Yeast zymosan, a stimulus for TLR2 and dectin-1, induces regulatory antigen-presenting cells and immunological tolerance

Stephanie Dillon, Emory University  
Sudhanshu Agrawal, Emory University  
Kaustuv Banerjee, Emory University  
John Letterio, National Cancer Institute  
Timothy Denning, Emory University  
Kyra Oswald-Richter, Vanderbilt University Medical School  
Deborah J. Kasprowicz, Benaroya Research Institute  
Kathryn Kellar, Emory University  
Jeff Pare, Emory University  
Thomas van Dyke, Boston University School of Medicine

Only first 10 authors above; see publication for full author list.

Journal Title: Journal of Clinical Investigation  
Volume: Volume 116, Number 4  
Publisher: American Society for Clinical Investigation | 2006-04-03, Pages 916-928  
Type of Work: Article | Final Publisher PDF  
Publisher DOI: 10.1172/JCI27203  
Permanent URL: http://pid.emory.edu/ark:/25593/fjkx1

Final published version: http://www.jci.org/articles/view/27203

Copyright information:  
© 2006, American Society for Clinical Investigation  
Accessed August 4, 2018 4:57 PM EDT
Yeast zymosan, a stimulus for TLR2 and dectin-1, induces regulatory antigen-presenting cells and immunological tolerance

Stephanie Dillon,1 Sudhanshu Agrawal,1 Kaustuv Banerjee,1 John Letterio,2 Timothy L. Denning,1 Kyra Oswald-Richter,3 Deborah J. Kasprwicz,4 Kathryn Kellar,5 Jeff Pare,6 Thomas van Dyke,7 Steven Ziegler,4 Derya Unutmaz,3 and Bali Pulendran1

1Emory Vaccine Research Center and Department of Pathology, Emory University, Atlanta, Georgia, USA. 2Immunoregulation Section, Lab of Cell Regulation and Carcinogenesis, Center for Cancer Research, National Cancer Institute, NIH, Bethesda, Maryland, USA. 3Department of Microbiology and Immunology, Vanderbilt University Medical School, Nashville, Tennessee, USA. 4Immunology Program, Benaroya Research Institute, Seattle, Washington, USA. 5Scientific Resources Program, National Center for Infectious Diseases, Centers for Disease Control and Prevention, Atlanta, Georgia, USA. 6Yerkes National Primate Research Center, Emory University, Atlanta, Georgia, USA. 7Department of Periodontology and Oral Biology, Boston University School of Medicine, Boston, Massachusetts, USA.

Emerging evidence suggests critical roles for APCs in suppressing immune responses. Here, we show that zymosan, a stimulus for TLR2 and dectin-1, regulates cytokine secretion in DCs and macrophages to induce immunological tolerance. First, zymosan induces DCs to secrete abundant IL-10 but little IL-6 and IL-12(p70). Induction of IL-10 is dependent on TLR2- and dectin-1-mediated activation of ERK MAPK via a mechanism independent of the activation protein 1 (AP-1) transcription factor c-Fos. Such DCs stimulate antigen-specific CD4+ T cells poorly due to IL-10 and the lack of IL-6. Second, zymosan induces F4-80+ macrophages in the splenic red pulp to secrete TGF-β. Consistent with these effects on APCs, injection of zymosan plus OVA into mice results in OVA-specific T cells that secrete little or no Th1 or Th2 cytokines, but secrete robust levels of IL-10, and are unresponsive to challenge with OVA plus adjuvant. Finally, coinjection of zymosan with OVA plus LPS suppresses the response to OVA via a mechanism dependent on IL-10, TGF-β, and lack of IL-6. Together, our data demonstrate that zymosan stimulates IL-10^+IL-12(p70)^−IL-6^low regulatory DCs and TGF-β^+ macrophages to induce immunological tolerance. These data suggest several targets for pharmacological modulation of immune responses in various clinical settings.

Introduction

Sensing a pathogen is the first, critical step in launching an immune defense. The immune system has evolved an elaborate system of pathogen surveillance, the so-called pathogen-recognition receptors (PRRs), which can recognize highly conserved molecular signatures contained in microbes and then decode this information to elicit an immune response (1–3). The prototypic examples of PRRs are the TLRs (4, 5) and the C-type lectins (6–8), which are expressed on and in DCs. Although DCs were initially thought to be important in initiating immune responses, more recent evidence points to a central role for them in tuning the quality of the immune response as well as in suppressing immune responses (1, 2). For example, there is now much evidence that triggering different TLRs on DCs results in distinct programs of gene expression and cytokine secretion that differentially regulate the type of adaptive immune responses (2, 4, 8–14). Furthermore, emerging evidence suggests that signaling through DC-SIGN, a C-type lectin, results in impaired DC maturation and antiinflammatory responses (15). Thus, determining the immunological consequences of triggering distinct PRRs on DCs might offer novel strategies for therapeutic immune intervention in various clinical settings. With this perspective, we embarked on a systematic screening of several PRR ligands for their effects on DCs and the adaptive immune response. In the present report, we describe the unique effects of zymosan, a yeast cell wall derivative which is recognized by dectin-1, a C-type lectin receptor for β-glucans (16–18) expressed in murine (18) and human (19) DCs in conjunction with TLR2 (20). Our data suggest that zymosan induces regulatory DCs, which secrete abundant IL-10 but little or no IL-6 and IL-12(p70) and induce impaired T cell responses. Such regulatory DCs appear to be induced via activation of TLR2- and dectin-1-dependent activation of ERK MAPK, which promotes IL-10 production. Furthermore, zymosan induces splenic F4-80+ macrophages to secrete TGF-β, another immunosuppressive cytokine. Consistent with this, injection of antigen plus zymosan into mice results in a transient but weak activation of antigen-specific T cells, which are resistant to further stimulation. Further, coinjection of zymosan with LPS plus antigen results in reduced antigen-specific T cell proliferation compared with LPS plus antigen injection alone. Thus zymosan appears to program DCs and macrophages to suppress immune responses via multiple mechanisms.

