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Toll-Like Receptor 4, But Not Toll-Like Receptor 2, Is a Signaling Receptor for *Escherichia* and *Salmonella* Lipopolysaccharides¹

Richard I. Tapping,* Sachiko Akashi,[†] Kensuke Miyake,[†] Paul J. Godowski,[‡] and Peter S. Tobias^{2*}

Two members of the mammalian Toll-like receptor (TLR) family, TLR2 and TLR4, have been implicated as receptors mediating cellular activation in response to bacterial LPS. Through the use of mAbs raised against human TLR2 and TLR4, we have conducted studies in human cell lines and whole blood to ascertain the relative contribution of these receptors to LPS induced cytokine release. We show that the contribution of TLR2 and TLR4 to LPS-induced cellular activation correlates with the relative expression levels of these two TLRs in a given cell type. In addition, we have found that significant differences in cell stimulatory activity exist between various smooth and rough LPS types that cannot be ascribed to known LPS structural features. These results suggest that impurities in the LPS may be responsible for some of the activity and this would be in agreement with recently published results of others. Upon repurification, none of the commercial LPS preparations activate cells through TLR2, but continue to stimulate cells with comparable activity through TLR4. Our results confirm recent findings that TLR4, but not TLR2, mediates cellular activation in response to LPS derived from both *Escherichia coli* and *Salmonella minnesota*. Additionally, we show that TLR4 is the predominant signaling receptor for LPS in human whole blood. *The Journal of Immunology*, 2000, 165: 5780–5787.

Initially identified in *Drosophila*, Toll receptors mediate release of antimicrobial and antifungal peptides in response to infection (1, 2). The cloning of the first human homologue of Toll revealed that expression of a variety of inflammatory cytokines is induced by a constitutively active form of this receptor (3). To date, at least nine human Toll-like receptors (TLRs),³ designated TLR1 through TLR9, have been identified (Refs. 3–6 and Genebank). Toll receptors are type I transmembrane proteins with extracellular domains comprised largely of leucine-rich repeats and intracellular signaling domains with homology to the IL-1 receptor. Not surprisingly, the human Toll receptors have been shown to transduce signals through intracellular components shared by the IL-1 signaling machinery, ultimately leading to activation of NF- κ B (7–9). Collectively, these findings led to the proposal that human Toll receptors are evolutionarily conserved components of the innate immune system. The identification of infectious pathogens and their products that activate mammalian cells through specific Toll receptors has been an intense area of research over the past 2 years.

One of the most potent pathogen-derived inflammatory mediators is LPS, a major structural component of Gram-negative bac-

teria. Activation of cells, most notably macrophages, results in activation of NF- κ B and production of cytokines and other inflammatory molecules. The identification of cell surface receptors capable of mediating LPS-induced inflammatory responses has been an intense area of investigation for many years (10, 11). The primary receptor for LPS is CD14, a cell surface marker of macrophages (12). Although CD14 has been shown to mediate LPS-induced activation in a wide variety of cell types, this receptor is GPI anchored and incapable of directly transducing signals across the cell membrane. Until recently, a receptor that directly transduces an activation signal in response to LPS has remained elusive.

Shortly after the discovery of mammalian TLRs, transfection of TLR2 was shown to confer LPS-induced cellular activation of NF- κ B in human embryonic kidney 293 cells (13, 14). In this system, coexpression of CD14 enhances LPS-induced cellular activation mediated by TLR2. Using transfected human embryonic kidney 293 cells, LPS was subsequently shown to cause the oligomerization of TLR2 and the recruitment of IL-1-receptor-associated kinase to the TLR2 complex (15). In support of a role for TLR2 in LPS signaling, expression of a dominant-negative form of the TLR2 receptor in RAW cells was shown to inhibit LPS-induced gene expression driven by the IL-12 gene promoter. In addition, a mAb directed against TLR2 was shown to inhibit LPS-mediated IL-12 release from human adherent monocytes (16). Taken together, this biochemical evidence implicates TLR2 as a receptor mediating LPS-induced cellular activation.

Concurrent with the studies on TLR2, a point mutation in the signaling domain of the gene encoding TLR4 was identified as the genetic defect of the C3H/HeJ mouse, an inbred strain long known to be hyporesponsive to LPS (17, 18). Subsequent studies revealed that overexpression of a TLR4 gene harboring this point mutation in RAW cells results in dampened TNF- α release in response to LPS (19, 20). Targeted disruption of genomic TLR4 in mice has confirmed that the TLR4 receptor is necessary for sensitive responses to LPS (21). In addition, certain cell lines transfected with

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³ Abbreviations used in this paper: TLR, Toll-like receptor; HKSA, heat-killed *Staphylococcus aureus*; PGN, peptidoglycan.

human TLR4 acquire the ability to activate NF- κ B in response to LPS (22, 23). Thus, genetic and biochemical evidence has identified TLR4 as a receptor that mediates cellular activation in response to LPS.

The idea of whether TLR2 or TLR4 represents the physiologically relevant LPS receptor has been the source of some debate especially as recently generated TLR2 knockout mice appear to have no significant defects in LPS responsiveness (24). In this study, we have studied the contribution of both TLR2 and TLR4 to LPS-induced production of TNF- α and IL-8 in both human cell lines and human whole blood. Through transfection studies and the use of blocking monoclonal anti-TLR2 and anti-TLR4 Abs, we have found that the contribution of each TLR to LPS-induced inflammatory responses is dependent upon both the cell type used and the source of the LPS. Most importantly, we have observed that after repurification, commercial preparations of both *Escherichia coli* and *Salmonella mimesota* LPS no longer induce cellular activation through TLR2, indicating that impurities in these LPS preparations are responsible for the observed TLR2-mediated signaling. Our results show that TLR4, and not TLR2, is the predominant receptor mediating LPS-induced cellular activation in human whole blood.

Materials and Methods

Reagents and Abs

Heat-killed *Staphylococcus aureus* (HKSA) was a kind gift of Dr. Colleen Fearn (The Scripps Research Institute, La Jolla, CA). Soluble peptidoglycan (PGN) purified from *S. aureus* was a kind gift of Dr. Roman Dziarski (Indiana University School of Medicine, Gary, IN). All commercial LPS preparations were purchased from List Biological Laboratories (Cambell, CA). Polymyxin B was obtained from Sigma (St. Louis, MO). The anti-CD14 mAb 63D3 was obtained from the American Type Culture Collection (Manassas, VA). The anti-CD14 mAb 28C5 was a gift from Dr. A. Moriarty and Dr. D. Leturcq (R.W. Johnson Pharmaceutical Research Institute, La Jolla, CA). The anti-TLR2 mAbs mAb 2380 and mAb 2392 have been previously described (25). The mAbs HTA405, HTA414, and HTA1216, against human TLR4, were generated by immunizing mice with TLR4-expressing Ba/F3 cells (23). Spleen cells from immunized mice were fused with SP2/0 myeloma cells and hybridomas were chosen that specifically stain TLR4-expressing Ba/F3 cells as described (23).

Repurification of LPS

Commercial LPS preparations were resuspended in endotoxin-free water containing 0.2% triethylamine followed by vortexing. A portion of each commercial LPS preparation was repurified using a modified phenol-water extraction procedure followed by ethanol precipitation as described (26–28). Recovery of LPS was determined by colitose assay for smooth LPS types and 3-deoxy-D-manno-octulosonic acid assay for rough LPS types as described (29). LPS recoveries were typically 65–85% and were confirmed by performing a *Limulus* amoebocyte lysate assay (BioWhittaker, Walkersville, MD) according to a protocol supplied by the manufacturer.

