

A Novel Cyclohexene Derivative, Ethyl (6*R*)-6-[*N*-(2-Chloro-4-fluorophenyl)sulfamoyl]cyclohex-1-ene-1-carboxylate (TAK-242), Selectively Inhibits Toll-Like Receptor 4-Mediated Cytokine Production through Suppression of Intracellular Signaling

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ABSTRACT

Proinflammatory mediators such as cytokines and NO play pivotal roles in various inflammatory diseases. To combat inflammatory diseases successfully, regulation of proinflammatory mediator production would be a critical process. In the present study, we investigated the *in vitro* effects of ethyl (6*R*)-6-[*N*-(2-chloro-4-fluorophenyl)sulfamoyl]cyclohex-1-ene-1-carboxylate (TAK-242), a novel small molecule cytokine production inhibitor, and its mechanism of action. In RAW264.7 cells and mouse peritoneal macrophages, TAK-242 suppressed lipopolysaccharide (LPS)-induced production of NO, tumor necrosis factor- α (TNF- α), and interleukin (IL)-6, with 50% inhibitory concentration (IC₅₀) of 1.1 to 11 nM. TAK-242 also suppressed the production of these cytokines from LPS-stimulated human peripheral blood mononuclear cells (PBMCs) at IC₅₀ values from 11 to 33 nM. In addition, the inhibitory effects on the LPS-induced IL-6 and IL-12 production were

similar in human PBMCs, monocytes, and macrophages. TAK-242 inhibited mRNA expression of IL-6 and TNF- α induced by LPS and interferon- γ in RAW264.7 cells. The phosphorylation of mitogen-activated protein kinases induced by LPS was also inhibited in a concentration-dependent manner. However, TAK-242 did not antagonize the binding of LPS to the cells. It is noteworthy that TAK-242 suppressed the cytokine production induced by Toll-like receptor (TLR) 4 ligands, but not by ligands for TLR2, -3, and -9. In addition, IL-1 β -induced IL-8 production from human PBMCs was not markedly affected by TAK-242. These data suggest that TAK-242 suppresses the production of multiple cytokines by selectively inhibiting TLR4 intracellular signaling. Finally, TAK-242 is a novel small molecule TLR4 signaling inhibitor and could be a promising therapeutic agent for inflammatory diseases, whose pathogenesis involves TLR4.

Cytokines and NO are involved in a variety of inflammatory diseases, including sepsis, rheumatoid arthritis (RA),

atherosclerosis, inflammatory bowel disease (IBD), asthma, and chronic obstructive pulmonary disease. In RA, for example, interleukin (IL)-1 is considered to be a mediator. Plasma concentrations of IL-1 in patients with RA are elevated, and they correlate with disease activity (Eastgate et al., 1988). The expression of IL-1 in the bronchial epithelium of patients

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ABBREVIATIONS: RA, rheumatoid arthritis; IBD, inflammatory bowel disease; IL, interleukin; TNF- α , tumor necrosis factor- α ; iNOS, inducible nitric-oxide synthase; IFN γ , interferon- γ ; LPS, lipopolysaccharide; LBP, lipopolysaccharide-binding protein; TLR, Toll-like receptor; MAPK, mitogen-activated protein kinase; NF- κ B, nuclear factor- κ B; TAK-242, ethyl (6*R*)-6-[*N*-(2-chloro-4-fluorophenyl)sulfamoyl]cyclohex-1-ene-1-carboxylate; LTA, lipoteichoic acid; GM-CSF, granulocyte macrophage-colony stimulating factor; PGN, peptidoglycan; poly(I:C), polyinosinic-polycytidylic acid; CpG DNA, nonmethylated CpG oligodeoxynucleotide; FCS, fetal calf serum; PBMC, peripheral blood mononuclear cell; BSA, bovine serum albumin; PCR, polymerase chain reaction; TBS-T, Tris-buffered saline/Tween 20; Ab, antibody; JNK/SAPK, c-Jun NH₂-terminal kinase/stress-activated protein kinase; MAb, monoclonal antibody; CCR5, CC-chemokine receptor 5; Erk, extracellular signal-regulated kinase; LPS(S), lipopolysaccharide from *S. typhimurium*; TIR, Toll/IL-1 receptor; TICAM, Toll/IL-1 receptor domain-containing adaptor molecule-1; tyrphostin AG126, (3-hydroxy-4-nitrobenzylidene)malononitrile; (3-hydroxy-4-nitro)cinnamonnitrile.

with asthma is significantly elevated compared with healthy volunteers (Sausa et al., 1996). In some animal models of sepsis, hemodynamics and survival are improved when the actions of IL-1 are blocked by an IL-1 receptor antagonist (Fischer et al., 1992; Norman et al., 1995). Tumor necrosis factor- α (TNF- α) is also known to exhibit diverse physiologic effects and is one of the most prominent proinflammatory mediators. It can exert host-damaging effects in sepsis, fever syndromes, and cachexia as well as in autoimmune diseases such as RA, psoriasis, and IBD (Raza, 2000; Hehlhans and Pfeffer, 2005). For example, TNF- α induces the secretion of inflammatory cytokines and chemokines from stroma cells, endothelial cells, and mucosal mononuclear cells in IBD (MacDermott, 1996). NO derived from inducible NO synthase (iNOS) also seems to be a proinflammatory mediator with immunomodulatory effects (Guzik et al., 2003). The toxic properties of NO are the key in the pathogenesis of septic shock, and overproduction of NO during septicemia is considered to be responsible for irreversible arterial hypotension, vasoplegia, lactic acidosis, necrosis, and apoptosis (Parrott, 1997). Furthermore, the manifestations of allergic airway disease, including infiltration of eosinophils, microvascular leakage, and airway occlusion are markedly less severe in iNOS^{-/-} animals, and iNOS promotes allergic inflammation in airways via down-regulation of interferon- γ (IFN- γ) (Ricciardolo et al., 2004).