Results

Zymosan induces DCs to secrete robust IL-10 but little or no IL-12(p70) and IL-6. We first determined the responses of human and murine DCs to zymosan. Human monocyte-derived DCs cultured for 24 hours with either zymosan or LPS (a TLR4 ligand) were observed to upregulate costimulatory molecules CD80 and CD86 as well as the maturation marker CD83 (Figure 1A). There are presently con-
conflicting reports regarding the cytokine profiles induced by zymosan. Although previous work suggests that zymosan stimulates DCs to produce proinflammatory cytokines, including IL-12(p40) (20), more recent studies have shown that zymosan also stimulates DCs to produce robust IL-10 (21, 22). Therefore, it was important to determine the induction of these cytokines in our system. In human monocyte-derived DCs, while LPS induced abundant levels of IL-12(p70), IL-6, and IL-10, zymosan induced barely detectable levels of IL-12(p70) and lower levels of IL-6 but abundant levels of IL-10 (Figure 1B). This was consistent with data from the murine system, in which splenic CD11c+CD11b–CD8α– and CD11c+CD11b–CD8α+ DC subsets were isolated by flow cytometry and cultured in vitro with E. coli LPS or zymosan for 24–48 hours in the presence of a CD40–L–expressing cell line. Cytokines were analyzed by ELISA. Data are representative of 10 experiments. (D) Immature, monocyte-derived DCs were cultured for 24–48 hours with laminarin (200 μg/ml) plus zymosan or with zymosan alone. IL-10 levels were measured after 24 hours by ELISA. Data are representative of 4 experiments. (E) CD11c– murine splenic DCs were cultured with laminarin (200 μg/ml) plus zymosan and CD40–L–expressing fibroblasts. IL-10 levels were measured after 24 hours by ELISA. Data are representative of 7 experiments.

Figure 1
Zymosan induces IL-10 in human and murine DCs via a mechanism involving dectin-1. (A) Immature, monocyte-derived DCs were cultured for 24–48 hours with E. coli LPS (1 μg/ml) or zymosan (50 μg/ml), and flow cytometric analyses of the expression of the costimulatory molecules CD80 and CD86 and the maturation marker CD83 were performed. Filled histograms show isotype; open histograms represent marker. Data are representative of 10 experiments. (B) Secretion of cytokines in the culture supernatants was measured by ELISA. Data are representative of 18 experiments. (C) Murine, splenic CD11c+CD11b+CD8α–, and CD11c+CD11b–CD8α+ DC subsets were isolated by flow cytometry and cultured in vitro with E. coli LPS or zymosan for 24–48 hours in the presence of a CD40–L–expressing cell line. Cytokines were analyzed by ELISA. Data are representative of 10 experiments. (D) Immature, monocyte-derived DCs were cultured for 24–48 hours with laminarin (200 μg/ml) plus zymosan or with zymosan alone. IL-10 levels were measured after 24 hours by ELISA. Data are representative of 4 experiments. (E) CD11c– murine splenic DCs were cultured with laminarin (200 μg/ml) plus zymosan and CD40–L–expressing fibroblasts. IL-10 levels were measured after 24 hours by ELISA. Data are representative of 7 experiments.
to be dependent on β-glucans, which are a major component of the yeast cell wall, because laminarin (a soluble β-glucan from the brown seaweed *Laminaria digitata*) can block this recognition (17, 18). Consistent with this, zymosan-induced IL-10 production by human monocyte-derived DCs was significantly blocked by laminarin (Figure 1D). In mice, there was a significant diminution of IL-10 production when laminarin was used to block zymosan–dectin-1 interactions in DCs from wild-type mice (Figure 1E). In addition to dectin-1, TLR2 is also known to recognize zymosan (20, 24). DCs from TLR2-deficient mice produced lower levels of IL-10 in response to zymosan, and a further decrease in IL-10 production was observed when laminarin was used to block signaling via dectin-1 on TLR2-deficient DCs (Figure 1E). Taken together, these data suggest an important role for both dectin-1 and TLR2 in the induction of IL-10 in DCs.

Zymosan induction of IL-10 in DCs via a mechanism dependent on ERK MAPK. (A) On day 6, human monocyte-derived DCs were cultured with LPS or zymosan for 0, 15, 60, or 240 minutes. At each time point, the expression of phosphorylated and total ERK was evaluated by ELISA. Data are presented as the fold increases in the phosphorylated to total protein ratios relative to the 0 minute value. Data are representative of 4 experiments. (B) Flow cytometric analyses of phospho-ERK expression in DCs. Filled histograms represent the staining in unstimulated DCs, and the open histograms represent staining after stimulation. Data are representative of 3 experiments. (C) Effect of blocking dectin-1–β-glucan interactions, with laminarin on ERK activation. Data are representative of 3 experiments. Numbers in histograms indicate mean fluorescent intensities of the zymosan-treated DCs. No stimulus indicates DCs cultured in medium alone for 60 or 90 minutes. (D) Effect of blocking ERK1 and 2 with U0126, a synthetic MEK1 and 2 inhibitor, on IL-10 induction by zymosan in human monocyte-derived DCs. Data are representative of 4 experiments. (E) Role of ERK1 and 2 on IL-10 induction by zymosan on CD11c+ murine splenic DCs. DCs from wild-type or ERK1−/− mice were cultured in vitro in the presence of zymosan for 24–48 hours and IL-10 levels assayed by ELISA. Data are representative of 3 experiments. *P < 0.05, control vs. U0126 and WT vs. ERK1−/−.