Construction of TLR4 expressing THP-1 cell lines

The cDNA encoding full length TLR4 was amplified by PCR using the primers 5'-CCTTGGTACCAAGCTTCTCGAGGCCAGGATGATGTC TGCCTCG-3' and 5'-CCTTGGATCCGTCGACCTATCAGATAGATG TTGCTTCTCGCC-3'. The resulting amplified DNA was cloned as a *XhoI*/*Bam*HI fragment into the *XhoI* and *Bg*II sites of the retroviral vector pMSCV-blasto (Gary Nolan, Stanford University School of Medicine, Stanford, CA) to create the plasmid pMSCV-blasto-TLR4. This construct was confirmed by sequencing at the Core Facility of The Scripps Research Institute. Phoenix-Ampho cells, an amphotropic retroviral packaging cell line derived from 293T cells (30, 31), were transfected with pMSCV-blasto-TLR4 by the calcium phosphate method. Replication-defective retrovirus was harvested from the cell supernatant 48 h after transfection and sterile filtered. The macrophage cell line THP1-CD14, a monocytic cell line that constitutively expresses CD14 (32, 33), was infected by centrifuging the cells in medium containing retrovirus plus 5 μ g/ml polybrene (30, 31). The medium was changed 24 h postinfection and cells were selected as a batch in medium containing 5 μ g/ml blasticidin. Vector control THP1-CD14 cells were generated by following the above procedure using the empty vector pMSCV-

blasto. Cells containing stably integrated vector sequences were selected for 3 wk in medium containing 5 μ g/ml blasticidin.

Cell activation assays

THP1-CD14 cells were grown in RPMI 1640 medium containing 10% FBS, 1% penicillin/streptomycin/glutamine, and 800 μ g/ml G418, to maintain CD14 expression. On the day of the assay, the cells were washed three times in serum-free RPMI 1640 medium and resuspended in the same medium containing 2% human serum. About 10⁵ cells were added to each well of a 96-well plate and activated with various agonists as indicated in the figures. Upon the addition of an agonist, the cells were placed in an incubator at 37°C and 5% carbon dioxide for 6 h. Where indicated, Abs were preincubated with cells for 30 min at a concentration of 10 μ g/ml before agonist addition.

U373 cells, a human astrocytoma cell line, were grown in RPMI 1640 medium containing 10% FBS and 1% penicillin/streptomycin/glutamine. The day before the assay, the cells were trypsinized, transferred into 96-well plates, and allowed to recover overnight. The adherent cells were washed three times with serum-free RPMI 1640 medium. Cells were stimulated for 6 h in the presence of 2% human serum using Re595 or 0111B4 LPS as indicated in the figure legends. The amount of LPS used in the Ab blocking experiments reflects the fact that the average molecular mass of rough Re595 LPS is 10-fold less than that of smooth 0111B4 LPS. Where indicated, Abs were preincubated with cells for 30 min at a concentration of 10 μ g/ml before agonist addition.

PCR analysis

Total RNA was isolated from U373 cells using TRIzol reagent (Life Technologies, Rockville, MD) according to protocols supplied by the manufacturer. The synthesis of cDNA was performed, in the presence and absence of reverse transcriptase, using the Superscript Preamplification system (Life Technologies) and oligo(dT) as recommended by the manufacturer. PCR amplification of 500 ng cDNA was performed using *Taq* polymerase (Life Technologies) and TLR2- or TLR4-specific primers. The sequence of the primers for TLR2 were 5'-GGCCAGCAAATTACCTGTGT-3' and 5'-TTCTCCACCCAGTAGGCATC-3'. The sequences of the primers for TLR4 were 5'-TGAGCAGTCGTGCTGGTATC-3' and 5'-CAGGGCTTTCT GAGTCGTC-3'. PCR products were analyzed on gels composed of 2% NuSieve (FMC, Chicago, IL) and 1% agarose and the DNA was visualized with ethidium bromide.

Northern blot analysis

Total RNA was isolated from either THP-1 cells or HUVECs using TRIzol reagent (Life Technologies) according to protocols supplied by the manufacturer. RNA samples, 10 μ g per lane, were separated on 1% agarose-formaldehyde gels and transferred to nitrocellulose (BA85, Schleicher & Schuell, Keene, NH) in 20 \times SSC overnight (1 \times SSC is 0.15 M NaCl and 0.015 M sodium citrate). The membranes were prehybridized for 6 h at 60°C in hybridization buffer (50 mM PIPES/50 mM sodium phosphate (pH 7), 100 mM NaCl, 0.1 mM EDTA, 5% SDS containing 200 μ g/ml yeast RNA and 50 μ g/ml salmon sperm DNA) then hybridized overnight in the same buffer containing ³²P-labeled DNA probes for either TLR2, TLR4, or GAPDH. The filter was washed with 1 \times SSC followed by autoradiography. The probe for TLR2 was generated by random priming of the 1002-bp *NdeI* to *EcoRI* fragment of the TLR2 gene. The probe for TLR4 was generated by random priming of the 621-bp *PstI* to *EcoRI* fragment of the TLR4 gene. The probe for GAPDH was generated by hybridizing the two partially complementary oligonucleotides for GAPDH, 5'-ATGTTCCAGTA TGATTCCACCCACGGCAAGTTCACGGCAGCGTCAAGGCTGAG AACGGG-3' and 5'-ATCTCGCTCTGGAAGATGGTIGATGGCCTTCCC GTTGATGACCAGCTTCCGTTCTCAGC-3', followed by labeling using the Klenow fragment of DNA polymerase I.

Flow cytometry analysis

THP1-CD14 cells were washed twice in ice cold FACS buffer (10 mM HEPES (pH 7.4), 150 mM NaCl, 1% BSA). Approximately 10⁵ cells were incubated for 1 h on ice in FACS buffer containing 5% normal rabbit serum and 5 μ g/ml primary Ab. The cells were washed and labeled in FACS buffer containing 5% normal rabbit serum and FITC sheep anti-mouse IgG (PharMingen, La Jolla, CA). After a final wash, the cells were resuspended in FACS buffer and analyzed by flow cytometry using a FACScan flow cytometer (Becton Dickinson).

Whole blood activation assay

Whole blood from healthy donors was collected into tubes containing heparin the day of the assay. The blood was diluted 1:4 in RPMI 1640 medium

and aliquoted into 96-well plates. Upon the addition of agonist, the plate was placed in an incubator at 37°C and 5% carbon dioxide for 4 h. Where indicated, Abs were preincubated in blood for 30 min at a concentration of 10 µg/ml before agonist addition.

ELISAs

After incubation, cell supernatants were removed and assayed for cytokine production by standard sandwich ELISA using 96-well Immunlon plates (Dynatech Laboratories, Chantilly, VA). The TNF-α ELISA was performed using mAbs 68B6A3 or 68B2B3 for capture and the biotinylated mAb 68B3C5 (BioSource International, Camarillo, CA) followed by streptavidin HRP for detection. The IL-8 ELISA was performed using the mAb MAB208 for capture and a biotinylated polyclonal rabbit anti-human IL-8 Ab (R&D Systems, Minneapolis, MN) followed by streptavidin HRP for detection. The IL-6 ELISA was performed using polyclonal goat anti-human IL-6 (R&D systems, Minneapolis, MN) for capture and polyclonal rabbit anti-human IL-6 (Endogen, Woburn, MA) followed by HRP-conjugated goat anti-rabbit IgG for detection (BioSource International). All ELISAs were developed using *o*-phenylenediamine as a substrate, and OD was determined at a wavelength of 490 nm using a Spectramax plate reader and software (Molecular Devices, Sunnyvale, CA). All values were interpolated from either a log-log or a four-parameter fit of a curve generated from appropriate standards.

Results

Previous studies have shown that THP-1 cells, a human monocytic cell line, are responsive to low concentrations of LPS. The LPS responsiveness of these and other cells is dependent upon the presence of the cell surface LPS receptor CD14 (34–36). THP-1 cells can be induced to express CD14 either by differentiation or by stable transfection, as shown by generation of the THP1-CD14 cell line (33). To ascertain the role of TLR4 in mediating LPS-induced cellular activation and cytokine production, we generated THP1-CD14 cells that overexpress TLR4 by retroviral gene transfer (see *Materials and Methods*). In addition, empty vector control THP1-CD14 cells were similarly generated. These two cell lines were subsequently compared for their responsiveness to a variety of agonists as measured by production of TNF-α and IL-8. Overexpression of TLR4 had no effect on the magnitude or sensitivity of THP1-CD14 cells in response to PMA, HKSA, or PGN (Fig. 1). In contrast, THP1-CD14 cells that overexpress TLR4 exhibited increased sensitivity and responsiveness to both Re595 LPS and 0111B4 LPS. These effects on cellular activation were reflected in measurements of both TNF-α and IL-8 release. Taken together, these results show that TLR4 enhances the ability of THP1-CD14 monocytic cells to respond to LPS. It is noteworthy that the magnitude of the cytokine response of THP1-CD14 cells to 0111B4 LPS was at least 20-fold higher than the response to Re595 LPS.