Lipopolysaccharide (LPS), a major constituent of Gram-negative bacterial outer membrane, can cause inflammatory responses such as the release of cytokines and NO from various types of cells, including monocytes and macrophages. To activate the cells, the lipid A moiety of LPS attaches to the LPS-binding protein (LBP), and the LPS/LBP complex binds to CD14 and is then transferred to the Toll-like receptor (TLR) 4-MD-2 complex (Wright et al., 1990; da Silva Correia et al., 2001). The resulting activation of the cells induces the activation of mitogen-activated protein kinases (MAPKs) and nuclear factor- κ B (NF- κ B) as well as release of inflammatory mediators (Guha and Mackman, 2001). TLR4 is also known to be a receptor for endogenous ligands such as fibrinogen, hyaluronic acid, and heat shock proteins (Rifkin et al., 2005). Thus, an agent that inhibits TLR4-mediated cytokine and NO production could be a promising drug for the treatment of inflammatory diseases. In fact, some synthetic lipid A analogs showed beneficial effects as TLR4 antagonists in septic shock models and IBD models in mice (Christ et al., 1995; Mullarkey et al., 2003; Fort et al., 2005).

We have discovered a novel cyclohexene derivative, TAK-242, which selectively inhibits the TLR4-mediated production of cytokines and NO. The chemical structure of TAK-242 is shown in Fig. 1. TAK-242 is the first small-molecule compound that selectively inhibits TLR4 signaling. In this study, we investigated the inhibitory effect of TAK-242 on the production of inflammatory mediators by macrophages and monocytes as well as its mode of action.

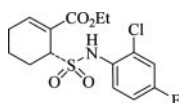


Fig. 1. Structure of TAK-242.

Materials and Methods

Materials. TAK-242 was synthesized at Takeda Pharmaceutical Company Limited (Osaka, Japan). AG126 was purchased from Calbiochem (San Diego, CA), LPS (from *Escherichia coli* serotype O111: B4) and lipoteichoic acid (LTA) (from *Staphylococcus aureus*) were from Sigma-Aldrich (St. Louis, MO), and LPS(S) (from *Salmonella typhimurium*) was from Difco (Detroit, MI). Recombinant mouse IFN- γ was purchased from Genzyme (Cambridge, MA), whereas recombinant human granulocyte macrophage-colony stimulating factor (GM-CSF) was purchased from PeproTech EC (London, UK). Peptidoglycan from *S. aureus* (PGN) was purchased from Fluka (Buchs, Switzerland); polyinosinic-polycytidylic acid [poly(I:C)] was from Amersham Biosciences Inc. (Piscataway, NJ); paclitaxel (Taxol) and recombinant human IL-1 β were from Wako Pure Chemicals (Osaka, Japan), nonmethylated CpG oligodeoxynucleotide (CpG DNA) was from Hokkaido System Science (Sapporo, Japan), and 2,3-diaminonaphthalene, which an agent for the detection of nitrite (Misko et al., 1993), was from Dojindo Laboratories (Kumamoto, Japan).

Cells. The murine macrophage cell line RAW264.7 was purchased from American Type Culture Collection (Manassas, VA). The cells were cultured in RPMI 1640 medium (Nikken Bio Medical Laboratories, Kyoto, Japan) containing 10% heat-inactivated fetal calf serum (FCS) and 10 μ g/ml kanamycin at 37°C under a humidified atmosphere with 5% CO₂. Resident mouse peritoneal macrophages were harvested from BALB/c mice (Charles River Japan, Kanagawa, Japan). The peritoneal cells were seeded at a density of 5×10^5 cells/well in 96-well culture plates (Nalge Nunc International, Naperville, IL) and cultured in RPMI 1640 medium containing 10% heat-inactivated FCS, 100 U/ml penicillin G, and 100 μ g/ml streptomycin for 2 h. After shaking the cultures, nonadhesive cells were aspirated. The adhesive cells were washed and used as peritoneal macrophages. Human peripheral blood mononuclear cells (PBMCs) were isolated from peripheral blood obtained from healthy human volunteers by density gradient centrifugation using Ficoll-Paque Plus (Amersham Pharmacia Biotech AB, Uppsala, Sweden) and suspended in RPMI 1640 medium containing 10% heat-inactivated FCS, 100 U/ml penicillin G, and 100 μ g/ml streptomycin. To obtain monocytes, PBMCs were washed and suspended in phosphate-buffered saline containing 0.5% bovine serum albumin (BSA) and 2 mM EDTA. The cells were then treated with microbeads coated with anti-CD14 monoclonal antibody (Miltenyi Biotec, Gladbach, Germany) and subjected to a magnetic cell separation system according to the manufacturer's protocol. To differentiate the monocytes into macrophages, monocytes obtained using the above-mentioned procedure were plated in 96-well culture plates (Corning Glassworks, Corning, NY) at a density of 1×10^4 cells/well and cultured for 7 days in RPMI 1640 medium supplemented with 10 ng/ml GM-CSF and 10% FCS at 37°C under a humidified atmosphere with 5% CO₂.