Our previous work suggests that Pam-3-cys, a synthetic TLR2 ligand, induces enhanced and sustained levels of ERK phosphorylation relative to TLR4 or TLR5 ligands (13, 14). The involvement of TLR2 in the induction of ERK phosphorylation in response to zymosan was demonstrated by lower levels being observed in TLR2-deficient DCs (Figure 2C). However, the induction of ERK phosphorylation by zymosan also appeared to be, at least in part, mediated by dectin-1, since laminarin could partially block this in wild-type DCs (Figure 2C). Crucial roles for the involvement of both dectin-1 and TLR2 in ERK phosphorylation were demonstrated by blocking dectin-1 receptors in TLR2-deficient DCs (Figure 2C).

We determined the role of ERK1 and 2 in IL-10 induction, using synthetic inhibitors of ERK activation as well as ERK1-deficient mice. In the presence of the synthetic inhibitor U0126, which inhibits MEK1 and 2, the upstream activators of ERK1 and 2, there was a profound impairment of IL-10 secretion by human DCs in response to zymosan (Figure 2D). Consistent with this, DCs from ERK1-deficient mice were significantly impaired in their ability to produce IL-10, and in the presence of U0126, there was a more profound reduction (Figure 2E). Therefore, zymosan appears to mediate IL-10 production in human and murine DCs via a mechanism involving ERK MAPK activation, and this is mediated through both TLR2 and dectin-1.
Zymosan induction of IL-10 in DCs is not dependent on c-Fos. We next addressed the question of what downstream transcription factors might mediate the induction of IL-10 in DCs by zymosan. Our previous work suggests that the synthetic TLR2 ligand Pam-3-cys, which induces enhanced and sustained ERK activation, results in phosphorylation and stabilization of the activation protein 1 (AP-1) transcription factor c-Fos, which plays a critical role in regulating IL-12(p70) and IL-10 (13, 14). Therefore, we determined whether c-Fos also plays a role in regulating IL-10 induction by zymosan (Figure 3). Thus, DCs from wild-type or c-Fos mice were cultured with zymosan or Pam-3-cys (100 μg/ml) and CD40 ligand cells. IL-10 levels were assayed by ELISA. Data are representative of 3 experiments.

**Figure 3**

Zymosan induction of IL-10 in DCs is not dependent on c-Fos. CD11c+ murine splenic DCs from wild-type or c-Fos–deficient mice were stimulated for 24 hours with zymosan or Pam-3-cys (100 μg/ml) and CD40 ligand cells. IL-10 levels were assayed by ELISA. Data are representative of 3 experiments.

IL-10 regulates the induction of TNF-α, IL-12, and IL-6 in DCs. IL-10 is known to be an antiinflammatory cytokine that inhibits the production of multiple, diverse inflammatory mediators from activated macrophages and DCs (25, 26). We thus determined whether the impairment of IL-6, IL-12, and other proinflammatory cytokines might be mediated by IL-10. DCs from IL-10–deficient mice were cultured in vitro with zymosan in the presence of a CD40-L–expressing fibroblast. As shown in Figure 4, there was a profound enhancement of IL-12(p40), IL-12(p70), IL-6, and TNF-α in response to zymosan in IL-10−/− DCs relative to wild-type DCs. Thus, IL-10 plays a critical regulatory role in limiting proinflammatory cytokines in DCs.

**Figure 4**

IL-10 regulates the induction of TNF-α, IL-12, and IL-6 in DCs. Wild-type or IL-10–deficient murine splenic DCs were cultured with zymosan (100 μg/ml) and CD40 ligand cells for 24 hours, and levels of cytokines were assayed by ELISA.
in the primary response (Figure 5A), T cells stimulated with zymo-
san-treated DCs proliferated even less than those stimulated with
DCs pulsed with OVA alone (Figure 5B).

We then determined whether the impaired responsiveness of T
cells stimulated with zymosan-pulsed DCs was caused by robust
induction of IL-10 or by the lack of high levels of proinflammatory
cytokines from such DCs (Figure 5C). Neutralizing the effects of
IL-10 in the primary cultures with an antibody against the IL-10
receptor appeared to have little or no effect on the weak T cell pro-
liferation induced by DCs pulsed with OVA plus zymosan. Howev-
er, the addition of recombinant IL-6 induced high levels of prolif-
eration similar to those induced by LPS. Interestingly, the addition
of recombinant IL-6 in conjunction with anti–IL-10 receptor anti-
body appeared to act in a synergistic manner to enhance T cell pro-
liferation. Thus, zymosan-pulsed DCs induce T cells that appear to
be unresponsive to rechallenge with antigen in vitro.

Zymosan induces TGF-β–producing macrophages but few proinflam-
matory cytokines in vivo. We wished to determine whether zymosan
could also induce T cell unresponsiveness in vivo. First, we deter-
mined whether i.v. or i.p. injections of zymosan or LPS resulted
in upregulation of the activation markers CD80, CD86, CD40,
and class II MHC. Consistent with our previous data (14), CD8α+
and CD8ε+ DCs in the spleens expressed greatly enhanced levels
of CD80, CD86, CD40, and I-Aβ within 4 hours of LPS injection,
and these levels remained high up to 10 hours (Figure 6A). In con-
trast, zymosan was much less effective at inducing these molecules
on either DC subset (Figure 6A). We also determined the kind of
cytokines induced in the serum by these stimuli. LPS induced abun-
dant levels of IL-12(p40), IL-12(p70), IL-6, and TNF-α (Figure 6B).
In contrast, zymosan induced little or no IL-12(p40), IL-12(p70), IL-6,
or TNF-α (Figure 6B), consistent with its effects on DCs in vitro (Figure 1).
However, it did induce significant levels of IL-10, albeit at lower levels than LPS, as well as robust levels of
TGF-β, another potent antiinflammatory cytokine (27) (Figure
7A). It should be noted that the sera of untreated mice contain sig-
nificant levels of TGF-β (27), but there was a very pronounced and
significant induction of TGF-β by zymosan above this baseline
level. The TGF-β present in the serum was biologically active as
demonstrated by the phosphorylation of Smad-2 (Figure 7B). The
question of exactly what cell types were induced to produce TGF-β
by zymosan was addressed by 2 different approaches. First, spleen
cells were isolated at 1, 4, or 10 hours from mice injected with
zymosan and costained with TGF-β–TRITC and a number of other
markers, including CD11b–FITC or F4-80–FITC. As indicated in
Figure 7C, the majority of T cells expressing TGF-β were CD11b+ or
CD8ε+ macrophages in the marginal zones and the red pulp of the spleens (Figure 7D).

