Table 1
Sequences of primers and annealing temperatures used for real-time RT-PCR analyses.

Target	Primer	Sequence	Annealing temperature (°C)
T-bet	FP	5′-CAA GTG GGT GCA GTG TGG AAA G-3′	68
	RP	5′-TGG AGA GAC TGC AGG ACG ATC-3′	
GATA-3	FP	5′-GGA GGA CTT CCC CAA GAG CA-3′	68
	RP	5′-CAT GCT GGA AGG GTG GTG A-3′	
RORγt	FP	5′-ACC TCC ACT GCC AGC TGT GTG CTG TC-3′	68
	RP	5′-TCA TTT CTG CAC TTC TGC ATG TAG ACT GTC CC-3′	
FoxP3	FP	5′-CTA GCA GTC CAC TTC ACC AAG-3′	66
	RP	5′-GCT GCT GAG ATG TGA GTG TC-3′	
IFNγ	FP	5′-GGC CAT CAG CAA CAT AAG C-3′	68
	RP	5′-TGG ACC ACT CGG ATG AGC TCA-3′	
IL-10	FP	5′-TGA AGA CCC TCA GGA TGC GG-3′	66
	RP	5′-AGA GCT CTG TCT AGG TCC TGG-3′	
TNFα	FP	5′-TGT CTC AGC CTC TTC TCA TTC C-3′	66
	RP	5′-TGA GGG TCT GGG CCA TAG AAC-3′	
MIP-2	FP	5′-AAG TTT GCC TTG ACC CTG AAG-3′	64
	RP	5′-ATC AGG TAC GAT CCA GGC TTC-3′	
GAPDH	FP	5′-AAA TGG GGT GAG GCC GGT-3′	64
	RP	5′-ATT GCT GAC AAT CTT GAG TGA-3′	

FP, forward primer, RP, reverse primer.

Meanwhile, ANIT also is known to induce intense neutrophil infiltrations primarily in the periportal area of the liver (Dahm et al., 1991). Dahm et al. (1991) also demonstrated that depletion of circulating neutrophils attenuates ANIT-induced liver injury, emphasizing the importance of the inflammatory reaction in the liver injury.

In this study, we investigated whether Th cells are involved in ANIT-induced liver injury in mice. First, the hepatic expressions of T box expressed in T cells (T-bet), GATA-binding protein (GATA-3), forkhead box P3 (FoxP3) and retinoid related orphan receptor γt (RORγt), which are transcriptional factors for Th1, Th2, Treg and Th17 cells, respectively, and cytokines specific for helper T cells were measured after ANIT administration to mice. Secondly, to investigate the IL-17 involvement, the plasma IL-17 levels were measured, and neutralization and administration of recombinant IL-17 were performed.

2. Materials and methods

2.1. Chemicals

α-Naphthylisothiocyanate (ANIT) was purchased from Wako Pure Chemical Industries (Osaka, Japan). RNAiso was from Nippon Gene (Tokyo, Japan). Rever-Tra Ace was from Toyobo (Tokyo, Japan). Random hexamer and SYBR Premix Ex Taq were from Takara (Osaka, Japan). All primers were commercially synthesized at Hokkaido System Sciences (Sapporo, Japan). Monoclonal anti-mouse IL-17 antibody,