Previous studies have implicated both TLR2 and TLR4 as receptors mediating LPS-induced cellular activation. Therefore, we used mAbs against these receptors to determine the contribution of TLR2 and TLR4 to LPS-induced cytokine release. The anti-TLR2 mAbs used were mAb 2380 and mAb 2392 and the anti-TLR4 mAbs used were HTA405, HTA414, and HTA1216. In addition, we tested the effects of two anti-CD14 mAbs, 63D3 and 28C5, on cellular activation. As shown in Fig. 2, none of the aforementioned Abs had any effect on PMA-mediated activation of THP1-CD14 cells as measured by TNF-α or IL-8 production. In addition, none of the anti-TLR4 Abs had any measurable effect on HKSA- or PGN-mediated cytokine release. However, cellular activation induced by either HKSA or PGN was almost completely blocked by mAb 2392, an antagonistic anti-TLR2 Ab.

Interestingly, the anti-TLR2 Abs had no effect, while two of the anti-TLR4 Abs inhibited over half of the Re595 LPS-induced cytokine release from THP1-CD14 cells. In sharp contrast, the anti-TLR2 Ab mAb 2392 inhibited almost 80% of cytokine release induced by 0111B4 LPS while the anti-TLR4 Abs were only marginally inhibitory. As observed in Fig. 1, cytokine release of

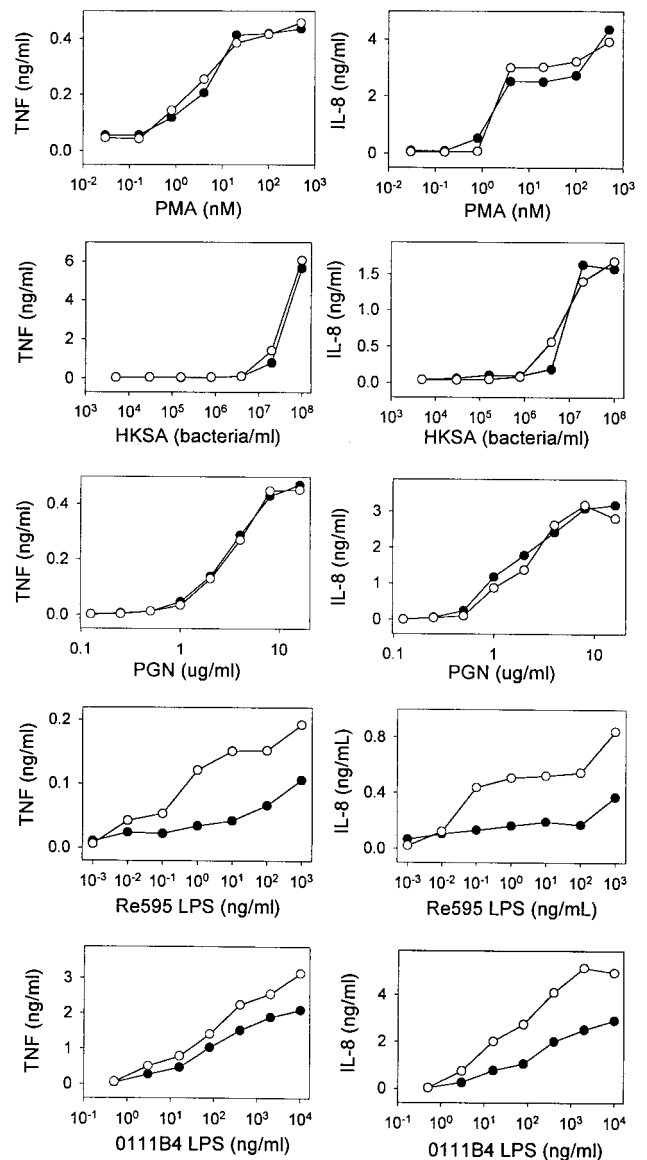


FIGURE 1. Overexpression of TLR4 in THP1-CD14 cells results in enhanced responsiveness to LPS but not other agonists. Empty vector and TLR4 expressing THP1-CD14 cell lines were generated by retroviral infection as described in *Materials and Methods*. Cells were stimulated with various agonists in the presence of 2% normal human serum for 6 h and cell supernatant was assayed for TNF-α and IL-8. ●, The vector control cell line. ○, The TLR4 cell line. Each point represents the average of duplicate values. The experiment was performed twice with similar results.

THP1-CD14 cells in response to Re595 LPS was at least 20-fold weaker than to 0111B4 LPS. Polymyxin B, a cationic peptide that inhibits LPS-induced cellular activation, blocked at least 80% of both Re595- and 0111B4-mediated cytokine release. In addition, 28C5, an Ab that blocks binding of LPS to CD14, greatly inhibited cellular responses to both Re595 LPS and 0111B4 LPS. Taken together, these results indicate that TLR2 and TLR4 are the predominant receptors of THP1-CD14 cells that mediate activation in response to 0111B4 LPS and Re595 LPS, respectively. Thus, the relative contribution of TLR2 and TLR4 to LPS-induced monocyte activation is dependent upon the type or source of LPS used.

To ascertain the generality of the above results we also tested the effects of the anti-TLR2 and anti-TLR4 Abs on the LPS-induced activation of U373 cells. U373 cells are a cell line derived

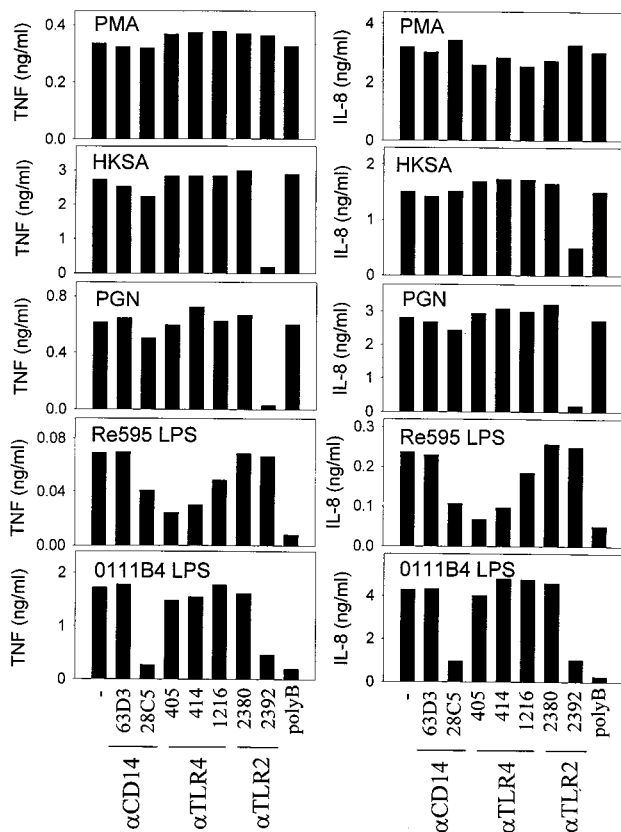


FIGURE 2. The contribution of TLR2 and TLR4 to LPS-mediated cytokine release of THP1-CD14 cells is dependent upon the specific agonist used. THP1-CD14 cells were preincubated with the various Abs for 30 min before the addition of either 10 nM PMA, 10^8 HKSA/ml, 10 μ g/ml PGN, 10 ng/ml Re595 LPS, or 100 ng/ml 0111B4 LPS. Cells were stimulated in the presence of 2% normal human serum for 6 h and cell supernatant was assayed for TNF- α and IL-8 as described in *Materials and Methods*. The bars represent the average of duplicate values. The experiment was performed twice with similar results.

from a human astrocytoma and release IL-6 in response to LPS in a CD14-dependent fashion (37). In contrast to THP1-CD14 cells, Re595 LPS and 0111B4 LPS induced roughly comparable levels of cytokine release in U373 cells (Fig. 3B). We also observed that the anti-TLR4 Ab HTA405 inhibited \sim 50 and 20% of IL-6 release from U373 cells induced with Re595 LPS and 0111B4 LPS, respectively (Fig. 3C). As expected, activation mediated by either Re595 or 0111B4 LPS was almost completely abrogated both by the anti-CD14 Ab 28C5 and by polymyxin B. Surprisingly, the anti-TLR2 Abs had no effect on cellular activation mediated by 0111B4 LPS indicating that, in contrast to THP1-CD14 cells, TLR2 makes no contribution to this event in U373 cells. This observation prompted us to examine the expression of TLR2 and TLR4 in U373 cells. RT-PCR analysis clearly detected the presence of TLR4 message but did not detect any TLR2 message in U373 cells (Fig. 3A). This finding has been previously noted (38), and demonstrates that U373 cells do not express TLR2. In support of this, we have found that neither HKSA or PGN activate IL-6 release of U373 cells (data not shown). Taken together, these results demonstrate that cellular responses to LPS occur in the absence of TLR2 and that the contribution of TLR2 and TLR4 to LPS-induced cellular activation is also a function of cell type.