Injection of zymosan plus antigen into mice results in antigen-specific
T cell tolerance. Given the potent induction of the 2 antiinflam-
matory cytokines IL-10 and TGF-β and the weak induction of proin-
flammatory cytokines in vivo, we determined the type of adaptive
immunity induced by zymosan in vivo. We addressed this question
using OVA-specific, MHC class II–restricted (I-Aβ), αβ TCR trans-
genic mice (OT-II mice) (14). In these mice, the CD4+ OVA-specific
T cells express Vα2 and Vβ5 and, as detailed above, recognize the amino acid 323–339 peptide fragment from OVA. TCR transgenic T cells were adoptively transferred into Thy-1 congenic B6.PL.Thy-1a (B6.PL) mice such that they constituted a small but detectable proportion of all T cells (14). In this system, the fate of OVA-specific, transgenic T cells was followed using the Thy-1.2 antibody, which stains the transferred cells but not the host cells. Cells with the phenotype Thy-1.2+CD4+Vα2+Vβ5+ are considered OVA-specific CD4+ T cells. In some of the experiments, we simply used Thy-1.2 in combination with CD4 to detect the OVA-specific T cells.

The reconstituted mice were injected with 50 μg of OVA323–339 peptide alone, OVA323–339 plus LPS, or OVA323–339 plus zymosan i.v. Injection of OVA323–339 alone did not induce any significant clonal expansion of the CD4+Thy-1.2+ cells in the spleens of mice although these levels were consistently above those detected in reconstituted mice that had been left untreated, indicating that a limited amount of proliferation of the transferred T cells has taken place in response to OVA in the absence of any adjuvant (Figure 8, A and B). However, LPS significantly enhanced the clonal expansion of CD4+Thy-1.2+ cells in contrast, zymosan induced a very weak response although this was still above the response to OVA peptide alone (Figure 8, A and B). There appeared to be no differences in the frequencies of CD4+Thy-1.2+CD25+ versus CD25– T cells between the various groups (data not shown).

Previous work has shown that productive T cell immunity is elicited only when the antigen is injected with an adjuvant and that injections of soluble antigens only result in a transient and abortive clonal expansion in which antigen-specific T cells cannot be efficiently restimulated in vitro with protein or peptide (14, 28). We thus examined the in vitro proliferative capacity of OVA-specific T cells from the various cohorts of mice by culturing single-cell suspensions of the spleen with varying concentrations of OVA. As shown in Figure 8C, mice that received OVA323–339 plus LPS had greatly enhanced responses compared with those that received OVA323–339 peptide alone; in contrast, mice injected with zymosan had responses that were scarcely different from those observed in mice injected with OVA alone (Figure 8C). Importantly, these differences were not due to the lower frequency of OVA-specific T cells present in the cultures, because as demonstrated by CFSE labeling, T cells from mice immunized with OVA plus zymosan underwent fewer cell divisions than T cells from mice immunized with OVA plus LPS after in vitro restimulation. (Figure 8D).

