function during Immunogenicity In Vivo. There are several components to the function of maturing DCs in initiating immunity, and these proved to be under distinct controls in lymphoid organs (Fig. S6, available at http://www.jem.org/cgi/content/full/jem.20040317/DC1). Antigen presentation, or signal one, occurred in the steady state, in the ostensible absence of a maturation stimulus (Fig. 5). Interestingly, bone marrow–derived DCs in culture showed greatly enhanced presentation on MHC class I as a result of CD40 ligation (23, 24). Such up-regulation also might take place in vivo, but our data indicate that DCs within lymphoid organs efficiently formed MHC class I and II–peptide complexes in the steady state (e.g., Fig. 5 A). We found previously that in the steady state, the processing of dying cells resulted in tolerance in vivo. Other studies in vitro concluded that DC maturation (maturation being defined as cell surface remodeling with increased expression of CD86) was required for deletional tolerance (49), although in our studies of cell-associated OVA in vivo, such tolerance occurs in the steady state (8).

The production of many cytokines by splenic DCs did require the α-GalCer/NKT maturation stimulus. There was strong and rapid production of IFN-γ, TNF-α, and IL-12p70 beginning within 2 h of glycolipid injection. We found that these cytokines led to the major surrogate marker for maturation, expression of high levels of CD80 and 86 costimulatory molecules (signal two) on most DCs. CD80 and 86 were clearly required for immunity to a coadministered antigen in the α-GalCer system (Fig. 6). In contrast, NKT cell–dependent cytokine production by DCs occurred to a substantial extent in CD80/86-deficient mice (Table I). However, the greatly increased expression of costimulatory molecules on maturing DCs did not independently link the innate response between DCs and NKT cells to the adaptive response, between DCs and $\alpha\beta$T cells; CD40 also was essential. Likewise, when TNF-α was given to mice, or when MLR stimulation was used to assess immune responses to DCs (Figs. 2 and 7), we again observed that inflammation and increased expression of CD80 and 86 did not lead independently to immunity; CD40 ligation played a major role.

CD40L likely was provided by NKT cells early in the DC–NKT interaction initiated by α-GalCer, but CD40L might additionally contribute to the DC–T cell interaction role when expressed by antigen-activated T cells. Interestingly CD40L-bearing CD4^{+} T cells were not essential for the initiation of OVA-specific CD8^{+} T cell immunity in our model. Other potential sources of a CD40L signal for DCs would include activated platelets, mast cells, and possibly, heat shock proteins (50, 51). However, at this time, we have not identified a means to selectively remove CD40L from different types of cells, especially NKT cells and TCR$\alpha\beta$ T cells, to directly assess the relative importance of each source of CD40L during the different stages of immunogenicity.

A valuable feature of the α-GalCer system was to be able to dissect the consequences of different components of DC maturation within a single system, and in vivo, rather than by comparing different complex stimuli in vitro, as previously was the case. The different stimuli for DC maturation (inflammatory cytokines, CD40 ligands, and microbial stimuli) each induce myriad distinct transcriptional changes, so that it is hard to draw conclusions concerning any one component by comparing cells stimulated in different ways. By dissecting the controls of DC maturation within a single system, we could observe that efficient expression of MHC–peptide complexes and CD86 costimulators did not lead to immunity in the absence of a CD40–CD40L interaction.

Roles for CD40–CD40L in DC Maturation. The effects of CD40–CD40L in the α-GalCer system extend earlier work on this TNF receptor family member. Previous reports had concluded that agonistic α-CD40 antibodies acted through DCs to bypass the need for CD4^{+} helper cells in CD8^{+} T cell responses (27–29). The implication of these and other studies (9, 10) was that CD40 was increasing immunity by increasing formation of MHC–peptide complexes and/or increasing expression of costimulatory molecules, either membrane bound like CD80 and CD86, or soluble cytokines including IL-12. The formation of these T cell costimulatory molecules is a well known feature of DCs maturing in response to CD40 ligation (21, 22, 25, 26). CD40 also influences DC survival (52), migration (53), and avoidance of suppression (54, 55). The surprise in the current work was the major dependence of both CD4^{+} and CD8^{+} T cell responses on CD40 expression by DCs, under circumstances when active CD40-independent antigen presentation and costimulation were already in place. Identification of the CD40-based changes in DCs should contribute to further understanding of DC function and immunogenicity mechanisms.