The ability of the anti-TLR2 Ab mAb 2392 to inhibit almost 80% of 0111B4 LPS-induced cytokine release from THP1-CD14

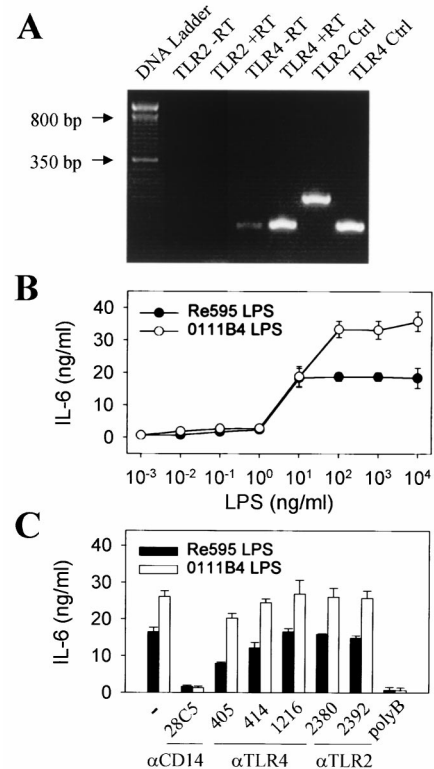


FIGURE 3. TLR4, but not TLR2, contributes to LPS-induced cytokine release of U373 cells. *A*, PCR analysis of U373 cellular RNA using primers to either TLR2 or TLR4 as indicated and as described in *Materials and Methods*. The presence or absence of reverse transcriptase (RT) is indicated. The two lanes on the right are controls using plasmid DNA encoding the genes for TLR2 or TLR4. *B*, U373 cells were stimulated with LPS for 6 h and cell supernatant was assayed for IL-6 as described in *Materials and Methods*. *C*, Cells were stimulated with either 10 ng/ml Re595 LPS or 100 ng/ml 0111B4 LPS for 6 h in the presence of various Abs as indicated. All error bars represent the SD of cellular activation experiments performed in triplicate. The experiment was performed twice with similar results.

cells demonstrates that a large portion of this activation is mediated by the TLR2 receptor (Fig. 2). RT-PCR analysis has shown that THP-1 cells possess message for both TLR2 and TLR4 (39). A quantitative northern blot analysis revealed that, in sharp contrast to HUVECs, THP-1 cells possess high levels of TLR2 message but barely detectable levels of TLR4 message (Fig. 4A). In support of this, FACS analysis indicates that cell surface expression of TLR2 is much higher than that of TLR4 in THP1-CD14 cells (Fig. 4B). Taken together with the data obtained using U373 cells, these results suggest that the cell-type-specific contribution of TLR2 and TLR4 to 0111B4 LPS-induced cellular activation may simply reflect different TLR expression levels. In support of this we have shown that overexpression of TLR4 in THP1-CD14 cells renders them more responsive to LPS (Fig. 1) and this enhanced response is inhibited by anti-TLR4 Abs (data not shown). Despite the significant expression level of TLR2 and the strong contribution of TLR2 to cytokine release induced by HKSA, PGN, or 0111B4 LPS, there is no measurable contribution of this receptor to cytokine release induced by Re595 LPS.

0111B4 is an *E. coli*-derived smooth-type LPS, possessing lipid A, inner core, outer core, and a large repeating oligosaccharide unit known as the O-Ag. In contrast, Re595 LPS is a deep rough type LPS, derived from an *S. minnesota* mutant, and missing part of the inner core as well as all of the outer core and O-Ag (40). We wanted to determine whether a structural difference between

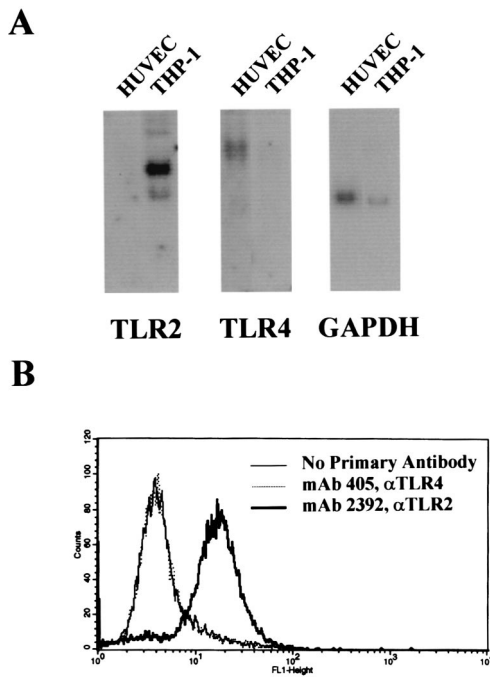


FIGURE 4. THP1-CD14 cells express greater levels of TLR2 than TLR4. **A**, Northern analysis of total RNA prepared from HUVECs or THP1-CD14 cells and probed for either TLR2, TLR4, or GAPDH as indicated and described in *Materials and Methods*. **B**, THP1-CD14 cells were stained with a primary mouse mAb as indicated followed by staining with FITC-labeled sheep anti-mouse secondary Ab. FACS analysis was performed as described in *Materials and Methods*. Expression of TLR4 was difficult to measure using any of the anti-TLR4 mAbs.

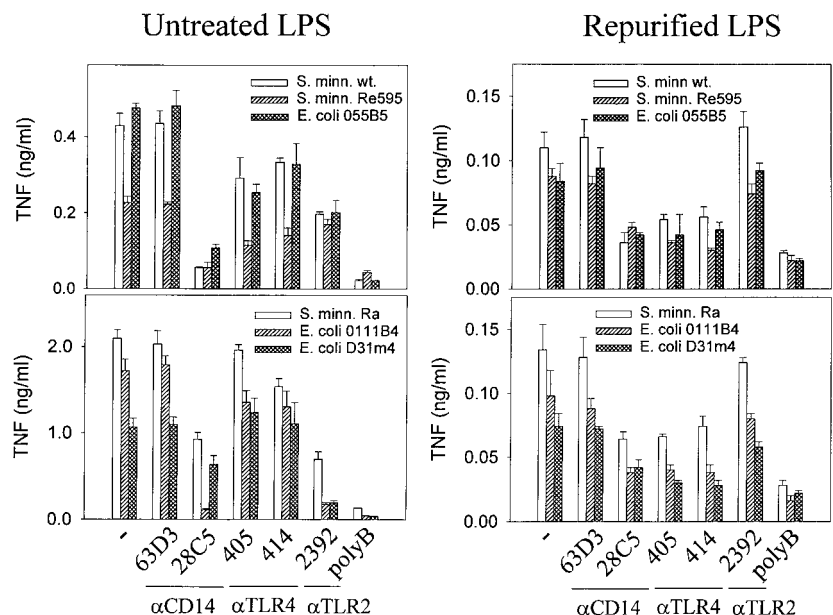
0111B4 and Re595 allowed the former LPS, but not the latter LPS, to act as an activator of TLR2 signaling. To this end, we tested the effect of the anti-TLR Abs on a number of smooth (wild type, 0111B4), rough (Ra) or deep rough (Re595, D31m4) LPS types derived from either *S. minnesota* or *E. coli*. Using THP1-CD14 cells, we found that LPS types including wild type, Re595, and 055B5 weakly induced TNF release, while other LPS types including Ra, 0111B4, and D31m4 more strongly induced TNF re-

lease (Fig. 5). In general, we found that weakly activating LPSs were significantly inhibited by anti-TLR4 Abs and that strongly activating LPSs were greatly inhibited by the anti-TLR2 Ab (Fig. 5). Moreover, we found that the level of stimulation, or the effect of anti-TLR Abs on LPS activities, could not be predicted based on the known structure of the LPSs or the bacterial species from which they were derived.