Cytokine production by antigen-specific T cells was measured by assaying the culture supernatants from the cultures described above for IFN-γ, IL-4, IL-5, and IL-10. There were significant differences between mice injected with OVA323–339 peptide alone, OVA323–339 plus LPS, or OVA323–339 plus zymosan (Figure 8E). In cultures from mice injected with OVA323–339 peptide alone, there was little, if any,
IFN-γ, IL-4, IL-5, or IL-10. In contrast and consistent with previous reports (14, 28), in cultures from mice injected with OVA323–339 plus LPS, there were high levels of IFN-γ and low levels of IL-4 and IL-5. In striking contrast to this response, in cultures from mice injected with OVA323–339 plus zymosan, there were much lower levels of IFN-γ, IL-4, and IL-5 but high levels of IL-10 (Figure 8E). The fact that IL-10 is only produced in culture when OVA is present suggests that IL-10 induction is dependent on T cells. Therefore, unlike LPS, zymosan induces an antigen-specific T cell response characterized by very weak clonal expansion and in vitro proliferation as well as minimal production of Th1 and Th2 cytokines but high levels of IL-10. These characteristics appeared to be indicative of regulatory or tolerogenic responses. We tested this hypothesis further by determining whether injections of OVA323–339 plus zymosan into mice result in a T-helper response that is characterized by very weak clonal expansion and in vitro restimulation and negligible levels of Th1 or Th2 cytokines but high levels of IL-10. Furthermore, such T cells appear to be unresponsive to a subsequent rechallenge with the same antigen plus a gold-standard adjuvant, such as IFA. Further evidence for zymosan inducing unresponsive T cells was observed when LPS and zymosan were coinjected with OVA323–339. As Figure 8H shows, coinjection of LPS and zymosan resulted in T cells that underwent a reduced number of cell divisions compared with LPS-stimulated T cells (Figure 8H) and had reduced proliferation (Figure 8I). Taken together, these data suggest that an injection of antigen plus zymosan induces a state of immunological unresponsiveness in antigen-specific T cells.
Figure 8
Zymosan induces antigen-specific T cell tolerance in vivo and suppresses the OVA-specific response when co-injected with OVA plus LPS. (A) B6.PL mice reconstituted with OT-II TCR transgenic T cells were injected i.p. with class II–restricted OVA peptide, OVA323–339 (50 μg) plus LPS (25 μg), OVA323–339 (50 μg) plus zymosan (various doses), or OVA323–339 alone (50 μg). Four days later, spleens were removed and clonal expansion of OVA323–339–specific T cells (A) and numbers of OVA323–339–specific CD4+ T cells per spleen (B) were determined by flow cytometry. (C–E) Spleens were isolated 4 days after immunization, and unfractionated spleen cells labeled with CFSE and restimulated in vitro with OVA323–339 for 72 hours. Proliferation as measured by thymidine uptake (C) or CFSE labeling (D) and cytokine production by ELISA (E) were determined. Zymosan induced T cells that produced only high levels of IL-10 (box). Data are representative of 5 independent experiments. (F and G) Mice immunized as above with OVA323–339 plus LPS or OVA323–339 plus zymosan were rechallenged 10 days later with OVA323–339 in IFA. Four days after challenge, clonal expansion and cytokine production upon in vitro restimulation were evaluated. Data are representative of 4 independent experiments. (H and I) B6.PL mice reconstituted with OT-II TCR transgenic T cells were injected with OVA323–339 (50 μg) plus LPS (25 μg), OVA323–339 (50 μg) plus zymosan (100 μg), OVA323–339 (50 μg) plus LPS (25 μg) plus zymosan (100 μg), or OVA323–339 alone (50 μg). Four days later, spleens were removed and unfractionated splenocytes were restimulated with OVA323–339 and (H) CFSE and (I) proliferation of OVA323–339–specific T cells determined.
Induction of immunological tolerance by zymosan is dependent on IL-10, TGF-β, and lack of IL-6. The potential importance of IL-10, TGF-β, and IL-6 in this induction of immunological unresponsiveness was evaluated in vivo studies using IL-10-knockout mice, in which TGF-β was neutralized with an anti-TGF-β antibody, IL-6 was supplemented, and the effect on OVA-specific immune responses induced by zymosan plus OVA was assessed (Figure 9). Blocking of TGF-β, addition of IL-6, and the absence of IL-10 in mice challenged with zymosan plus OVA323–339 each showed small increases in clonal expansion of OVA323–339-specific T cells (Figure 9A) and more impressive increases in the number of cell divisions by those T cells after in vitro restimulation (Figure 9B). The greatest increase, however, was observed when anti-TGF-β antibody and recombinant murine IL-6 were injected into IL-10–/– mice challenged with zymosan plus OVA323–339. This injection regime resulted in the largest increase in clonally expanded OVA323–339-specific T cells compared with the zymosan plus OVA323–339–challenged C57BL/6 mice injected with isotype antibody (Figure 9A). Importantly, the combination of all 3 allowed T cells to undergo the same number of divisions as those T cells from LPS plus OVA323–339 underwent upon restimulation in vitro (Figure 9B). Thus, the immunological unresponsiveness induced by zymosan in vivo can be abrogated by blocking TGF-β and IL-10 and by the addition of IL-6.

**Discussion**

In summary, these data suggest that the yeast cell wall, zymosan, previously considered to be a proinflammatory stimulus (20, 27), is a potent inducer of IL-10 and TGF-β as well as T cell unresponsiveness via multiple mechanisms. First, it induces regulatory-type DCs that produce few proinflammatory cytokines but abundant IL-10 and induce tolerogenic T cell responses. With regard to the mechanism of induction of IL-10, our data suggest a critical role for ERK activation after signaling through TLR2 and dectin-1 via a mechanism that is independent of c-Fos. Second, zymosan induces abundant levels of biologically active TGF-β, another antiinflammatory cytokine, from splenic F4-80+ macrophages in the red pulp. Thus, the dual antiinflammatory effects of IL-10 and TGF-β in concert with diminished proinflammatory cytokines likely result in the induction of impaired T cell responses and tolerance. These antiinflammatory effects appear to be in contrast to numerous previous reports of the ability of zymosan to induce proinflammatory cytokines such as TNF-α from macrophage cell lines in vitro (20, 27, 29, 30) and to augment inflammatory responses in vivo (30–32). However, in contrast to these studies and in agreement with our study is recent work that suggests that zymosan is also a potent inducer of IL-10 from DCs (22, 33). The
The single injection of 10–100 μg of IL-10 versus splenic DCs), the dose of zymosan being injected in vivo (a function of abundant IL-10 but little IL-12(p70) or IL-6. Unlike the case with Pam-3-cys, impairment of IL-12(p70) and induction of c-Fos are not dependent on c-Fos. Induction of IL-10 represses the induction of proinflammatory cytokines, including IL-12, IL-6, and TNF-α. In addition to these effects on DCs, zymosan also induces biologically active TGF-β in macrophages. In this case, the robust induction of IL-10 and TGF-β coupled with impaired induction of IL-6 and IL-12(p70) appears to induce immunological tolerance.