Treatments of the Cells. RAW264.7 cells were plated at a density of 1×10^5 cells/well in 96-well culture plates and incubated overnight. After removing cell culture supernatants, the cells were stimulated with various concentrations of TLR ligands in the presence or absence of IFN- γ for 20 h in a stimulation medium (phenol red-free RPMI 1640 medium containing 1% heat-inactivated FCS and 10 μ g/ml kanamycin). Resident mouse peritoneal macrophages were stimulated with 1 ng/ml LPS and 1 U/ml IFN- γ in RPMI 1640 medium containing 10% heat-inactivated FCS, 100 U/ml penicillin G, and 100 μ g/ml streptomycin for 4 h (for TNF- α and IL-6 assay) or 20 h (for IL-1 β and NO assay). For PBMC assay, PBMCs were seeded at a density of 8×10^4 cells/well in 96-well culture plates and stimulated with 1 ng/ml LPS and 1 U/ml IFN- γ for 20 h. To examine the efficacy on IL-8 production induced by LPS and IL-1 β , PBMCs were stimulated with 1 ng/ml LPS or 10 ng/ml IL-1 β for 20 h. For the comparison of the efficacy on PBMCs, monocytes and macrophages, the cells were stimulated with 10 ng/ml LPS in the presence of TAK-242 for 18 h. In another experiment, human macrophages were

stimulated with 10 ng/ml LPS or 20 μ g/ml PGN for 18 h. For all the experiments, TAK-242 was dissolved in *N,N*-dimethylformamide, diluted with appropriate medium, and added to the cells just before the stimulation.

Measurement of the Concentrations of Nitrite and Cytokines in the Culture Supernatants. Using 2,3-diaminonaphthalene, the production of NO was estimated by measuring the amount of nitrite, a stable metabolite of NO, by a fluorometric method (Misko et al., 1993). The concentration of TNF- α , IL-6, IL-1 β , IL-8, and IL-12 in the culture supernatants were determined by specific enzyme-linked immunosorbent assay [Amersham Pharmacia Biotech UK (Little Chalfont, Buckinghamshire, UK), R&D Systems (Minneapolis, MN), or Genzyme Techno (Minneapolis, MN)]. Fifty percent inhibitory concentration (IC₅₀) values of TAK-242 were calculated by least-squares linear regression analysis over the descending linear portion of the log dose-response curve.

Real-Time Quantitative Polymerase Chain Reaction Analysis of TNF- α and IL-6 Expression. RAW264.7 cells were seeded at a density of 3×10^6 cells/well in six-well culture plate (BD Biosciences, Bedford, MA) and incubated overnight. After washing with RPMI 1640 medium supplemented with 1% FCS and 10 μ g/ml kanamycin, the cells were stimulated with 5 ng/ml LPS and 1 U/ml IFN- γ in the presence or absence of TAK-242 (1–100 nM) for the indicated time. Culture supernatants were removed, and total RNA was isolated using the total RNA isolation reagent ISOGEN (Nippon Gene, Tokyo, Japan). Total RNA was reverse transcribed into cDNA by using TaqMan reverse transcription reagents (Applied Biosystems, Foster City, CA). Quantitative real-time PCR analysis of TNF- α and IL-6 was performed on ABI Prism 7700 (Applied Biosystems) using predeveloped TaqMan assay reagents and Universal PCR master mix (Applied Biosystems) according to the manufacturer's instructions. Quantitation of mRNA was performed using the comparative threshold cycle method. The highest control level attained by the stimulation (without TAK-242) was regarded as 100%, and the levels of control group at other time points and TAK-242-added group were expressed as the percentage of the highest control level.

Western Blot Analysis. RAW264.7 cells were plated at a density of 5×10^5 cells/well in 24-well culture plates and incubated overnight. TAK-242 or tyrphostin AG126, a tyrosine kinase inhibitor, was added to the cells and incubated for 15 min before 30-min stimulation with LPS. After the removal of cell culture supernatants, the cells were incubated in lysis buffer [25 mM Tris-HCl, pH 7.4, 1 mM EDTA, 100 mM NaCl, 30 mM NaF, 1% Nonidet P-40, 1 mM Na₃VO₄, 1 mM phenylmethylsulfonyl fluoride, 1 μ M leupeptin, and 1 mM (4-amidino-phenyl)-methylsulfonyl fluoride] on ice for 10 min. The cell lysates were centrifuged at 15,000 rpm (Himac CF15D2; Hitachi, Ibaragi, Japan) for 10 min. The resultant supernatant was mixed with 1/4 volume of 5 \times SDS sample buffer (312.5 mM Tris-HCl, pH 6.8, 5% SDS, 50% glycerol, 25% 2-mercaptoethanol, and 0.1% bromophenol blue). The proteins in the lysates were separated by SDS-polyacrylamide gel electrophoresis (10.5% gel), and blotted onto polyvinylidene difluoride Immobilon membranes (Millipore, Molsheim, France). After blocking the membrane in TBS-T (25 mM Tris-HCl, pH 8.0, 150 mM NaCl, and 0.05% Tween 20) containing 3%

bovine serum albumin, membranes were washed in TBS-T and probed for 1 h with anti-phospho-p44/42 MAPK antibody (Ab) (New England Biolabs, Beverly, MA), anti-phospho-p38 MAPK Ab (New England Biolabs), anti-I κ B β (C-20) Ab (Santa Cruz Biotechnology, Inc., Santa Cruz, CA), anti-phospho-c-Jun NH₂-terminal kinase/stress-activated protein kinase (JNK/SAPK) Ab (New England Biolabs), or anti-p67^{phox} Ab (BD Biosciences, San Jose, CA). The membranes were washed four times in TBS-T and incubated with secondary horseradish peroxidase-conjugated goat anti-rabbit IgG Fc(ab) (Cappel, Aurora, OH). After washing the membranes four times in TBS-T, the bands were detected using enhanced luminol reagent (New England Biolabs) according to the manufacturer's instruction.

Assay for LPS Binding to PBMCs. PBMCs were suspended in BSA solution (phosphate-buffered saline containing 0.1% BSA and 0.01% sodium azide). In a total volume of 50 μ l, PBMCs (3×10^5 cells) were incubated with TAK-242, anti-human CD14 monoclonal antibody (MAb) MEM-18 (Monosan, Uden, The Netherlands), or anti-human CC-chemokine receptor 5 (CCR5) MAb (2D7; BD Biosciences Pharmingen, San Diego, CA) as a negative control for 30 min at 4°C. The cells were further incubated with 50 ng/ml LPS from *E. coli* serotype O55:B5 conjugated with Alexa Fluor 488 (Molecular Probes, Eugene, OR) per milliliter in the presence of human serum at a final concentration of 1% for 45 min at 37°C. After washing twice with BSA solution, 1×10^4 cells were analyzed by flow cytometry using CytoACE300 cytofluorometer (Jasco, Tokyo, Japan). The assays were performed in triplicate for each preparation of PBMCs obtained from four different donors. Specific LPS binding was estimated by subtracting the percentage of LPS-binding cells in the absence of LPS from that in the presence of LPS.