Previous studies have shown that LPS preparations, repurified by a method that removes contaminating proteins, completely lack the ability to activate TLR4-defective C3H/HeJ macrophages (26–28, 41, 42). These findings, coupled with our inability to assign the aforementioned effects of the anti-TLR Abs to known LPS properties, prompted us to repurify our commercial LPSs using a published modified phenol-water repurification procedure (26–28). The recovery of the repurified LPSs was typically 65 to 85% as determined by a KDO or colitose assay and confirmed by a *Limulus* ameobocyte lysate assay (see *Materials and Methods*). Upon repurification, every LPS type now displayed a low and comparable level of activity for the stimulation of THP1-CD14 cells (Fig. 5). Moreover, while the anti-TLR4 Abs inhibited at least 50% of the TNF release induced by every repurified LPS, the anti-TLR2 Ab had no effect on the activity of any repurified LPS. Similar results were obtained using repurified LCD25 and K235 LPS from *E. coli* as well as repurified Rb, Rc, and Rd LPS from *S. minnesota* (data not shown). Taken together, these results demonstrate that upon repurification commercial LPS preparations lose the ability to mediate cellular activation through TLR2 suggesting that impurities in these LPS preparations are responsible for the TLR2-mediated signaling. In contrast, repurified LPS appears to retain the ability to activate cells through TLR4 indicating that this receptor is a signaling receptor for *E. coli* and *S. minnesota* LPS.

To ascertain the contribution of TLR2 and TLR4 to LPS-induced immune responses under more physiologic conditions, we tested the effect of the anti-TLR2 and anti-TLR4 Abs on LPS-mediated cytokine release in human whole blood. Fig. 6 shows that all the anti-TLR4 Abs significantly inhibited TNF- α and IL-8 release from whole blood treated with either commercial Re595 or 0111B4 LPS. In contrast, the anti-TLR2 Abs had no effect on cytokine production in whole blood treated with Re595 LPS and only marginally, but reproducibly, inhibited cytokine production

FIGURE 5. Repurification of LPS eliminates cellular activation mediated by TLR2, but not TLR4. THP1-CD14 cells were preincubated with the various Abs for 30 min before the addition of 100 ng/ml of various untreated or repurified commercial LPS preparations as indicated. Cells were stimulated in the presence of 2% normal human serum for 6 h and cell supernatant was assayed for TNF- α as described in *Materials and Methods*. Error bars represent the SD of cellular activation experiments performed in triplicate. The experiment was performed twice with similar results.



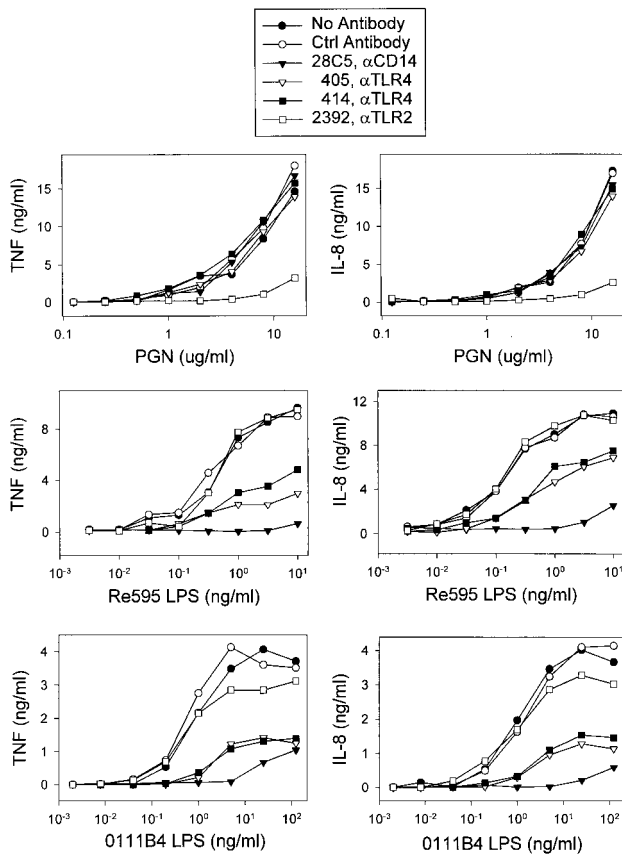


FIGURE 6. TLR4 is the predominant TLR receptor mediating LPS-induced cytokine release in whole blood. Whole blood was preincubated with different mAbs for 30 min and stimulated for 4 h with various concentrations of PGN, Re595 LPS or 0111B4 LPS as indicated. TNF- α and IL-8 release was measured as described in *Materials and Methods*. The data shown are from one blood donor but are representative of results independently obtained from three different donors.

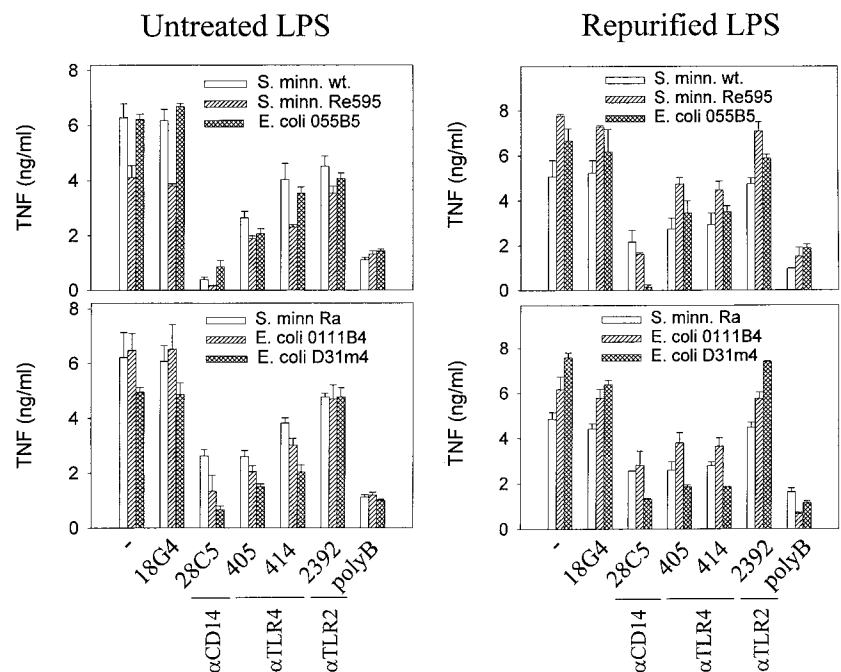
induced by commercial 0111B4 LPS. This low level of inhibition was only observed at higher LPS concentrations in agreement with the idea that the TLR2-mediated response is due to impurities in the commercial 0111B4 LPS. The anti-TLR2 Ab mAb 2392 specifically blocked cytokine release induced by PGN, demonstrating that this Ab is blocking the TLR2 receptor under the conditions of this whole blood assay. As expected, the anti-CD14 mAb 28C5 dramatically inhibited LPS-induced cytokine production in whole blood.

To extend these observations we assayed the previously tested series of smooth and rough LPS types from *E. coli* and *S. minnesota* in human whole blood. Levels of TNF release mediated by all of the LPS preparations in whole blood was comparable and inhibited by anti-TLR4 Abs regardless of whether the LPS was repurified or not (Fig. 7). The anti-TLR2 Ab only weakly inhibited whole blood TNF release mediated by commercial LPS preparations and this weak inhibition was not detected using repurified LPSs. Taken together, these results confirm that impurities in commercial LPS preparations activate cells through TLR2. In addition, these results demonstrate that in human whole blood, TLR4 is a predominant receptor mediating LPS-induced cellular activation.