reason for the discrepancies between these studies is not clear but may be due to differences in the subsets of cells being examined (macrophage cell lines in vitro versus bone marrow–derived DCs versus splenic DCs), the dose of zymosan being injected in vivo (a single injection of 10–100 μg in our study versus repeated injections of several milligrams in other studies; ref. 32), or the strains of mice used (C57BL/6 in our studies versus Zap-70 knockouts in the study by Yoshitomi et al.; ref. 32). Consistent with a dose-dependent effect, we observed that concentrations of zymosan higher than 200 μg/ml (up to 500 μg/ml) stimulated higher levels of IL-6 and IL-12(p70) from DCs in vitro although even at the highest dose of 500 μg/ml, the levels of these cytokines induced were not as much as those induced by LPS (Supplemental Figure 3). Furthermore, the induction of IL-10 appeared to be largely unaffected by these higher concentrations of zymosan. This suggests that the dose of zymosan may in part explain the apparently contradictory observations that zymosan induced proinflammatory versus antiinflammatory cytokines. The mechanism by which such dose differences result in distinct cytokine profiles is of considerable interest. One possibility is that varying the concentration of ligands within zymosan might result in quantitative differences in the affinity, avidity, or threshold of signaling via dectin-1, TLR2,

or some other receptor and that this translates into qualitative changes in the signaling pathways and biological response.

The question of which signaling pathway and transcription factors in DCs mediate IL-10 production is of great interest (Figure 10). Our recent work suggests that stimulation of human (13) or murine (14) DCs with the synthetic TLR2 ligand Pam-3-cys results in robust production of IL-10 and IL-6 but little IL-12(p70). The induction of IL-10 and impaired production of IL-12(p70) appear to be regulated by phosphorylation of ERK MAPK since blocking ERK signaling enhances IL-12(p70) while reducing IL-10 induction (13, 14). Furthermore, enhanced ERK induction appears to phosphorylate c-Fos, an AP-1 transcription factor, which represses IL-12 production in DCs (13, 14). However, zymosan, which signals through both TLR2 and dectin-1, appears to utilize an overlapping but distinct signaling pathway to mediate its distinctive effects. First, although zymosan is similar to Pam-3-cys in that it induces robust IL-10 and weak IL-12(p70), it differs in its failure to induce abundant IL-6. The mechanism underlying this difference is unclear, but one possibility is that IL-6 production by zymosan is regulated by some TLR2-independent signaling, perhaps via dectin-1. Consistent with this, our recent work suggests that laminarin results in an enhancement of IL-6 induction by zymosan-treated DCs, particularly at the lower doses of zymosan (Supplemental Figure 4). In contrast, DCs from TLR2-knockout mice produce reduced levels of IL-6. Thus, signaling via TLR2 and dectin-1 appear to exert opposing effects on IL-6 induction by zymosan at the lower doses. Second, although zymosan also induces robust ERK activation, c-Fos does not appear to be involved in regulating IL-12(p70) or IL-10 in zymosan-treated DCs since DCs from c-Fos–knockout mice do not show profound differences in these cytokines (Figure 3). Exactly what transcription factor(s) downstream of ERK might mediate IL-10 induction by zymosan is presently being investigated. Furthermore, which transcription factors might regulate the weak IL-6 and IL-12(p70) responses in zymosan-treated DCs is also being investigated. Whatever such factors might be, it is clear that IL-10 exerts a potent feedback regulatory mechanism that inhibits the production of IL-12, IL-6, and TNF-α, consistent with other studies (25, 26). Interestingly, 2 recent reports suggest that the adaptor protein Syk, which is involved in signaling via dectin-1 in macrophages (29) and DCs (33), mediates the induction of IL-10 (33). However, these reports did not describe the signaling events downstream of Syk. Our present data suggest that ERK activation occurs downstream of Syk and is consistent with similar findings in a different system (34).

Finally, it is intriguing to consider these data from an evolutionary perspective. It has been proposed that pathogens such as HIV, cytomegalovirus, hepatitis C virus, and Mycobacterium tuberculosis target another member of the C-type lectin family, DC-SIGN, to impair DC maturation and adaptive immunity (15, 16). One common characteristic of these pathogens is that they can cause chronic infection, during which the Th1/Th2/T regulatory balance is a critical determinant of pathogen persistence in the host. Thus, it is possible that zymosan induces IL-10 and TGF-β but suppresses IL-12 and IL-6 to disarm host immunity. However, since zymosan is not considered to be pathogenic in humans, the evolutionary significance of such an immune evasion mechanism may not be obvious. One possibility is that this mechanism may be equally beneficial for the host and the microbe. Thus, the initial, transient suppression of proinflammatory cytokines might permit the microbe to establish infection in the host, unhindered by the
host’s innate immune system — indeed, the observation that fun-
genal pneumonia can occur after TNF-α ablation therapy underscores
the critical role of proinflammatory cytokines in the control of
infection (35, 36). Later, during an established infection, IL-10 and
TGF-β may serve to keep the inflammation in check, thus avoid-
ing immune pathology, which could be detrimental to the host.
Thus, the persistent antiinflammatory response induced by the
microbe may be beneficial for both the microbe and host. Such a
mechanism may well operate in various chronic infections caused
by pathogens, such as HIV, HCV, and M. tuberculosis. Whatever the
evolutionary significance, our results highlight several molecular
targets, such as TLR2, dectin-1, and ERK, in the therapeutic modu-
lation of innate and adaptive immunity in the context of many
pathologic states, such as autoimmunity, allergy, transplantation,
and infectious diseases.