Results

Inhibitory Effect of TAK-242 on the Production of Inflammatory Cytokines and Nitric Oxide from LPS-Stimulated Monocytes, Macrophages, and PBMCs. Resident mouse peritoneal macrophages were stimulated with 1 ng/ml LPS and 1 U/ml IFN- γ in the presence of various concentrations of TAK-242, and the amounts of nitrite (a stable metabolite of NO), TNF- α , IL-6, and IL-1 β produced in the supernatants were measured. TAK-242 inhibited the production of these proinflammatory mediators in a concentration-dependent manner, with IC₅₀ values ranging from 5.7 to 11 nM (Table 1, Fig. 2). TAK-242 also suppressed the production of NO, TNF- α , and IL-6 from RAW264.7 cells stimulated with 5 ng/ml LPS and 1 U/ml IFN- γ with IC₅₀ values ranging from 1.1 to 3.9 nM. In addition, TAK-242 showed similar suppressive effects on the proinflammatory mediator production when RAW264.7 cells were stimulated with a high concentration (1 μ g/ml) of LPS alone. NO production from RAW264.7 cells induced by IFN- γ alone was partially suppressed only by more than several hundreds times higher concentrations of TAK-242 compared with those for sup-

TABLE 1
IC₅₀ values of TAK-242 for NO, TNF- α , IL-6, and IL-1 β production by mouse macrophages

Cell Type and Stimuli	IC ₅₀ (95% Confidence Interval)			
	NO	TNF- α	IL-6	IL-1 β
	nM			
Peritoneal macrophages				
1 ng/ml LPS and 1 U/ml IFN- γ	7.7 (3.6–34)	8.7 (5.2–16)	11 (8.2–16)	5.7 (4.2–8.1)
RAW264.7				
5 ng/ml LPS and 1 U/ml IFN- γ	3.8 (2.7–5.3)	3.9 (2.5–7.6)	1.1 (0.79–1.6)	N.D.
1 μ g/ml LPS	3.9 (1.1–9.8)	4.6 (1.9–10)	3.7 (2.1–6.0)	N.D.

N.D., not determined.

pressing the LPS-induced activation (data not shown). TAK-242 did not show cytotoxicity at a concentration of 10 μ M by using the thiazolyl blue tetrazolium bromide method (data not shown).

TAK-242 was also effective in human cells and inhibited the production of TNF- α , IL-6, and IL-1 β from PBMCs stimulated with 1 ng/ml LPS and 1 U/ml IFN- γ , with IC₅₀ values of TAK-242 ranging from 5.3 to 58 nM (Table 2; Fig. 3). No marked difference in the IC₅₀ values of TAK-242 was observed among PBMCs derived from four different donors. The efficacy of TAK-242 in human PBMCs was similar to but slightly lower than that in the resident mouse peritoneal macrophages under the same stimulation condition. As shown in Table 3, TAK-242 also inhibited the LPS-induced IL-12 production, with IC₅₀ values similar to those for IL-6. Furthermore, it should be noted that TAK-242 showed similar effects on human PBMCs, monocytes, and GM-CSF-differentiated macrophages. These results suggest that TAK-242 could show suppressive effects on the production of various inflammatory mediators from both mouse and human monocytes and macrophages stimulated with LPS.

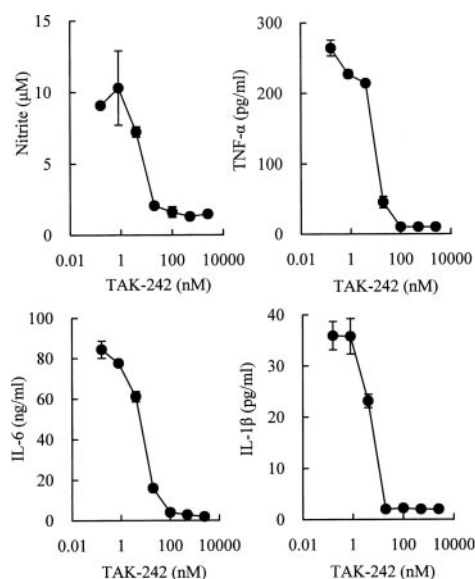


Fig. 2. Inhibitory effect of TAK-242 on NO and cytokine production from mouse peritoneal macrophages. The cells were stimulated with LPS (1 ng/ml) and IFN- γ (1 U/ml) in the presence or absence of TAK-242, and the levels of nitrite and cytokines in culture supernatants were measured as described under *Materials and Methods*. The data are expressed as mean \pm S.E. ($n = 3$).

TABLE 2

IC₅₀ values of TAK-242 for inhibition of IL-1 β , TNF- α , and IL-6 production by human PBMCs

The 95% confidence intervals of the IC₅₀ values have not been shown because the variance of the duplicate data in low concentrations of TAK-242 was too large for precise estimation.