A distinctive role for CD40 was envisaged by other studies in which CD40-ligated, bone marrow–derived DCs proved to be better inducers of T cell responses than DCs matured by other stimuli in culture (56, 57). Our results show that CD40 ablation in vivo does not retard antigen presentation and the expression of high levels of costimulators by DCs in lymphoid tissues. Yet CD40 still has a major role in linking innate to adaptive immunity and for both CD4^{+} and CD8^{+} T cell responses. These observations suggest changes in the standard signal one–signal two theory as a sufficient mechanism used by DCs to link innate with adaptive immunity.

References

1. Heath, W.R., and F.R. Carbone. 2001. Cross-presentation, dendritic cells, tolerance and immunity. *Annu. Rev. Immunol.* 19:47–64.

2. Moser, M. 2003. Dendritic cells in immunity and tolerance-do they display opposite functions? *Immunity*. 19:5–8.

3. Steinman, R.M., and M.C. Nussenzweig. 2002. Avoiding horror autotoxicus: the importance of dendritic cells in peripheral T cell tolerance. *Proc. Natl. Acad. Sci. USA*. 99:351–358.

4. De Smedt, T., B. Pajak, E. Muraille, L. Lespagnard, E. Heinen, P. De Baetselier, J. Urbain, O. Leo, and M. Moser. 1996. Regulation of dendritic cell numbers and maturation by lipopolysaccharide in vivo. *J. Exp. Med*. 184:1413–1424.

5. Sparwasser, T., R.M. Vabulas, B. Villmow, G.B. Lipford, and H. Wagner. 2000. Bacterial CpG-DNA activates dendritic cells in vivo: T helper cell-independent cytotoxic T cell responses to soluble proteins. *Eur. J. Immunol*. 30:3591–3597.

6. Kamath, A.T., J. Pooley, M.A. O'Keeffe, D. Vremec, Y. Zhan, A. Lew, A. D'Amico, L. Wu, D.F. Tough, and K.S. Shortman. 2000. The development, maturation, and turnover rate of mouse spleen dendritic cell populations. *J. Immunol*. 165:6762–6770.

7. Iyoda, T., S. Shimoyama, K. Liu, Y. Omatsu, Y. Maeda, K. Takahara, Y. Akiyama, R.M. Steinman, and K. Inaba. 2002. The CD8+ dendritic cell subset selectively endocytoses dying cells in culture and in vivo. *J. Exp. Med*. 195:1289–1302.

8. Liu, K., T. Iyoda, M. Saternus, K. Kimura, K. Inaba, and R.M. Steinman. 2002. Immune tolerance after delivery of dying cells to dendritic cells in situ. *J. Exp. Med*. 196:1091–1097.

9. Hawiger, D., K. Inaba, Y. Dorsett, K. Guo, K. Mahnke, M. Rivera, J.V. Ravetch, R.M. Steinman, and M.C. Nussenzweig. 2001. Dendritic cells induce peripheral T cell unresponsiveness under steady state conditions in vivo. *J. Exp. Med*. 194:769–780.

10. Bonifaz, L., D. Bonnyay, K. Mahnke, M. Rivera, M.C. Nussenzweig, and R.M. Steinman. 2002. Efficient targeting of protein antigen to the dendritic cell receptor DEC-205 in the steady state leads to antigen presentation on major histocompatibility complex class I products and peripheral CD8+ T cell tolerance. *J. Exp. Med*. 196:1627–1638.

11. Wilson, N.S., D. El-Sukkari, G.T. Belz, C.M. Smith, R.J. Steptoe, W.R. Heath, K. Shortman, and J.A. Villadangos. 2003. Most lymphoid organ dendritic cell types are phenotypically and functionally immature. *Blood*. 102:2187–2194.

12. Hawiger, D., R.F. Masilamani, E. Bettelli, V.K. Kuchroo, and M.C. Nussenzweig. 2004. Dynamic regulation of T cell tolerance induced by dendritic cells in vivo. *Immunity*. In press.

13. Yamazaki, S., T. Iyoda, K. Tarbell, K. Olson, K. Velinzon, K. Inaba, and R.M. Steinman. 2003. Direct expansion of functional CD25+ CD4+ regulatory T cells by antigen processing dendritic cells. *J. Exp. Med*. 198:235–247.

14. Brimnes, M.K., L. Bonifaz, R.M. Steinman, and T.M. Moran. 2003. Influenza virus-induced dendritic cell maturation is associated with the induction of strong T cell immunity to a coadministered, normally nonimmunogenic protein. *J. Exp. Med*. 198:133–144.

15. Fujii, S., K. Shimizu, C. Smith, L. Bonifaz, and R.M. Steinman. 2003. Activation of natural killer T cells by α-galactosylceramide rapidly induces the full maturation of dendritic cells in vivo and thereby acts as an adjuvant for combined CD4 and CD8 T cell immunity to a coadministered protein. *J. Exp. Med*. 198:267–279.