Methods
Mice. C57BL/6 mice were purchased from Jackson Laboratory. Male B6.PL
mice were purchased from Jackson Laboratory or bred at the Rodent Vivari-
um of the Yerkes National Primate Center of Emory University. IL-10−/− mice
(B6.129P2-Il10tm1Rtm/J) were purchased from Jackson Laboratory. B6.129/F1/
Tac (B6.129 mice were purchased from Taconic). ERK1-knockout (ERK1 −/−) (37)
mouse on the C57BL/6 background were kindly provided by G. Landreth
(Case Western Reserve University, Cleveland, Ohio, USA) and bred at the
Yerkes Rodent Vivarium. c-Fos-knockout mice were kindly provided by L.
McCauley (University of Michigan, Ann Arbor, Michigan, USA). OT-II TCR
transgenic mice (strain 426-6) (38), generated by W. Heath (Walter and Elisa
Hall Institute, Melbourne, Victoria, Australia) and F. Carbone (Monash Uni-
versity, Melbourne, Victoria, Australia), were obtained from J. Kapp (Emory
University) and bred at the Yerkes Animal Facility. All mice were aged 6–10
weeks. All animal studies were approved by the Institutional Animal Care
and Use Committee of Emory University. For adoptive transfer studies, age-
matched B6.PL recipients were given 2.5 × 106 OT-II transgenic T cells i.v.
Reagents. Zymosan (Sigma-Aldrich) was boiled for 30 minutes, washed
extensively, and stored at −70°C. Highly purified Escherichia coli LPS (Strain
25922) was a generous gift from T. Van Dyke. Recombinant Flt3 ligand was
expressed in CHO cells and purified at the Emory Vaccine Cen-
ter. Recombinant GM-CSF and IL-4 were purchased from PeproTech. The
3T3-CD40 ligand fibroblasts (39) (a kind gift of P. Hwu, National Cancer
Institute, Bethesda, Maryland, USA) were grown in complete DMEM plus
10% FBS and irradiated at 28.53 Gy (Gammacell 3000 Elan; MDS Nordion)
to prevent further replication. Cells were plated at 4 × 104 cells per well in a
48-well plate and incubated overnight at 37°C in a humidified atmosphere
of 5% CO2 in air. Both the MAPK inhibitor U0126 (Calbiochem) and the
dectin-1 receptor inhibitor laminarin (from L. digitata; Sigma-Aldrich) were
added prior to the addition of stimuli.
Injections. B6.PL mice reconstituted with OT-II TCR transgenic T cells
were injected i.p. or i.v. with 50 μg MHC class II-restricted OVA peptide
(ISQVHAAHAEINEGR; OVA223-339) in PBS alone or PBS containing
either 25 μg E. coli LPS or various doses of zymosan. The OVA peptides
were from Brian Evavold (Emory University). To investigate the effect of
LPS or zymosan on DCs in vivo, C57BL/6 mice were injected with PBS con-
taining either 25 μg E. coli LPS or various doses of zymosan. Six hours later,
the spleens were removed and a small portion digested with collagenase
type 4 (1 mg/ml; Worthington Biochemical Corp.) in complete DMEM
plus 2% FBS for 30 minutes at 37°C. The red blood cells were lysed and
the cell suspension washed twice prior to analysis of cell surface expres-
sion of activation markers by flow cytometry. For rechallenge experiments,
OT-II–reconstituted mice were injected with OVA223-339 in PBS alone or
PBS containing LPS or zymosan as detailed above. Additionally, 1 group
received PBS without OVA223-339. Seven days later, all groups were injected
i.p. with OVA223-339 emulsified 1:1 in IFA.
Flow cytometry. All antibodies used were from BD Biosciences unless
otherwise stated. For determination of activation of DCs injection of LPS
or zymosan in vivo, rbc-lysed, collagenase-digested spleen cells were incu-
bated at 4°C with FITC-conjugated CD11c, APC-conjugated CD11b, and
PE-conjugated CD80, CD86, CD40, or MHC class II. For analysis of
OT-II cells, cell suspensions prepared from spleen cells were incubated at
4°C with APC-conjugated CD4 and PE-conjugated Thy 1.2. Levels of
phosphorylated ERK (phospho-ERK) were determined by using phospho-
ERK1 and 2 antibody on fixed and permeabilized (90% methanol) murine
CD11c+ DCs or human monocyte-derived DCs as detailed below.

**In vivo cultures of murine DCs and T cells.** CD11c−enriched DCs or
CD11c+CD11b− and CD11c+CD11b+ DC subsets were purified from spleen cell suspensions from mice
for 9 days with Flt3 ligand. In brief, spleens from Flt3 ligand–treated mice were dissected, cut into small fragments, and then digested with
collagenase type 4 (1 mg/ml) in complete DMEM plus 2% FBS for 30 min-
utes at 37°C. Cells were washed twice and frozen in FBS plus 10% DMSO
(Sigma-Aldrich). Thawed cells were washed twice, and the CD11c+ DCs
were enriched using the CD11c+ microbeads from Miltenyi Biotec. The result-
ing purity of CD11c+ DCs was approximately 95%. The enriched DCs were
stained with FITC-conjugated CD11c and PE-conjugated CD11b and sort-
ted into the CD11c+CD11b+CD8α+ and CD11c+CD11b+CD8α− DC subsets
using a high-speed modular flow cytometer (MoFlo; Cytomation Inc.).