Donor	IC ₅₀		
	IL-1 β	TNF- α	IL-6
	nM		
A	10	6.0	28
B	21	11	37
C	26	20	11
D	14	5.3	58
Mean \pm S.E.	18 \pm 3.5	11 \pm 3.3	33 \pm 9.8

Inhibitory Effect on mRNA Expression in RAW264.7 Cells. To determine whether the suppressive effect of TAK-242 on the cytokine production occurs at mRNA expression level, we used quantitative real-time PCR to examine IL-6 and TNF- α mRNA expressions in RAW264.7 cells stimulated with LPS and IFN- γ . As shown in Fig. 4, IL-6 mRNA expression was detected at 2 h after the stimulation, and the level of expression increased thereafter. On the other hand, TNF- α mRNA expression increased rapidly and reached a maximum level at 1 h after the stimulation with LPS and IFN- γ . These increases in TNF- α and IL-6 mRNA expression levels were clearly suppressed by TAK-242 at concentrations of 10 to 100 nM (Fig. 4), indicating that TAK-242 suppresses the production of cytokines by inhibiting the mRNA expression.

Inhibitory Effect on the LPS-Induced Activation of MAPK Cascades and I κ B Degradation in RAW264.7 Cells. LPS activates various intracellular signaling cascades such as MAPK pathway and NF- κ B pathway in monocytes and macrophages, which are required for the induction of many cytokines (Guha and Mackman, 2001). Therefore, we next examined the effect of TAK-242 on the LPS-induced phosphorylation of MAPKs and I κ B degradation in RAW264.7 cells. TAK-242 markedly inhibited the LPS-in-

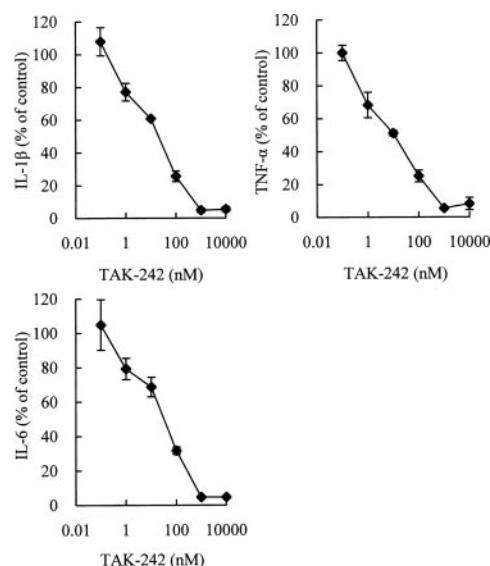


Fig. 3. Inhibitory effect of TAK-242 on IL-1 β , TNF- α , and IL-6 production from human PBMCs. The cells were stimulated with LPS (1 ng/ml) and IFN- γ (1 U/ml) in the presence or absence of TAK-242, and the levels of nitrite and cytokines in culture supernatants were measured as described under *Materials and Methods*. The data are expressed as mean \pm S.E. of percentage of inhibition for PBMCs prepared from four different donors. The levels of IL-1 β , TNF- α , and IL-6 produced by PBMCs of each donor were 12 to 38, 34 to 120, and 450 to 740 pg/ml, respectively.

TABLE 3

IC₅₀ values of TAK-242 for inhibition of IL-6 and IL-12 production by human PBMCs, monocytes, and macrophages

Cell Type	IC ₅₀ (95% Confidence Interval)	
	IL-6	IL-12
	nM	
PBMCs	330 ^a	98 (62–160)
Monocytes	130 (71–270)	56 (22–100)
Macrophages	76 (37–190)	32 (23–47)

^a The 95% confidence interval of the IC₅₀ value has not been shown because the variance of duplicate data in low concentrations of TAK-242 was too large for precise estimation.

duced phosphorylation of extracellular signal-regulated kinase 1/2 (Erk1/2), p38, and JNK/SAPK as well as degradation of I κ B β at a concentration of 100 nM (Fig. 5). Tyrosine kinase inhibitor AG126 also inhibited the LPS-induced phosphorylation of Erk1/2 and JNK/SAPK however, it did not inhibit p38 phosphorylation.

Effect of TAK-242 on LPS Binding to PBMCs. The results described above suggest that TAK-242 might target an upstream event in LPS signaling or inhibit LPS binding to the cells. It is known that LPS binds to CD14/TLR4/MD-2 complex on host cells such as monocytes and macrophages (Wright et al., 1990; da Silva Correia et al., 2001; Guha and Mackman, 2001). We conducted experiments to evaluate the effect of TAK-242 on LPS binding to the cells. Human PBMCs were used in this experiment to use a neutralizing anti-human CD14 MAb as a positive control. The cells were incubated with fluorescein-conjugated LPS, and the LPS binding was analyzed by flow cytometry. Preincubation of PBMCs with anti-CD14 MAb resulted in complete inhibition of the binding of LPS to PBMCs; however, the binding was not blocked by anti-CCR5 MAb. Thus, the binding of LPS to PBMCs was CD14-dependent. In contrast to the anti-CD14 MAb, TAK-242 did not block the binding of LPS to PBMCs even at a concentration of 10 μ M (Fig. 6). However, TAK-242 at a concentration of 1 μ M inhibited the production of TNF- α and IL-6 from PBMCs stimulated under conditions similar to those of the LPS binding assay (50 ng/ml LPS) by more than 85% compared with that in the absence of TAK-242 (data not shown). These results suggest that TAK-242 inhibits cyto-

kine production without antagonizing the binding of LPS to CD14/TLR4/MD-2 complex.