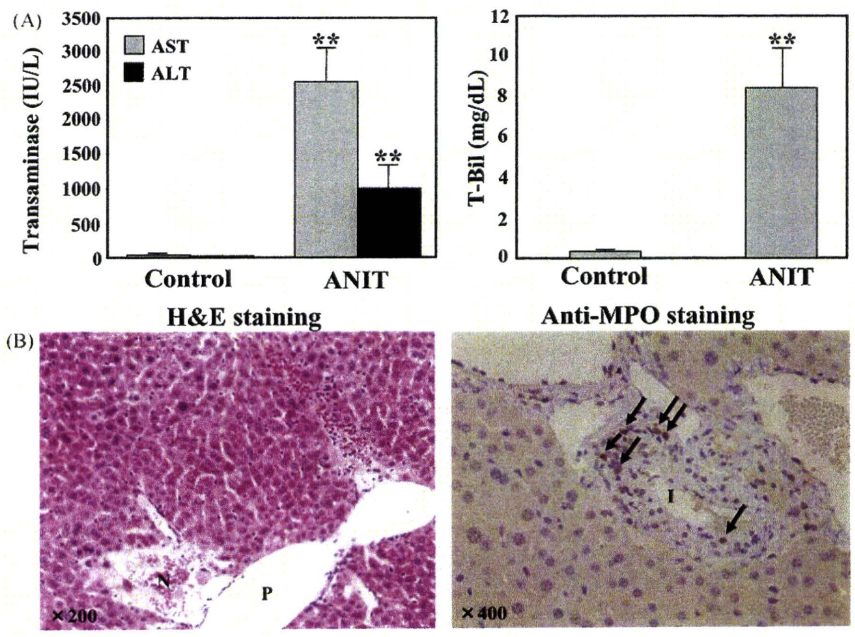

Fig. 1. Plasma AST, ALT and T-Bil levels and histopathological presentation of liver injury in ANIT-administered mice.
Mice were administered ANIT (50 mg/kg, p.o.), and plasma for AST and ALT (A) and T-Bil (B) was collected 24 h after administration. Data are mean ± SD of 6 mice. Significantly different from control group (**$P < 0.01$). Histopathological examination of the liver (C). Liver specimens were sampled 24 h after ANIT administration. The liver tissue sections were stained with H&E or immunostained with anti-MPO antibody. Arrows indicated MPO-positive cells. N, necrotic area; P, portal vein; I, intralobular bile duct.

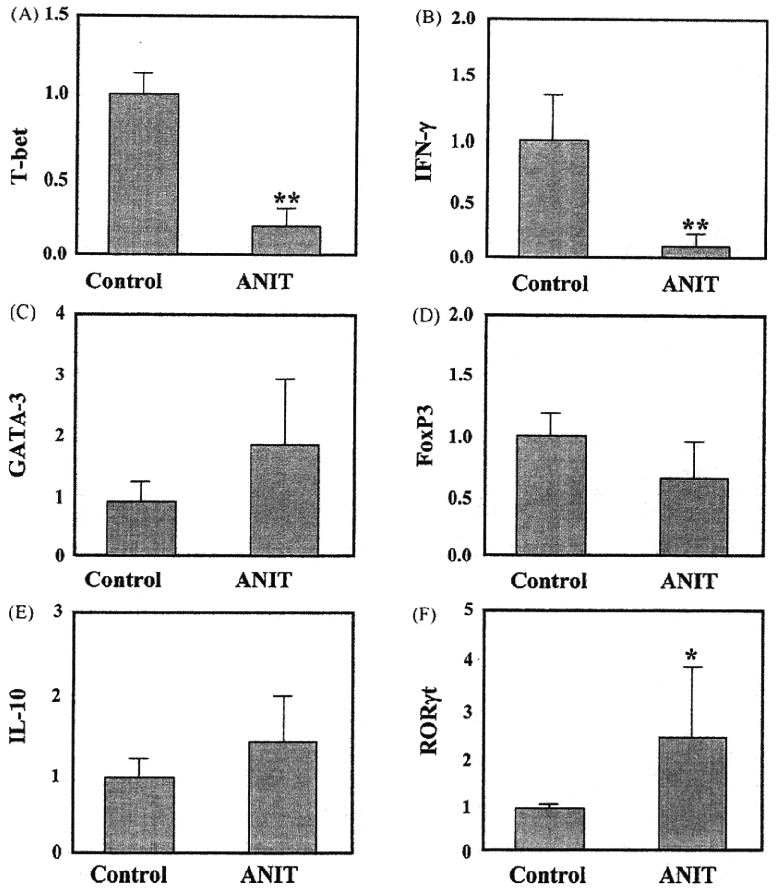

Fig. 2. Hepatic mRNA expression of transcriptional factors and cytokine genes 24 h after ANIT administration.
Relative expressions of T-bet (A), IFN-γ (B), GATA-3 (C), FoxP3 (D), IL-10 (E) and RORγt (F) were measured by real-time RT-PCR and normalized to GAPDH mRNA. Data are mean ± SD of 6 mice. Significantly different from control group ($^{*}P < 0.05$ and $^{**}P < 0.01$).

rat IgG2a isotype and recombinant mouse IL-17 were from R&D Systems (Abingdon, UK). A Ready-SET-GO! Mouse Interleukin-17A (IL-17A) enzyme-linked immunosorbent assay (ELISA) kit was from eBioscience (San Diego, CA). Dri-Chem 4000 was from FUJIFILM Corporation (Saitama, Japan). Other chemicals were of analytical or the highest grade commercially available.