Discussion

Our studies began by attempting to assess the relative contribution of TLR2 and TLR4 to LPS-induced cellular activation. We observed that while commercial preparations of both *E. coli* 0111B4 LPS and *S. minnesota* Re595 LPS activate cells through TLR4, only the former LPS stimulates cells through TLR2. The difference in activity between these two LPSs is most apparent in THP1-CD14 cells, a cell type that expresses significantly more TLR2 than TLR4; less apparent in whole blood, where isolated polymorphonuclear leukocytes and monocytes have been shown to express comparable levels of TLR2 and TLR4 (43); and nonexistent in U373 cells, a cell line that does not express any TLR2. The simplest interpretation of our results is that the relative contribution of TLR2 and TLR4 to LPS-induced signaling is a reflection of the relative cellular expression levels of these two TLRs. In support of this, we have found that overexpression of TLR4 in THP1-CD14 cells reduces the difference in signaling observed between commercial preparations of 0111B4 and Re595 LPS (Fig. 1).

FIGURE 7. Repurification of LPS eliminates cellular activation mediated by TLR2, but not TLR4, in whole blood. Whole blood was preincubated with different mAbs for 30 min and stimulated for 4 h with 25 ng/ml of various untreated or repurified commercial LPS preparations as indicated. TNF- α release was measured as described in *Materials and Methods*. Error bars represent the SD of cellular activation experiments performed in triplicate. The experiment was performed twice with similar results.



To determine a structural basis for the difference in activity observed between 0111B4 and Re595 LPS we extended our experiments to a range of rough and smooth LPS types from both *E. coli* and *S. minnesota*. However, the differences in cellular activity we observed that were mediated by TLR2 could not be ascribed to the known different structural features between these LPSs. In this regard, LPS has proven difficult to completely purify and there exists a long history of contaminating molecules in LPS with cell stimulatory activity (reviewed in Refs. 26, 27). Therefore, we repurified the commercial LPS preparations using a modified phenol-water extraction method followed by ethanol precipitation, a procedure that has been shown to remove trace proteins (26, 27). Repurification of the commercial LPS preparations eliminated TLR2-mediated cell signaling but retained TLR4-mediated cell signaling, demonstrating that TLR4, but not TLR2, is a signaling receptor for pure *E. coli*- and *S. minnesota*-derived LPS.

The idea that TLR4, and not TLR2, mediates LPS-induced cellular activation has been strongly argued in a recent review (44). Central to this argument is that a mutation in the gene encoding TLR4 underlies the genetic defect of C3H/HeJ mice, an inbred strain that is hyporesponsive to LPS (17, 18). Accordingly, targeted disruption of the TLR4 gene in mice results in an LPS-hyporesponsive phenotype (21). In this regard, it is noteworthy that C3H/HeJ macrophages exposed to IFN- γ , a treatment that is thought to render them sensitive to LPS, are not responsive to LPS preparations repurified by the modified phenol-water extraction method used in this study (26, 41, 42). Thus, that IFN- γ reverses the sensitivity of C3H/HeJ macrophages to LPS (45) is likely attributable to contaminants within the LPS preparations.

Lipid A has long been established as the bioactive component of LPS (reviewed in Ref. 46). As this is the common structural feature shared by all of the LPSs we tested, it is reasonable that upon repurification all of our LPSs exhibit similar levels of biological activity, mediated through TLR4, in our assays. The idea that TLR4 is responsive to the lipid A portion of LPS gains support from the finding that this receptor appears to mediate the species specific responses induced by synthetic lipid IVa, a precursor and closely related structure to lipid A (47, 48). Additionally, several lines of evidence have shown that TLR2 is not required for mediating LPS-induced signaling. One group has found that hamster cells genomically encode a nonfunctional gene for TLR2 even though these cells are fully LPS responsive (49). In agreement with this, U373 cells also retain LPS responsiveness despite a lack of expression of TLR2 (Fig. 3). Most compelling is the observation that recently generated TLR2 knockout mice have no significant defects in LPS responsiveness (24). Together, these findings demonstrate that TLR2 is not required for LPS signaling and suggest that this receptor plays no significant physiologic role in LPS signaling. Interestingly, LPSs derived from oral black-pigmented bacteria, *Porphyromonas gingivalis* and *Prevotella intermedia*, whose lipid A structures are different from the commonly studied LPSs of *Enterobacteriaceae*, stimulate C3H/HeJ macrophages even after repurification by the method described in this study (50). Thus, the idea that TLR4 is a signaling receptor for lipid A may be restricted to LPSs derived from the family of *Enterobacteriaceae*.

The idea that impurities in LPS are responsible for TLR2-mediated signaling is supported by several observations in the literature. TLR2 was initially identified as an LPS receptor by stimulating cells that over express TLR2 with commercial LPS preparations (13, 14), an approach confirmed by a number of studies (16, 25, 38, 51–53). Accordingly, we have found that THP1-CD14 cells that express significantly greater levels of TLR2 compared with TLR4 are most sensitive to impure commercial LPS preparations. The contention that the observed activation is due to

impurities in the LPS is supported by studies showing that the sensitivity of TLR2 transfected cells to other TLR2 agonists is severalfold greater than it is to LPS (25, 38). In addition, in contrast to the robust effect of TLR4, overexpression of TLR2 has been shown to only modestly enhance LPS responsiveness of Chinese hamster ovary cells (52). Moreover, during our studies we became aware of results demonstrating that repurification of LPS by the modified phenol-water extraction method used in this study eliminates activation of cells transfected with TLR2, but maintains activation of cells transfected with TLR4 (28). Our data are a direct extension of these studies and have confirmed the original observation that was made with *E. coli* smooth and rough LPS preparations. Moreover, we have now demonstrated this to be true of *S. minnesota* LPS and have found TLR4 to be the predominant signaling molecule in human peripheral blood cells stimulated with repurified LPS preparations.

At present, we do not know the nature of the contaminant(s) in commercial LPS preparations responsible for TLR2-dependent signaling. Recent studies have implicated TLR2 as a mediator of cellular responses to a wide variety of infectious pathogens and their products including yeast cell walls (19), spirochetal lipoproteins (16, 38, 54), whole mycobacteria (55), mycobacterial lipoarabinomannan (52, 56), whole Gram-positive bacteria (19, 57), as well as Gram-positive bacterial lipoteichoic acid (51) and PGN (24, 51, 54, 57). The fact that our TLR2-dependent signaling is markedly inhibited by an anti-CD14 Ab demonstrates that this signaling is also mediated through CD14. In this regard, CD14, like TLR2, has been implicated as a receptor for a variety of fungal and bacterial products (58–61). The TLR2-dependent activation induced by commercial LPS preparations is inhibited by polymyxin B, a cationic peptide that has historically been used to block LPS-induced cellular stimulation. At present we do not know whether polymyxin B is inhibiting TLR2-dependent cellular activation by interacting with the impurity itself or by interacting with the LPS with which it is associated. Regardless, these results demonstrate a necessity to carefully assess the purity and potency of pathogen-derived components when assigning their actions to the function of individual TLRs.

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References

- Lemaitre, B., E. Nicolas, L. Michaut, J.-M. Reichhart, and J. A. Hoffmann. 1996. The dorsoventral regulatory gene cassette *spatzle/Toll/cactus* controls the potent antifungal response in *Drosophila* adults. *Cell* 86:973.
- Williams, M. J., A. Rodriguez, D. A. Kimbrell, and E. D. Eldon. 1999. The 18-wheeler mutation reveals complex antibacterial gene regulation in *Drosophila* host defense. *EMBO J.* 16:6120.
- Medzhitov, R., P. Preston-Hurlburt, and C. A. Janeway. 1998. A human homologue of the *Drosophila* Toll protein signals activation of adaptive immunity. *Nature* 388:394.
- Rock, F. L., G. Hardiman, J. C. Timans, R. A. Kastelein, and J. F. Bazan. 1998. A family of receptors structurally related to *Drosophila* Toll. *Proc. Natl. Acad. Sci. USA* 95:588.
- Chaudhary, P. M., C. Ferguson, V. Nguyen, O. Nguyen, H. F. Massa, M. Eby, A. Jasmin, B. J. Trask, L. Hood, and P. S. Nelson. 1999. Cloning and characterization of two Toll/interleukin-1 receptor-like genes TIL3 and TIL4: evidence for a multigenic receptor family in humans. *Blood* 91:4020.
- Takeuchi, O., T. Kawai, H. Sanjo, N. G. Copeland, D. J. Gilbert, N. A. Jenkins, K. Takeda, and S. Akira. 1999. TLR6: a novel member of an expanding toll-like receptor family. *Gene* 231:59.
- Medzhitov, R., P. Preston-Hurlburt, E. Kopp, A. Stadlen, C. Chen, S. Ghosh, and C. A. Janeway. 1999. MyD88 is an adapter protein in the hToll/IL-1 receptor family signaling pathways. *Mol. Cell* 2:253.