Selective Inhibitory Effect on TLR4-Mediated Signaling Pathway. We investigated whether the inhibitory effect of TAK-242 is specific for LPS-induced responses. A lot of studies have revealed that TLRs are the key molecules for recognizing pathogen-associated molecular patterns to elicit inflammatory responses, and LPS is a well known TLR4 ligand. Therefore, RAW264.7 cells were stimulated with various TLR ligands, and the effect of TAK-242 on cytokine production was examined. In addition to LPS from *E. coli*, we used LPS(S) (LPS from *S. typhimurium*), LTA, and paclitaxel (a diterpene from a plant) as TLR4 ligands (Takeuchi et al., 1999; Byrd-Leifer et al., 2001). PGN, poly(I:C), and CpG DNA were used as ligands for TLR2, -3, and -9, respectively (Takeuchi et al., 1999; Hemmi et al., 2000; Alexopoulou et al., 2001). As shown in Fig. 7, TAK-242 inhibited TNF- α production from RAW264.7 cells stimulated with LPS(S), LTA, and paclitaxel in a concentration-dependent manner similar to LPS from *E. coli*. In contrast, TAK-242 did not show an inhibitory effect on the TNF- α production induced by PGN, poly(I:C), and CpG DNA. TNF- α production induced by a cell permeable ceramide-C2 was not also inhibited by TAK-242 (data not shown). In addition, similar selective inhibitory

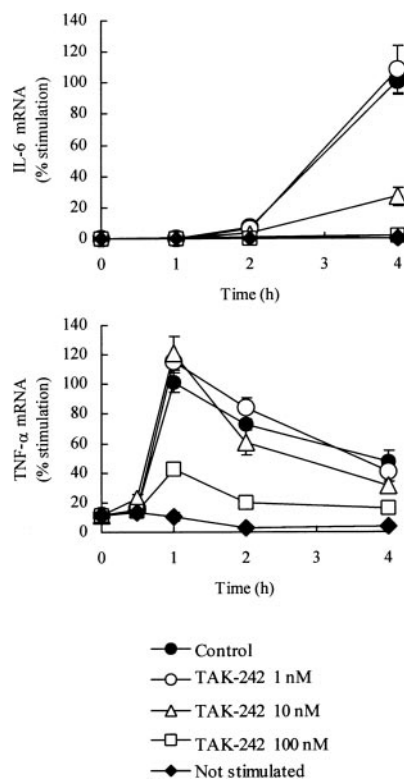


Fig. 4. Inhibitory effect of TAK-242 on mRNA expression induced by LPS and IFN- γ in RAW264.7 macrophages. Cells were incubated with LPS (5 ng/ml) and IFN- γ (1 U/ml) in the presence or absence of TAK-242. Expression levels of TNF- α and IL-6 mRNA were determined by real-time quantitative PCR and expressed as the percentage of the highest control level (the expression level at 1 h for TNF- α and at 4 h for IL-6). The data are expressed as mean \pm S.E. ($n = 3$).

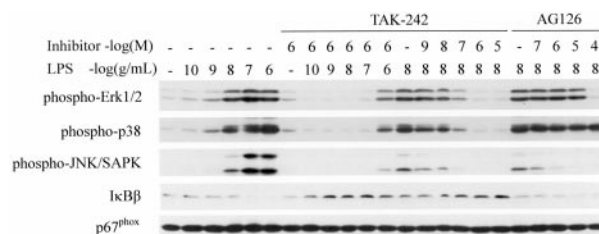


Fig. 5. Inhibitory effect of TAK-242 on the LPS-induced phosphorylation of MAPKs and I κ B degradation in RAW264.7 macrophages. Cells were treated with the indicated concentrations of TAK-242 or tyrphostin AG126 for 15 min before stimulation. After the LPS stimulation for 30 min, whole cell lysates were prepared and subjected to Western blot analysis using antibodies specific for phospho-Erk1/2, phospho-p38, phospho-JNK/SAPK, I κ B β , or p67^{phox}. p67^{phox} was used as control.

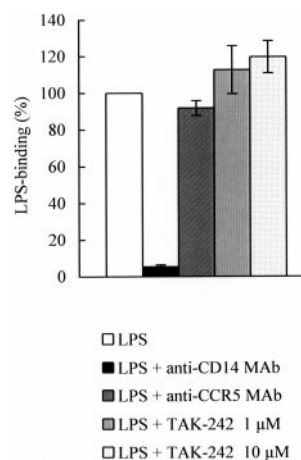


Fig. 6. Effect of TAK-242 on LPS-binding to PBMCs in the presence of human serum. PBMCs were incubated with anti-human CD14 MAb MEM-18, anti-human CCR5 MAb, or TAK-242 for 30 min at 4°C and further incubated with 50 ng/ml Alexa Fluor 488-conjugated LPS in the presence of 1% human serum for 45 min at 37°C. The cells were analyzed by flow cytometry. The data are expressed as mean \pm S.E. of four independent experiments using PBMCs prepared from four different donors.

patterns were observed in IL-6 and NO production (data not shown). We confirmed the selective inhibitory effect of TAK-242 on TLR4-mediated cytokine production in human macrophages. TAK-242 inhibited IL-6 and IL-12 production in human macrophages stimulated with LPS, with IC_{50} values of 32 and 16 nM, respectively. In contrast, TAK-242 did not inhibit IL-6 and IL-12 production induced by PGN even at a concentration of 2500 nM (Table 4). Furthermore, TAK-242 markedly inhibited IL-8 production from PBMCs induced by LPS but showed only a marginal inhibitory effect on IL-1 β -induced IL-8 production at higher concentrations (Fig. 8). These results suggest that TAK-242 selectively inhibits cytokine production mediated by TLR4 but not by TLR2, -3, and -9 or IL-1 β .