In vitro cultures of murine DCs and T cells. CD11c−enriched DCs or
CD11c+CD11b− and CD11c+CD11b+ DC subsets were plated with either
LPS or zymosan in complete DMEM plus 10% FBS onto a confluent layer
of irradiated CD40 ligand fibroblasts to induce CD40 ligand triggering.
MAPK inhibitor U0126 (10 μM) or laminarin (200 μg/ml) was added prior
to the addition of stimuli to the CD11c−enriched DCs. Cultures were incu-
bated in a humidified atmosphere of 5% CO2 in air at 37°C for 24–48 hours.
The culture supernatants were collected and assayed for the presence
of IL-12(p40), IL-12(p70), IL-10, IL-6, and TNF-α. For in vitro T cell assays,
CD11c−enriched DCs were cultured with naive OT-II CD4+CD45R B1−
and OVA peptide and either LPS (1 μg/ml) or zymosan (10 μg/ml). Various con-
centrations of recombinant murine IL-6 (PeproTech) or anti–IL-10 receptor
antibody (BD Biosciences) were added to appropriate wells. Either 2 or 5 days
later, the T cells were restimulated with plate-bound anti-CD3 (10 μg/ml) and
anti-CD28 (2 μg/ml) for an additional 3 days. Cultures were pulsed with
1 μCi [3H]thymidine for 12 hours, and incorporation of the radionucleotide
was measured by β-scintillation spectroscopy. Eight days after in vivo prim-
ing with OVA peptide plus ligand, rbc-depleted spleen cells were cultured in
triplicate in 96-well round-bottomed plates (1 × 106 cells/well) in com-
plete DMEM plus 10% FBS together with different concentrations of OVA
peptide. Proliferative responses were assessed after 72 hours of culture in a
humidified atmosphere of 5% CO2 in air at 37°C. Cultures were pulsed with
1 μCi [3H]thymidine for 12 hours, and incorporation of the radionucleotide
was measured by β-scintillation spectroscopy. For cytokine assays, aliquots
of culture supernatants were removed after 90 hours, pooled, and assayed for
the presence of IL-2, IL-4, IL-5, IL-13, IL-10, and IFN-γ by ELISA.

**In vivo blocking and addition of recombinant cytokines.** OT-II T cells
were transferred into C57BL/6 or IL-10−/− mice as described above. On the same
day, anti–TGF-β antibody (150 μg per mouse; Harlan) or 500 ng recombi-
nant murine IL-6 (PeproTech,) was injected i.p. Mice were challenged with
50 μg OVA223-339 in PBS alone or PBS containing either 25 μg E. coli LPS or
100 μg zymosan the next day. Anti–TGF-β antibody or recombinant IL-6
were injected the same day and again 2 days later.

**Measurement of cytokine production.** IL-2, IL-4, IL-5, IL-6, IL-12(p40),
IL-12(p70), IL-10, TNF-α, and IFN-γ in cell culture supernatants or serum

were quantitated by ELISA antibody sets from BD Biosciences, and IL-13 was measured by an ELISA kit from R&D Systems. TGFB-1 was measured by an ELISA kit from BioSource International.

Isolation, culture, and phenotyping of human monocyte-derived DCs. CD14+ monocytes were enriched from peripheral blood mononuclear cells and cultured for 6 days with recombinant human GM-CSF at 100 ng/ml plus recombinant human IL-4 at 20 ng/ml. At day 6, the cultures consisted uniformly of CD1a+CD14 HLA-DR+CD11c+ cells, which were negative for CD83. These immature DCs were pulsed with LPS or zymosan for 24–48 hours. Phenotype was determined by flow cytometry using a FACScalibur (BD Biosciences). Briefly, gated CD1a+CD14+CD11c+HLA-DR+DCs were analyzed for the expression of CD80, CD86, or CD83. Cytokine production was measured by ELISA.

Evaluation of ERK MAPK signaling. This was done using commercially available ELISA kits (BioSource International), or flow cytometry. Briefly, on day 6, immature, human monocyte-derived DCs (2x 10^6) were cultured for the indicated times with the stimuli. ELISA assays were performed according to manufacturer instructions. Flow cytometric evaluation of phospho-ERK1 in DCs was determined by stimulating day-6, human monocyte-derived DCs for 15 minutes, 1 hour, and 4 hours with LPS or zymosan and then fixing the cells in 2% paraformaldehyde (10% ultrapure EM Grade; Polysciences Inc.) for 10 minutes at 37°C. After washing, the cells were permeabilized with freshly prepared 90% ice-cold methanol for 30 minutes on ice. Then the cells were washed twice in staining buffer (3% FCS in PBS) and labeled with phospho-ERK for 30 minutes on ice, then washed in staining buffer and labeled using FITC-labeled goat–anti-rabbit Ig. Flow cytometry was done on FACScalibur. Detection of phospho-ERK1 and 2 was detected in murine CD11c+ in a similar fashion.

Detection of biological activity of serum TGF-β. Spleen cells were incubated with serum from mice previously challenged with PBS, LPS (25 μg/ml), or zymosan (25 μg/ml or 100 μg/ml). Lysates of cells treated with 2.5 ng TGF-β1/ml in RPMI medium with 0.5% fetal bovine serum were separated on 8% tris-glycine gels (Invitrogen Corp.). Immunoblotting was performed with an anti–phosho-Smad2, rabbit polyclonal antibody (Upstate Biotechnology Inc.) at room temperature for 1 hour (antibody dilutions were performed in PBS containing 1/200 Fc block). Normal rabbit IgG (Santa Cruz Biotechnology Inc.) was used as an isotype control, and staining was undetectable with this antibody. Washed sections were mounted with Vectashield Hard set (Vector Laboratories). Three images were acquired for each field using a Zeiss Axiosvert LSM-410 confocal microscope (showing FITC, TRITC, and both dyes simultaneously on the cells).

Statistics. Statistical significance of differences in means ± SD of cytokines released by cells from different groups was calculated using the 2-tailed Student’s t-test. P values less than 0.05 were considered statistically significant.

Acknowledgments

This work was supported by NIH grants AI0564499, AI048638, AI05726601, DK057665, AI057157, and AI05726601. We thank Mike Huley for help with the FACS sorting experiments and Pearl Backman for help with preparation of the manuscript.

Received for publication October 24, 2005, and accepted in revised form January 24, 2006.

Address correspondence to: Bali Pulendran, Emory Vaccine Center, 954 Gatewood Road, Atlanta, Georgia 30329, USA. Phone: (404) 727-8945; Fax: (404) 727-8199; E-mail: bpulend@emory.edu.

S. Dillon and S. Agrawal contributed equally to this work.