8. Burns, K., F. Martinon, C. Esslinger, H. Pahl, P. Schneider, J.-L. Bodmer, F. Di Marco, L. French, and J. Tschopp. 1999. MyD88, an adapter protein involved in Interleukin-1 signaling. *J. Biol. Chem.* 273:12203.
9. Muzio, M., G. Natoli, S. Sacconi, M. Levrero, and A. Mantovani. 1999. The human Toll signaling pathway: divergence of nuclear factor κ B and JNK/SAPK activation upstream of tumor necrosis factor receptor-associated factor 6 (TRAF6). *J. Exp. Med.* 187:2097.
10. Ulevitch, R. J., and P. S. Tobias. 1995. Receptor-dependent mechanisms of cell stimulation by bacterial endotoxin. *Annu. Rev. Immunol.* 13:437.
11. Fenton, M. J., and D. T. Golenbock. 1998. LPS-binding proteins and receptors. *J. Leukocyte Biol.* 64:25.
12. Wright, S. D., R. A. Ramos, P. S. Tobias, R. J. Ulevitch, and J. C. Mathison. 1990. CD14, a receptor for complexes of lipopolysaccharide (LPS) and LPS binding proteins. *Science* 249:1431.
13. Yang, R.-B., M. R. Mark, A. Gray, A. Huang, M.-H. Xie, M. Zhang, A. Goddard, W. I. Wood, A. L. Gurney, and P. J. Godowski. 1998. Toll-like receptor-2 mediates lipopolysaccharide-induced cellular signalling. *Nature* 395:284.
14. Kirschning, C. J., H. Wesche, T. M. Ayres, and M. Rothe. 1999. Human Toll-like receptor 2 confers responsiveness to bacterial lipopolysaccharide. *J. Exp. Med.* 188:2091.
15. Yang, R.-B., M. R. Mark, A. L. Gurney, and P. J. Godowski. 1999. Signaling events induced by lipopolysaccharide-activated Toll-like receptor 2. *J. Immunol.* 163:639.
16. Brightbill, H. D., D. H. Libraty, S. R. Krutzik, R.-B. Yang, J. T. Belisle, J. R. Bleharski, M. Maitland, M. V. Norgard, S. E. Plevy, S. T. Smale, et al. 1999. Host defense mechanisms triggered by microbial lipoproteins through Toll-like receptors. *Science* 285:732.
17. Poltorak, A., X. He, I. Smirnova, M. Y. Liu, C. V. Huffel, D. Birdwell, E. Alejos, M. Silva, C. Galanos, M. Freudenberg, et al. 1998. Defective LPS signaling in C3H/HeJ and C57BL/10ScCr mice: mutations in the *Tlr4* gene. *Science* 282:2085.
18. Qureshi, S. T., L. Lariviere, G. Leveque, S. Clermont, K. J. Moore, P. Gros, and D. Malo. 1999. Endotoxin-tolerant mice have mutations in Toll-like receptor 4 (*Tlr4*). *J. Exp. Med.* 189:615.
19. Underhill, D. M., A. Ozinsky, A. M. Hajjar, A. Stevens, C. B. Wilson, M. Bassetti, and A. Aderem. 1999. The Toll-like receptor 2 is recruited to macrophage phagosomes and discriminates between pathogens. *Nature* 401:811.
20. Du, X., A. Poltorak, M. Silva, and B. Beutler. 1999. Analysis of Tlr4-mediated LPS signal transduction in macrophages by mutational modification of the receptor. *Blood Cells Mol. Dis.* 25:328.
21. Hoshino, K., O. Takeuchi, T. Kawai, H. Sanjo, T. Ogawa, Y. Takeda, K. Takeda, and S. Arika. 1999. Toll-like receptor 4 (TLR4)-deficient mice are hyporesponsive to lipopolysaccharide: evidence for TLR4 as the *lps* gene product. *J. Immunol.* 162:3749.
22. Chow, J. C., D. W. Young, D. T. Golenbock, W. J. Christ, and F. Gusovsky. 1999. Toll-like receptor-4 mediates lipopolysaccharide-induced signal transduction. *J. Biol. Chem.* 274:10689.
23. Shimazu, R., S. Akashi, H. Ogata, Y. Nagai, K. Fukudome, K. Miyake, and M. Kimoto. 1999. MD-2, a molecule that confers lipopolysaccharide responsiveness on Toll-like receptor 4. *J. Exp. Med.* 189:1777.
24. Takeuchi, O., K. Hoshino, T. Kawai, H. Sanjo, H. Takada, T. Ogawa, K. Takeda, and S. Akira. 1999. Differential roles of TLR2 and TLR4 in recognition of Gram-negative and Gram-positive bacterial cell wall components. *Immunity* 11:443.
25. Aliprantis, A. O., R.-B. Yang, M. R. Mark, S. Suggett, B. Devaux, J. D. Radolf, G. R. Klimpel, P. Godowski, and A. Zychlinsky. 1999. Cell activation and apoptosis by bacterial lipoproteins through Toll-like receptor 2. *Science* 285:736.
26. Manthey, C. L., P.-Y. Perera, B. E. Henricson, T. A. Hamilton, N. Qureshi, and S. N. Vogel. 1994. Endotoxin-induced early gene expression in C3H/HeJ (Lps^d) macrophages. *J. Immunol.* 153:2653.
27. Manthey, C. L., and S. N. Vogel. 1994. Elimination of trace endotoxin protein from rough chemotype LPS. *J. Endotoxin Res.* 1:84.
28. Hirschfeld, M., Y. Ma, J. H. Weis, S. N. Vogel, and J. J. Weis. 2000. Repurification of LPS eliminates signaling through both human and murine Toll-like receptor 2. *J. Immunol.* 165:618.
29. Cynkin, M. A., and G. Ashwell. 1960. Estimation of 2-deoxy sugars by means of the malonaldehyde-thiobarbituric acid reaction. *Nature* 186:155.
30. Swift, S., J. Lorens, P. Achacoso, and G. Nolan. 1999. Rapid production of retroviruses for efficient gene delivery to mammalian cells using 293T cell-based systems. In *Current Protocols in Immunology*. J. E. Coligan, A. M. Kruisbeek, D. H. Margulies, E. M. Shevach, and W. Strober, eds. Wiley, New York, p. 10.28.
31. Shaw, M. K., J. B. Lorens, A. Dhawan, R. Dalcanto, H. Y. Tse, A. B. Tran, C. Bonpane, S. L. Eswaran, S. Brocke, N. Sarvetnick, et al. 1997. Local delivery of interleukin 4 by retrovirus-transduced T lymphocytes ameliorates experimental autoimmune encephalomyelitis. *J. Exp. Med.* 185:1711.
32. Schiff, D. E., L. Kline, G. Soldau, J. D. Lee, J. Pugin, P. S. Tobias, and R. J. Ulevitch. 1997. Phagocytosis of Gram-negative bacteria by a unique CD14-dependent mechanism. *J. Leukocyte Biol.* 62:786.
33. Pugin, J., V. V. Kravchenko, J. D. Lee, L. Kline, R. J. Ulevitch, and P. S. Tobias. 1998. Cell activation mediated by glycosylphosphatidylinositol-anchored or transmembrane anchored forms of CD14. *Infect. Immun.* 66:1174.
34. Zoeller, R. A., Y. Liu, F. H. Millham, M. W. Freeman, and D. T. Golenbock. 1993. Surface expression of human CD14 in Chinese hamster ovary fibroblasts imparts macrophage-like responsiveness to bacterial endotoxin. *J. Biol. Chem.* 268:22055.
35. Lee, J. D., K. Kato, P. S. Tobias, T. N. Kirkland, and R. J. Ulevitch. 1992. Transfection of CD14 into 70Z/3 cells dramatically enhances the sensitivity to complexes of lipopolysaccharide (LPS) and LPS binding protein. *J. Exp. Med.* 175:1697.