Discussion

In this article, we have presented a novel small molecule cytokine production inhibitor, TAK-242 (Fig. 1), which selectively suppresses TLR4-mediated production of cytokines and NO from monocytes and macrophages. Some synthetic lipid A analogs have been reported as LPS antagonists or TLR4 antagonists (Christ et al., 1995; Rossignol and Lynn, 2002; Fort et al., 2005). However, TAK-242 is the first small-

molecule compound that selectively suppresses TLR4-mediated cytokine production. TAK-242 suppressed the LPS-induced production of TNF- α , IL-1 β , IL-6, and NO at similar concentrations (Tables 1 and 2; Figs. 2 and 3). These data suggest that TAK-242 could show suppressive effects on the production of various types of inflammatory mediators, including those examined in this study. In addition, the inhibitory effects of TAK-242 on cytokine production were similar in both mouse and human macrophages, which suggests that differences in species do not greatly affect the efficacy of TAK-242. The LPS plus IFN- γ -induced increase in mRNA expression levels of IL-6 and TNF- α was also suppressed by TAK-242 at similar concentrations (Fig. 4). These observations have led us to speculate that TAK-242 targets an event that is elicited earlier than the transcription of cytokine genes. Therefore, we examined the effect of TAK-242 on MAPK and NF- κ B signaling pathways. TAK-242 inhibited the LPS-induced phosphorylation of Erk1/2, p38, and JNK/SAPK as well as I κ B degradation in RAW264.7 cells to a similar extent (Fig. 5). Although we did not address the effect of TAK-242 on the direct NF- κ B activation, it is suggested that TAK-242 might inhibit the early process of LPS signaling upstream of the phosphorylation of MAPKs and the I κ B degradation.

The initial process in the activation of immune cells by LPS is the recognition of LPS by a receptor complex composed of CD14, TLR4, and MD-2 on the cell surface (da Silva Correia et al., 2001). However, it has been reported that LPS binding to the complex is two types, namely, LBP/CD14-dependent and -independent types. The binding of LPS to the cells is LBP/CD14-dependent for LPS concentrations up to 100 ng/ml, and at higher LPS concentrations, the binding of LPS is LBP/CD14-independent (Triantafyllou et al., 2000). To determine whether TAK-242 inhibits cytokine production through both these types, we used two stimulation conditions with

TABLE 4
 IC_{50} values of TAK-242 for LPS- and PGN-induced IL-6 and IL-12 production by human macrophages

Stimuli	IC_{50} (95% Confidence Interval)	
	IL-6	IL-12
	nM	
LPS	32 (19–67)	16 (6.2–36)
PGN	>2500	>2500

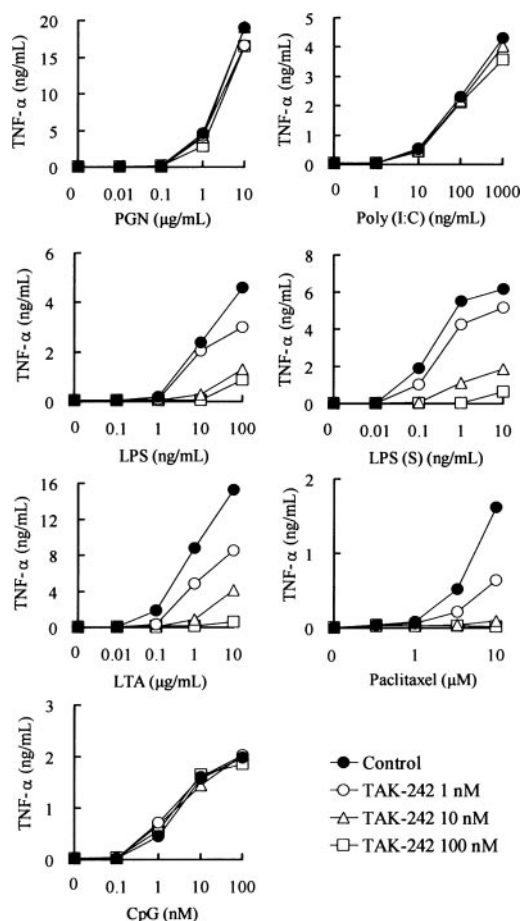


Fig. 7. Ligand specificity for the inhibitory effect of TAK-242 on TNF- α production from RAW264.7 macrophages. Cells were plated at a density of 1×10^5 cells/well in 96-well culture plates and incubated overnight. After removing the cell culture supernatants, the cells were stimulated with various TLR ligands described in the presence or absence of TAK-242 for 20 h. The concentration of TNF- α in the culture supernatant was determined in duplicate by specific enzyme-linked immunosorbent assay.

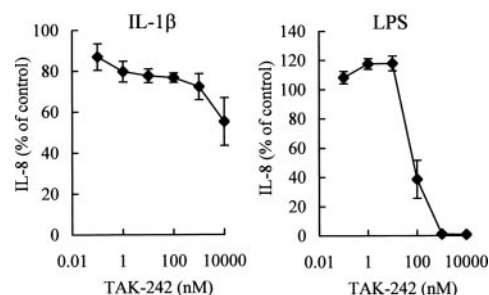


Fig. 8. Effect of TAK-242 on IL-8 production from human PBMCs stimulated with LPS or IL-1 β . The cells were stimulated with IL-1 β (10 ng/ml) or LPS (1 ng/ml) in the presence or absence of TAK-242, and IL-8 levels in culture supernatants were measured as described under *Materials and Methods*. The data are expressed as mean \pm S.E. of percentage of inhibition for PBMCs prepared from four different donors. The IL-8 levels produced by PBMCs of each donor were from 0.85 to 1.6 ng/ml and from 7.7 to 14 ng/ml for IL-1 β and LPS stimulation, respectively.

different concentrations of LPS [i.e., 5 ng/ml (plus IFN- γ) and 1 μ g/ml]. Regardless of the LPS concentrations, TAK-242 showed similar suppressive effects on the production of these mediators from RAW264.7 cells (Table 1). Furthermore, TAK-242 did not block the CD14-mediated binding of LPS to PBMCs, although it suppressed the cytokine production (Fig. 6). Together, TAK-242 is not an LPS antagonist but can inhibit an LPS-induced signaling process that is elicited after binding of LPS to the receptor complex.