16. Hermans, I.F., J.D. Silk, U. Gileadi, M. Salio, B. Mathew, G. Ritter, R. Schmidt, A.L. Harris, L. Old, and V. Cerundolo. 2003. NKT cells enhance CD4+ and CD8+ T cell responses to soluble antigen in vivo through direct interaction with dendritic cells. *J. Immunol*. 171:5140–5147.

17. Bonifaz, L.C., D.P. Bonnyay, A. Charalambous, D.I. Darguste, S. Fujii, H. Soares, M.K. Brimnes, B. Moltedo, T.M. Moran, and R.M. Steinman. 2004. In vivo targeting of antigens to the DEC-205 receptor on maturing dendritic cells improves T cell vaccination. *J. Exp. Med*. 199:815–824.

18. Kawano, T., J. Cui, Y. Koezuka, I. Toura, Y. Kaneko, K. Motoki, H. Ueno, R. Nakagawa, H. Sato, E. Kondo, et al. 1997. CD1d-restricted and TCR-mediated activation of Va14 NKT cells by glycosylceramides. *Science*. 278:1626–1629.

19. Gonzalez-Aseguinolaza, G., L. Van Kaer, C.C. Bergmann, J.M. Wilson, J. Schmieg, M. Kronenberg, T. Nakayama, M. Taniguchi, Y. Koezuka, and M. Tsuji. 2002. Natural killer T cell ligand α-galactosylceramide enhances protective immunity induced by malaria vaccines. *J. Exp. Med*. 195:617–624.

20. Shah, J.A., P.A. Darrah, D.R. Ambrozak, T.N. Turon, S. Mendez, J. Kirman, C.Y. Wu, N. Glaichenhaus, and R.A. Seder. 2003. Dendritic cells are responsible for the capacity of CpG oligodeoxynucleotides to act as an adjuvant for protective vaccine immunity against *Leishmania major* in mice. *J. Exp. Med*. 198:281–291.

21. Caux, C., C. Massacrier, B. Vanbervliet, B. Dubois, C. Van Kooten, I. Durand, and J. Banchereau. 1994. Activation of human dendritic cells through CD40 cross-linking. *J. Exp. Med*. 180:1263–1272.

22. Flores-Romo, L., P. Bjorck, V. Duvert, C. Van Kooten, S. Saeland, and J. Banchereau. 1997. CD40 ligation on human CD34+ hematopoietic progenitors induces their proliferation and differentiation into functional dendritic cells. *J. Exp. Med*. 185:341–349.

23. Delamarre, L., H. Holcombe, and I. Mellman. 2003. Presentation of exogenous antigens on major histocompatibility complex (MHC) class I and MHC class II molecules is differentialy regulated during dendritic cell maturation. *J. Exp. Med*. 198:111–122.

24. Machy, P., K. Serre, M. Baillet, and L. Leserman. 2002. Induction of MHC class I presentation of exogenous antigen by dendritic cells is controlled by CD4(+) T cells engaging class II molecules in cholesterol-rich domains. *J. Immunol*. 168:1172–1180.

25. Cella, M., D. Scheidegger, K. Palmer-Lehmann, P. Lane, A. Lanzavecchia, and G. Alber. 1996. Ligation of CD40 on dendritic cells triggers production of high levels of interleukin-12 and enhances T cell stimulatory capacity: T-T help via APC activation. *J. Exp. Med*. 184:747–752.

26. Koch, F., U. Stanzl, P. Jennewien, K. Janke, C. Heufler, E. Kämpgen, N. Romani, and G. Schuler. 1996. High level IL-12 production by murine dendritic cells: upregulation via MHC class II and CD40 molecules and downregulation by IL-4 and IL-10. *J. Exp. Med*. 184:741–746.

27. Ridge, J.P., F. Di Rosa, and P. Matzinger. 1998. A conditioned dendritic cell can be a temporal bridge between a CD4+ T helper and a T-killer cell. *Nature*. 393:474–478.

28. Bennett, S.R.M., F.R. Carbone, F. Karamalis, R.A. Flavell, J.F.A.P. Miller, and W.R. Heath. 1998. Help for cytotoxic-T-cell responses is mediated by CD40 signalling. *Nature*. 393:478–480.

29. Schoenberger, S.P., R.E.M. Toes, E.I.H. van der Voort, R. Offringa, and C.J.M. Melief. 1998. T-cell help for cytotoxic T lymphocytes is mediated by CD40-CD40L interactions. *Nature*. 393:480–483.