2.2. ANIT-administration

Female BALB/cCrSlc mice (6 weeks old, 15–20 g) were obtained from SLC Japan (Hamamatsu, Japan). Animals were housed in a controlled environment (temperature 25 ± 1 °C, humidity 50 ± 10%, and 12-h light/12-h dark cycle) in the institutional animal facility with access to food and water *ad libitum*. Animals were acclimatized before use for the experiments. ANIT was dissolved in olive oil (10 mg/mL) and orally administered to mice at a dose of 50 mg/kg following overnight fasting. An hour after ANIT administration, mice were returned to access to food and water *ad libitum*. Twenty-four hours after ANIT administration, the animals were sacrificed and the blood and livers were collected. A portion of each excised liver was fixed in 10% formalin neutral buffer solution and used for immunohistochemical staining. The degree of liver injury was assessed by hematoxylin–eosin (H&E) staining, and the plasma aspartate aminotransferase (AST), alanine aminotransferase (ALT), and total bilirubin (T-Bil) levels were measured by Dri-Chem 4000 according to the manufacturer's instructions. The neutrophil infiltration was assessed by immunostaining for myeloperoxidase (MPO). Animal maintenance and treatment were conducted in accordance with the National Institutes of Health Guide for Animal Welfare of Japan, as approved by the Institutional Animal Care and Use Committee of Kanazawa University, Japan.

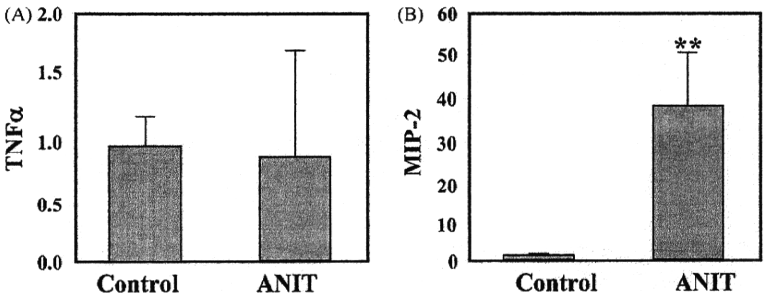

Fig. 3. Hepatic mRNA expression of proinflammatory cytokine and CXC chemokine.
Relative expressions of TNFα (A) and MIP-2 (B) were measured by real-time RT-PCR and normalized to GAPDH mRNA. Data are mean ± SD of 6 mice. Significantly different from control group ($^{**}P < 0.01$).

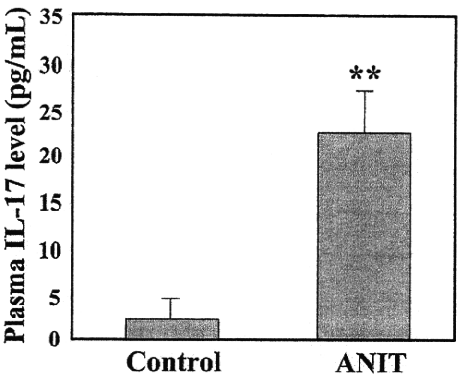

Fig. 4. Plasma IL-17 levels 24 h after ANIT administration.
The plasma IL-17 level was measured 24 h after ANIT administration to mice using ELISA. Data are mean ± SD of 6 mice. Significantly different from control group (**$P < 0.01$).

2.3. Real-time reverse transcription (RT)-PCR

RNA from the mouse liver was isolated using RNAiso according to the manufacturer's instructions. T-bet, GATA-3, RORγt, FoxP3, IFN-γ, IL-10, tumor necrosis factor α (TNFα), macrophage inflammatory ptrotein-2 (MIP-2) and GAPDH were quantified by real-time RT-PCR. The primer sequences used in this study are shown in Table 1. For the RT-process, total RNA (10 μg) and 150 ng random hexamer were mixed and incubated at 70 °C for 10 min. RNA solution was added to a reaction mixture containing 100 units of ReverTra Ace, reaction buffer and 0.5 mM dNTPs in a final volume of 40 μL. The reaction mixture was incubated at 30 °C for 10 min, 42 °C for 1 h, and heated at 98 °C for 10 min to inactivate the enzyme. The real-time RT-PCR was performed using the Mx3000P (Stratagene, La Jolla, CA). The PCR mixture contained 1 or 2 μL of template cDNA, SYBR Premix Ex Taq solution and 8 pmol of forward and reverse primers. Amplified products were monitored directly by measuring the increase of the dye intensity of the SYBR Green I (Molecular Probes, Eugene, OR) that binds to the double-strand DNA amplified by PCR.