LPS as well as other microbial components initiate signal transduction through TLRs, resulting in the release of inflammatory cytokines. TLRs are broadly distributed on the cells of the immune system (Muzio and Mantovani, 2000) and recognize a remarkably diverse array of bacterial, viral, and fungal molecular patterns (Hopkins and Sriskandan, 2005). For example, it is well known that TLR2, -3, -4, and -9 recognize PGN, poly(I:C), LPS, and CpG DNA, respectively (Takeuchi et al., 1999; Hemmi et al., 2000; Alexopoulou et al., 2001). It is noteworthy that experiments using cell stimulation with various ligands for TLR/IL-1 receptor family showed that TAK-242 selectively suppressed TLR4-mediated cytokine production. TAK-242 inhibited cytokine production in RAW264.7 cells stimulated with TLR4 ligands; however, it did not show inhibitory effects on ligands for TLR2, -3, or -9 (Fig. 7). In addition, the TLR4-selective inhibition was also observed in human PBMCs and macrophages (Table 4; Fig. 8). Furthermore, TAK-242 showed similar inhibitory effects on cytokine production from RAW264.7 cells stimulated with not only LPS from *E. coli* but also LPS from *S. typhimurium*, LTA from *S. aureus*, and paclitaxel (Fig. 7). It should be noted that we used commercial LTA from *S. aureus* as a TLR4 ligand, as reported previously (Takeuchi et al., 1999). Although it has been reported that highly purified LTA is a TLR2 ligand (Ellingsen et al., 2002), cytokine production induced by cell walls derived from *S. aureus* is partially abolished in TLR4-deficient macrophages (Takeuchi et al., 1999). It is plausible that TAK-242 inhibits the cytokine production induced by an unknown active TLR4 ligand contaminated in commercial LTA. Thus, these data suggest that TAK-242 does not discriminate between TLR4 ligands with regard to the structural differences and could suppress the activation of cells by a wide range of TLR4 ligands. Further investigation on its precise mechanism of action is needed along with the elucidation of target molecules of TAK-242. However, based on the data reported in this study, it can be inferred that TAK-242 might target an upstream event in TLR4-mediated signaling.

Intracellular signaling of TLRs is elicited from Toll/IL-1 receptor (TIR) domain, which is conserved among the cytoplasmic regions of TLRs. After the exposure of the cells to LPS, TLR4 homodimerizes and recruits four adaptor molecules that contain TIR domain: MyD88, MyD88 adaptor-like (also known as TIRAP), TIR domain-containing adaptor molecule-1 (TICAM-1, also known as TRIF), and TICAM-2 (also known as TRAM) (Dunne and O'Neill, 2005). Two signaling pathways have been suggested downstream of TLR4, namely, MyD88-dependent and MyD88-independent pathways. MyD88-deficient mice did not show production of inflammatory cytokines induced by various TLR ligands. MyD88 adaptor-like/TIRAP has been shown to be essential for the MyD88-dependent signaling pathway via TLR2 and TLR4. TICAM-1/TRIF has been demonstrated to be essential

for TLR3- and TLR4-mediated MyD88-independent pathways (Yamamoto et al., 2002; Fitzgerald et al., 2003; Oshiumi et al., 2003a). Among the four adaptors, TICAM-2/TRAM specifically interacts with TLR4 and is involved in a TLR4-mediated signaling pathway (Fitzgerald et al., 2003; Oshiumi et al., 2003b; Yamamoto et al., 2003). TICAM-2/TRAM-deficient mice show defects in cytokine production in response to TLR4 ligand but not to other TLR ligands. MD-2 is also a TLR4-specific molecule; it is a coreceptor of TLR4, which is essential for LPS signaling of TLR4 (Shimazu et al., 1999; Nagai et al., 2002). MD-2 is physically associated with the extracellular domain of TLR4 and augments TLR4-dependent LPS responses. In MD-2-deficient embryonic fibroblasts, TLR4 does not reach to the plasma membrane and predominantly resides in the Golgi apparatus; this suggests that MD-2 is also essential for appropriate intracellular distribution of TLR4. Although the target molecule of TAK-242 remained to be identified, TLR4 and its associated molecules MD-2, CD14, LBP, and TICAM-2/TRAM may be involved in its inhibitory mechanism. Among these, TLR4, MD-2, and TRAM might be the most probable candidates for the target because TAK-242 is a selective inhibitor for TLR4-mediated cytokine production. TAK-242 might directly inhibit TLR4, TRAM, or MD-2. Otherwise, TAK-242 might suppress or activate an unknown molecule that is uniquely required to regulate TLR4 signaling.

Some TLRs play an important role in the pathogenesis of infectious and inflammatory diseases such as sepsis, meningitis, atherosclerosis, inflammatory bowel disease, hepatitis, and autoimmune diseases (e.g., multiple sclerosis and systemic lupus erythematosus) (O'Neill, 2003). The involvement of TLR4 in some diseases such as sepsis and atherosclerosis was indicated based on studies on polymorphisms in the TLR4 gene (Kiechl et al., 2002; Lorenz et al., 2002). In addition, because tissue macrophages play an important role in the pathogenesis of various inflammatory diseases (Linton and Fazio, 2003; Schwacha, 2003), it is essential that drugs used to treat these diseases should act effectively on macrophages as well as on monocytes. The efficacy of TAK-242 against the LPS-induced IL-6 and IL-12 production was almost the same between human monocytes and GM-CSF-differentiated macrophages (Table 3). Thus, TAK-242 could offer a new therapeutic approach for inflammatory diseases whose pathogenesis involves TLR4. In fact, TAK-242 protected mice when tested in the endotoxin shock model and showed beneficial effects in some sepsis models (T. Sha, M. Ii, M. Sunamoto, T. Kitazaki, J. Sato, and Y. Iizawa, manuscript in preparation). Based on the beneficial effects observed in preclinical studies, a clinical trial of TAK-242 in severe sepsis is now ongoing.

In conclusion, we discovered a novel cyclohexene derivative, TAK-242, which selectively suppresses TLR4-mediated cytokine production. TAK-242 could be a promising drug for the treatment of inflammatory diseases involving TLR4, such as sepsis. The precise mechanism of action of TAK-242 is being investigated.

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