36. Martin, T. R., S. M. Mongovin, P. S. Tobias, J. C. Mathison, A. M. Moriarty, D. J. Leturcq, and R. J. Ulevitch. 1994. The CD14 differentiation antigen mediates the development of endotoxin responsiveness during differentiation of mononuclear phagocytes. *J. Leukocyte Biol.* 56:1.
37. Frey, E. A., D. S. Miller, T. G. Jahr, A. Sundan, V. Bazil, T. Espevik, B. B. Finlay, and S. D. Wright. 1992. Soluble CD14 participates in the response of cells to lipopolysaccharide. *J. Exp. Med.* 176:1665.
38. Hirschfeld, M., C. J. Kirschning, R. Schwandner, H. Wesche, J. H. Weis, R. M. Wooten, and J. J. Weis. 1999. Inflammatory signaling by *Borrelia burgdorferi* lipoproteins is mediated by Toll-like receptor 2. *J. Immunol.* 163:2382.
39. Zhang, F. X., C. J. Kirschning, R. Mancinelli, X.-P. Xu, Y. Jin, E. Faure, A. Mantovani, M. Rothe, M. Muzio, and M. Arditi. 1999. Bacterial lipopolysaccharide activates nuclear factor- κ B through interleukin-1 signaling mediators in cultured human dermal endothelial cells and human mononuclear phagocytes. *J. Biol. Chem.* 274:7611.
40. Raetz, C. R. H. 1990. Biochemistry of endotoxins. *Annu. Rev. Biochem.* 59:129.
41. Hogan, M. M., and S. N. Vogel. 1987. LipidA-associated proteins provide an alternative "second signal" in the activation of recombinant IFN- γ -primed, C3H/HeJ macrophages to a fully tumoricidal state. *J. Immunol.* 139:3697.
42. Hogan, M. M., and S. N. Vogel. 1988. Production of tumor necrosis factor by rIFN- γ -primed C3H/HeJ (Lps^d) macrophages requires the presence of lipid A-associated proteins. *J. Immunol.* 131:4196.
43. Muzio, M., D. Bosisio, N. Polentarutti, G. D'Amico, A. Stoppacciaro, R. Mancinelli, C. van't Veer, G. Penton-Rol, L. P. Ruco, P. Allavena, and A. Mantovani. 2000. Differential expression and regulation of Toll-like receptors (TLR) in human leukocytes: selective expression of TLR3 in dendritic cells. *J. Immunol.* 164:5998.
44. Beutler, B. 2000. Tlr4: central component of the sole mammalian LPS sensor. *Curr. Opin. Immunol.* 12:20.
45. Beutler, B., V. Tkachenko, I. Milsark, N. Krochin, and A. Cerami. 1986. Effect of γ interferon on cachectin expression by mononuclear phagocytes: reversal of the *lps*^d (endotoxin resistance) phenotype. *J. Exp. Med.* 164:1791.
46. Rietschel, E. T., T. Kirikae, F. U. Schade, U. Mamat, G. Schmidt, H. Loppnow, A. J. Ulmer, U. Zahring, U. Seydel, F. di Padova, et al. 1994. Bacterial endotoxin: molecular relationships of structure to activity and function. *FASEB J.* 8:217.
47. Poltorak, A., P. Ricciardi-Castagnoli, S. Citterio, and B. Beutler. 2000. Physical contact between lipopolysaccharide and Toll-like receptor 4 revealed by genetic complementation. *Proc. Natl. Acad. Sci. USA* 97:2163.
48. Lien, E., T. K. Means, H. Heine, A. Yoshimura, S. Kusumoto, K. Fukase, M. J. Fenton, M. Oikawa, N. Qureshi, B. Monks, et al. 1999. Toll-like receptor 4 imparts ligand-specific recognition of bacterial lipopolysaccharide. *J. Clin. Invest.* 105:497.
49. Heine, H., C. J. Kirschning, E. Lien, B. G. Monks, M. Rothe, and D. T. Golenbock. 1999. Cells that carry a null allele for Toll-like receptor 2 are capable of responding to endotoxin. *J. Immunol.* 162:6971.
50. Kirikae, T., T. Nitta, F. Kirikae, Y. Suda, S. Kusumoto, N. Qureshi, and M. Nakano. 1999. Lipopolysaccharides (LPS) of oral black-pigmented bacteria induce tumor necrosis factor production by LPS-refactory C3H/HeJ macrophages in way different from that of *Salmonella* LPS. *Infect. Immun.* 67:1736.
51. Schwandner, R., R. Dziarski, H. Wesche, M. Rothe, and C. J. Kirschning. 1999. Peptidoglycan- and lipoteichoic acid-induced cell activation is mediated by Toll-like receptor 2. *J. Biol. Chem.* 274:17406.
52. Means, T. K., E. Lien, A. Yoshimura, S. Wang, D. T. Golenbock, and M. J. Fenton. 1999. The CD14 ligands lipoarabinomannan and lipopolysaccharide differ in their requirement for Toll-like receptors. *J. Immunol.* 163:6748.
53. Flo, T. H., O. Halaas, E. Lien, L. Ryan, G. Teti, D. T. Golenbock, A. Sundan, and T. Espevik. 2000. Human Toll-like receptor 2 mediates monocyte activation by *Listeria monocytogenes*, but not by group B streptococci or lipopolysaccharide. *J. Immunol.* 164:2064.
54. Lien, E., T. J. Sallati, A. Yoshimura, T. H. Flo, G. Rawadi, R. W. Finberg, J. D. Carroll, T. Espevik, R. R. Ingalls, J. D. Radolf, and D. T. Golenbock. 1999. Toll-like receptor 2 functions as a pattern recognition receptor for diverse bacterial products. *J. Biol. Chem.* 274:33419.
55. Underhill, D. M., A. Ozinsky, K. D. Smith, and A. Aderem. 1999. Toll-like receptor-2 mediates mycobacteria-induced proinflammatory signaling in macrophages. *Proc. Natl. Acad. Sci. USA* 96:14459.
56. Means, T. K., S. Wang, E. Lien, A. Yoshimura, D. T. Golenbock, and M. J. Fenton. 1999. Human Toll-like receptors mediate cellular activation by *Mycobacterium tuberculosis*. *J. Immunol.* 163:3920.
57. Yoshimura, A., E. Lien, R. R. Ingalls, E. Tuomanen, R. Dziarski, and D. T. Golenbock. 1999. Recognition of Gram-positive bacterial cell wall components by the innate immune system occurs via Toll-like receptor 2. *J. Immunol.* 163:1.
58. Zhang, Y., M. Doerfler, T. C. Lee, B. Guillemin, and W. N. Rom. 1993. Mechanisms of stimulation of interleukin-1 β and tumor necrosis factor- α by *Mycobacterium tuberculosis* components. *J. Clin. Invest.* 91:2076.
59. Weidemann, B., H. Brade, E. T. Rietschel, R. Dziarski, V. Bazil, S. Kusumoto, H.-D. Flad, and A. J. Ulmer. 1994. Soluble peptidoglycan-induced monokine production can be blocked by anti-CD14 monoclonal antibodies and by lipid A partial structures. *Infect. Immun.* 62:4709.
60. Juan, T. S. C., E. Hailman, M. J. Kelley, S. D. Wright, and H. S. Lichenstein. 1995. Identification of a domain in soluble CD14 essential for lipopolysaccharide (LPS) signaling but not LPS binding. *J. Biol. Chem.* 270:17237.
61. Pugin, J., D. Heumann, A. Tomasz, V. Kravchenko, Y. Akamatsu, M. Nishijimi, M.-P. Glauser, P. S. Tobias, and R. J. Ulevitch. 1994. CD14 is a pattern recognition receptor. *Immunity* 1:509.