2.4. Administration of anti-mouse IL-17 antibody or recombinant mouse IL-17

Nine hours after ANIT administration, mice were administered anti-mouse IL-17 antibody intraperitoneally (100 μg of anti-mouse IL-17 antibody in 0.5 mL of sterile PBS). As a control, rat IgG2a was administered (100 μg of rat IgG2a in 0.5 mL of sterile PBS). Recombinant mouse IL-17 was intraperitoneally administered (1 μg of recombinant IL-17 in 0.2 mL of sterile PBS containing 0.5% BSA) immediately after ANIT administration.

2.5. Measurement of plasma IL-17 level

The plasma IL-17 level was measured by enzyme-linked immunosorbent assay (ELISA) using a Ready-SET-GO! Mouse Interleukin-17A (IL-17A) kit from eBioscience according to the manufacturer's instructions.

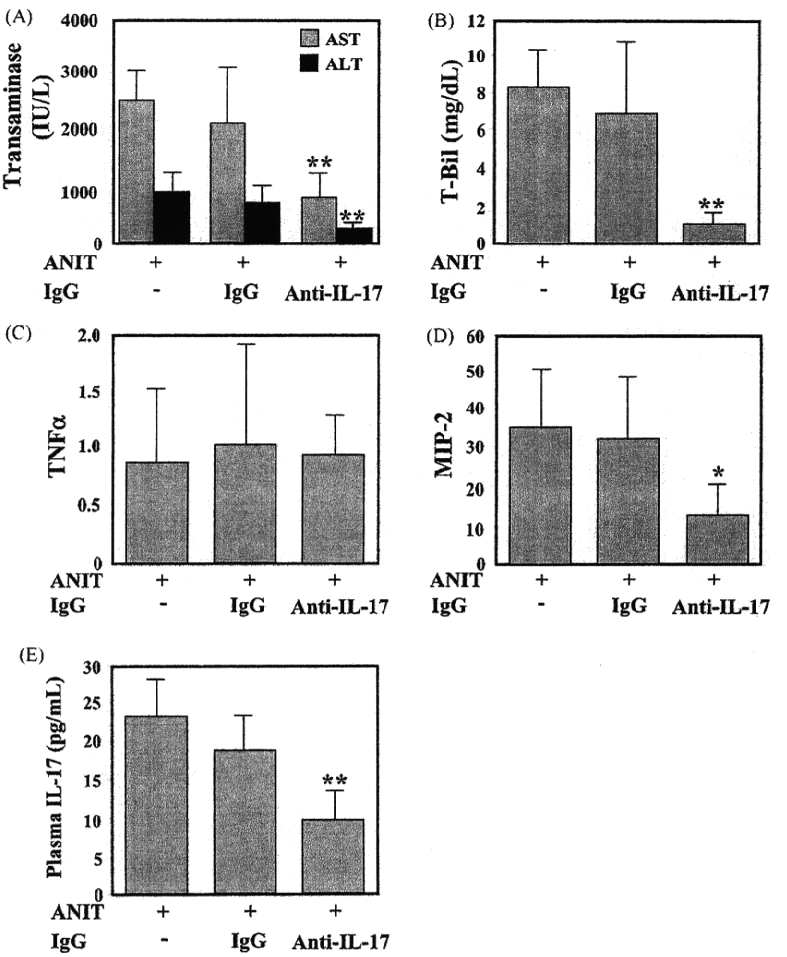

Fig. 5. Effect of anti-mouse IL-17 antibody on plasma AST, ALT and T-Bil, hepatic mRNA expression of TNFα and MIP-2 and plasma IL-17 levels in ANIT-administered mice. Mice were injected monoclonal anti-mouse IL-17 antibody (100 μg/mouse, i.p.) or rat IgG2a 9 h after the ANIT administration. Twenty-four hours after ANIT administration, plasma for the AST, ALT and T-Bil analyses was collected (A and B). Relative expressions of hepatic TNFα (C) and MIP-2 (D) mRNA were measured by real-time RT-PCR and normalized to GAPDH mRNA. The plasma IL-17 level was measured using ELISA (E). Data are mean ± SD of 5–6 mice. Significantly different from the ANIT-administered group (*$P < 0.05$ and **$P < 0.01$).