30. Inaba, K., N. Romani, G. Schuler, A. Mirza, and R.M. Steinman. 1997. Generation of dendritic cells from proliferating

mouse bone marrow progenitors. *In* Current Protocols in Immunology. J.E. Coligan, A.M. Kruisbeek, D.H. Margulies, E.M. Shevach, and W. Strober, editors. Greene Publishing Associates and Wiley-Interscience, New York. 3.7.7–3.7.15.

31. Sallusto, F., and A. Lanzavecchia. 1994. Efficient presentation of soluble antigen by cultured human dendritic cells is maintained by granulocyte/macrophage colony-stimulating factor plus interleukin 4 and down-regulated by tumor necrosis factor α. *J. Exp. Med.* 179:1109–1118.

32. Inaba, K., S. Turley, T. Iyoda, F. Yamaide, S. Shimoyama, C. Reis e Sousa, R.N. Germain, I. Mellman, and R.M. Steinman. 2000. The formation of immunogenic MHC class II–peptide ligands in lysosomal compartments of dendritic cells is regulated by inflammatory stimuli. *J. Exp. Med.* 191:927–936.

33. Le Bon, A., G. Schiavoni, G. D'Agostinio, I. Gresser, F. Belardelli, and D.F. Tough. 2001. Type I interferons potently enhance humoral immunity and can promote isotype switching by stimulating dendritic cells in vivo. *Immunity.* 14:461–470.

34. Matsuda, J.L., O.V. Naidenko, L. Gapin, T. Nakayama, M. Taniguchi, C.R. Wang, Y. Koezuka, and M. Kronenberg. 2000. Tracking the response of natural killer T cells to a glycolipid antigen using CD1d tetramers. *J. Exp. Med.* 192:741–754.

35. Hochrein, H., K. Shortman, D. Vremec, B. Scott, P. Hertzog, and M. O'Keeffe. 2001. Differential production of IL-12, IFN-a, and IFN-g by mouse dendritic cell subsets. *J. Immunol.* 166:5448–5455.

36. Kitamura, H., A. Ohta, M. Sekimoto, M. Sato, K. Iwakabe, M. Nakui, T. Yahata, H. Meng, T. Koda, S. Nishimura, et al. 2000. a-Galactosylceramide induces early B-cell activation through IL-4 production by NKT cells. *Cell. Immunol.* 199:37–42.

37. Matsuda, J.L., L. Gapin, J.L. Baron, S. Sidobre, D.B. Stetson, M. Mohrs, R.M. Locksley, and M. Kronenberg. 2003. Mouse Va14i natural killer T cells are resistant to cytokine polarization in vivo. *Proc. Natl. Acad. Sci. USA.* 100:8395–8400.

38. Tomura, M., W.G. Yu, H.J. Ahn, M. Yamashita, Y.F. Yang, S. Ono, T. Hamaoka, T. Kawano, M. Taniguchi, Y. Koezuka, and H. Fujiwara. 1999. A novel function of Va14+ CD4+ NKT cells: stimulation of IL-12 production by antigen-presenting cells in the innate immune system. *J. Immunol.* 163:93–101.

39. Limmer, A., J. Ohl, C. Kurts, H.G. Ljunggren, Y. Reiss, M. Groettrup, F. Momburg, B. Arnold, and P.A. Knolle. 2000. Efficient presentation of exogenous antigen by liver endothelial cells to CD8+ T cells results in antigen-specific T-cell tolerance. *Nat. Med.* 6:1348–1354.

40. Bennett, S.R.M., F.R. Carbone, F. Karamalis, J.J.A.P. Miller, and W.R. Heath. 1997. Induction of a CD8+ cytotoxic T lymphocyte response by cross-priming requires cognate CD4+ T cell help. *J. Exp. Med.* 186:65–70.

41. Schulz, O., A.D. Edwards, M. Schito, J. Aliberti, S. Manickasingham, A. Sher, and C. Reis e Sousa. 2000. CD40 triggering of heterodimeric IL-12 p70 production by dendritic cells in vivo requires a microbial priming signal. *Immunity.* 13:453–462.

42. Edwards, A.D., S.P. Manickasingham, R. Sporri, S.S. Diebold, O. Schulz, A. Sher, T. Kaisho, S. Akira, and E.S.C. Reis. 2002. Microbial recognition via toll-like receptor-dependent and –independent pathways determines the cytokine response of murine dendritic cell subsets to CD40 triggering. *J. Immunol.* 169:3652–3660.