2.6. Quantitation of hepatic MPO-positive cells

Five visual fields of ×400 magnification (0.1 mm^2 each) were randomly selected from each MPO-immunostained specimen and taken picture by digital camera (D-33E, OLYMPUS, Tokyo). The MPO-positive mononuclear cells were counted from five pictures of each specimen. The total number of MPO-positive cells from five randomly selected visual fields was compared amongst the specimens.

2.7. Statistical analysis

Statistical analyses were performed with SAS 9.1.3. Comparison of two groups was made with Wilcoxon test. Comparison of multiple groups was made with non-parametrical Dunnet test using joint rankings. $P < 0.05$ was considered statistically significant.

3. Results

3.1. Increase of plasma AST, ALT and T-Bil levels in ANIT-administered mice

Female BALB/c mice were administered ANIT at a dose of 50 mg/kg. The dose of ANIT was determined as described by Kodali et al. (2006). A marked increase of the AST, ALT and T-Bil levels in plasma was observed 24 h after ANIT administration (Fig. 1A and B).

3.2. Histopathological changes in mouse liver after ANIT administration

Histopathological changes in mouse liver 24 h after ANIT administration are shown in Fig. 1C. In H&E staining, lack of hepatocytes due to necrosis and infiltration of inflammation cells such as neutrophils and mononuclear cells around the portal area was observed (Fig. 1C). In addition, the destruction and degeneration of the interlobular bile ducts occurred. Immunohistochemically, most of the infiltrating cells reacted to anti-MPO antibody 24 h after ANIT administration.

3.3. Expression of transcription factors and cytokine genes in ANIT-administered mouse liver

To investigate the involvement of Th cells in the ANIT-induced liver injury, the hepatic mRNA expression levels of transcriptional factors for each T helper lineage were measured by real-time RT-PCR (Fig. 2). The hepatic mRNA expression level of T-bet, which is a master regulator of Th1 cells, in ANIT-administered mice was significantly decreased to 16% compared with that of control mice (Fig. 2A). The hepatic mRNA expression level of interferon-γ (IFN-γ), which is a major cytokine of Th1 cells, significantly decreased after ANIT administration compared with that of control mice (Fig. 2B). Hepatic mRNA expression levels of GATA-3 and FoxP3 in ANIT-administered mice showed tendencies to increase and decrease, respectively (Fig. 2C and D). There was no difference in the hepatic mRNA expression level of IL-10 between ANIT-treated and control mice (Fig. 2D). Hepatic mRNA expression level of RORγt, which is master regulator for Th17 cells, was shown 2.5-fold higher in ANIT-administered than in control mice (Fig. 2E).

3.4. Changes of proinflammatory cytokine and CXC chemokine

To investigate whether the changes in liver injury and neutrophil infiltration observed in ANIT-administered mice resulted from the increases of proinflammatory cytokines and CXC chemokines, hepatic TNFα and MIP-2 mRNA expressions were measured. TNFα mRNA was not changed by ANIT administration (Fig. 3A). However, MIP-2 mRNA was markedly increased 24 h after ANIT administration (Fig. 3B).