43. Sporri, R., and E.S.C. Reis. 2003. Newly activated T cells promote maturation of bystander dendritic cells but not IL-12 production. *J. Immunol.* 171:6406–6413.

44. Schuurhuis, D.H., S. Laban, R.E. Toes, P. Ricciardi-Castagnoli, M.J. Kleijmeer, E.I. van Der Voort, D. Rea, R. Offringa, H.J. Geuze, C.J. Melief, and F. Ossendorp. 2000. Immature dendritic cells acquire CD8+ cytotoxic T lymphocyte priming capacity upon activation by T helper cell–independent or -dependent stimuli. *J. Exp. Med.* 192:145–150.

45. Schuler, G., and R.M. Steinman. 1985. Murine epidermal Langerhans cells mature into potent immunostimulatory dendritic cells in vitro. *J. Exp. Med.* 161:526–546.

46. Inaba, K., G. Schuler, M.D. Witmer, J. Valinsky, B. Atassi, and R.M. Steinman. 1986. The immunologic properties of purified Langerhans cells: distinct requirements for the stimulation of unprimed and sensitized T lymphocytes. *J. Exp. Med.* 164:605–613.

47. Romani, N., S. Koide, M. Crowley, M. Witmer-Pack, A.M. Livingstone, C.G. Fathman, K. Inaba, and R.M. Steinman. 1989. Presentation of exogenous protein antigens by dendritic cells to T cell clones: intact protein is presented best by immature, epidermal Langerhans cells. *J. Exp. Med.* 169:1169–1178.

48. Romani, N., K. Inaba, E. Pure, M. Crowley, M. Witmer-Pack, and R.M. Steinman. 1989. A small number of anti-CD3 molecules on dendritic cells stimulate DNA synthesis in mouse T lymphocytes. *J. Exp. Med.* 169:1153–1168.

49. Albert, M.L., M. Jegathesan, and R.B. Darnell. 2001. Dendritic cell maturation is required for the cross-tolerization of CD8+ T cells. *Nat. Immunol.* 2:1010–1017.

50. Henn, V., J.R. Slupsky, M. Grafe, I. Anagnostopoulos, R. Forster, G. Muller-Berghaus, and R.A. Kroczek. 1998. CD40 ligand on activated platelets triggers an inflammatory reaction of endothelial cells. *Nature.* 391:591–594.

51. Millar, D.G., K.M. Garza, B. Odermatt, A.R. Elford, N. Ono, Z. Li, and P.S. Ohashi. 2003. Hsp70 promotes antigen-presenting cell function and converts T-cell tolerance to autoimmunity in vivo. *Nat. Med.* 9:1469–1476.

52. Josien, R., H.-L. Hi, E. Ingulli, S. Sarma, B.R. Wong, M. Vologodskaia, R.M. Steinman, and Y. Choi. 2000. TRANCE, a tumor necrosis family member, enhances the longevity and adjuvant properties of dendritic cells in vivo. *J. Exp. Med.* 191:495–501.

53. Moodycliffe, A.M., V. Shreedhar, S.E. Ullrich, C. Walterscheid, C. Bucana, M.L. Kripke, and L. Flores-Romo. 2000. CD40-CD40 ligand interactions in vivo regulate migration of antigen-bearing dendritic cells from the skin to draining lymph nodes. *J. Exp. Med.* 191:2011–2020.

54. Serra, P., A. Amrani, J. Yamanouchi, B. Han, S. Thiessen, T. Utsugi, J. Verdaguer, and P. Santamaria. 2003. CD40 ligation releases immature dendritic cells from the control of regulatory CD4+CD25+ T cells. *Immunity.* 19:877–889.

55. Grohmann, U., F. Fallarino, S. Silla, R. Bianchi, M.L. Belladonna, C. Vacca, A. Micheletti, M.C. Fioretti, and P. Puccetti. 2001. CD40 ligation ablates the tolerogenic potential of lymphoid dendritic cells. *J. Immunol.* 166:277–283.

56. Labeur, M.S., B. Roters, B. Pers, A. Mehling, T.A. Luger, T. Schwarz, and S. Grabbe. 1999. Generation of tumor immunity by bone marrow-derived dendritic cells correlates with dendritic cell maturation stage. *J. Immunol.* 162:168–175.

57. Kelleher, M., and P.C. Beverley. 2001. Lipopolysaccharide modulation of dendritic cells is insufficient to mature dendritic cells to generate CTLs from naive polyclonal CD8+ T cells in vitro, whereas CD40 ligation is essential. *J. Immunol.* 167:6247–6255.