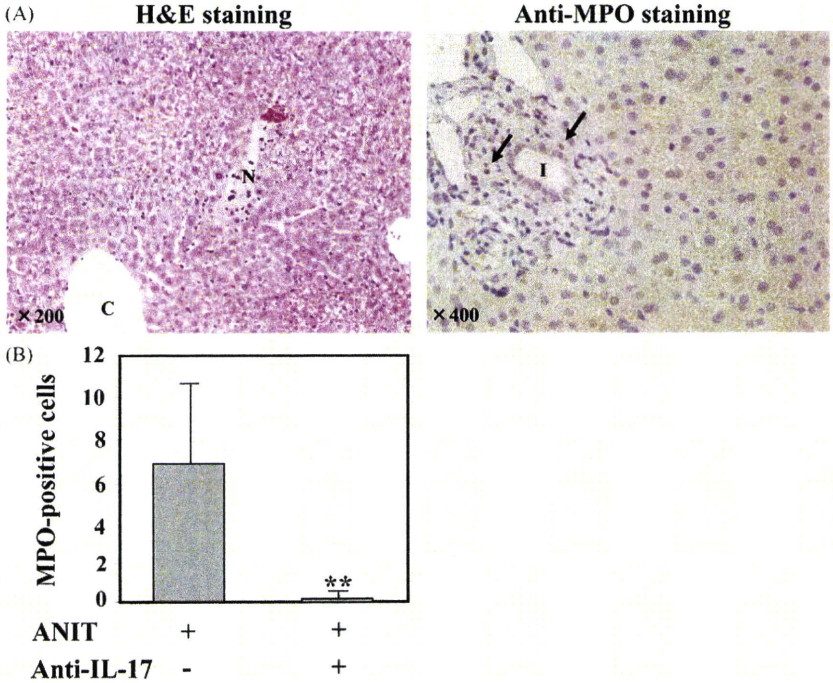

Fig. 6. Effect of anti-mouse IL-17 antibody on histopathological changes of liver injury in ANIT-administered mice and number of hepatic MPO-positive cells.
Mice were injected monoclonal anti-mouse IL-17 antibody (100 μg/mouse, i.p.) 9 h after the ANIT administration. Liver specimens were sampled 24 h after the ANIT administration. The liver tissue sections were stained with H&E or immunostained with anti-MPO antibody (A). Arrows indicated MPO-positive cells. C, central vein; N, necrotic area; I, intralobular bile duct.
The number of MPO-positive mononuclear cells was counted from five pictures of each specimen. The total number of MPO-positive cells from five randomly selected visual fields was compared with mice administered ANIT alone (B). Significantly different from ANIT-administered group ($^{**}P < 0.01$).

3.5. Changes of plasma IL-17 levels

IL-17 plays an important role in neutrophil infiltration and activation. The hepatic mRNA expression level of RORγt, which is a master regulator for Th17 cells, was increased after ANIT administration. Then, the plasma IL-17 level was measured using ELISA. The plasma IL-17 level in ANIT-administered mice was significantly increased (9.5-fold) compared with control mice (Fig. 4).

3.6. Effects of anti-IL-17 antibody administration in ANIT-administered mice

To investigate whether IL-17 was involved in the ANIT-induced liver injury, we conducted a neutralization study. In the neutralization study, a monoclonal anti-mouse IL-17 antibody injected intraperitoneally 9 h after ANIT administration significantly reduced the plasma AST, ALT and T-Bil levels at 24 h after ANIT administration (Fig. 5A and B). There were no significant differences in the hepatic mRNA expressions of TNFα, however hepatic MIP-2 mRNA was significantly decreased compared with mice administered ANIT alone (Fig. 5C and D). The plasma IL-17 level in anti-mouse IL-17 antibody-treated mice was significantly decreased compared with mice administered ANIT alone (Fig. 5E). In the histopathological study, no lack of hepatocytes or destruction of the interlobular bile ducts around the portal area was observed, and the number of MPO positive cells was decreased in ANIT and anti-mouse IL-17 antibody-administered mice (Fig. 6A and B) compared with mice administered ANIT alone (Fig. 1C). These effects were not observed by the administration of rat IgG2a.

3.7. Recombinant IL-17 exacerbated hepatotoxic effect of ANIT

To further investigate whether IL-17 was involved in the ANIT-induced liver injury, we performed a recombinant mouse IL-17 injection study. No change of biochemical parameters such as ALT, AST and T-Bil was observed in mice injected recombinant IL-17 alone in our previous study (Kobayashi et al., 2009). The intraperitoneal injection of recombinant IL-17 immediately after the ANIT administration caused remarkable increases of the plasma AST, ALT and T-Bil levels at 24 h after ANIT administration (Fig. 7A and B). The hepatic mRNA expressions of TNFα and MIP-2 in recombinant IL-17 and ANIT-administered mice were the same as those in mice administered ANIT alone (Fig. 7C and D). In the recombinant IL-17 and ANIT-administered mice, the plasma IL-17 level at 24 h after the ANIT administration was significantly increased compared with mice administered ANIT alone (Fig. 7E). Histopathologically, hep-

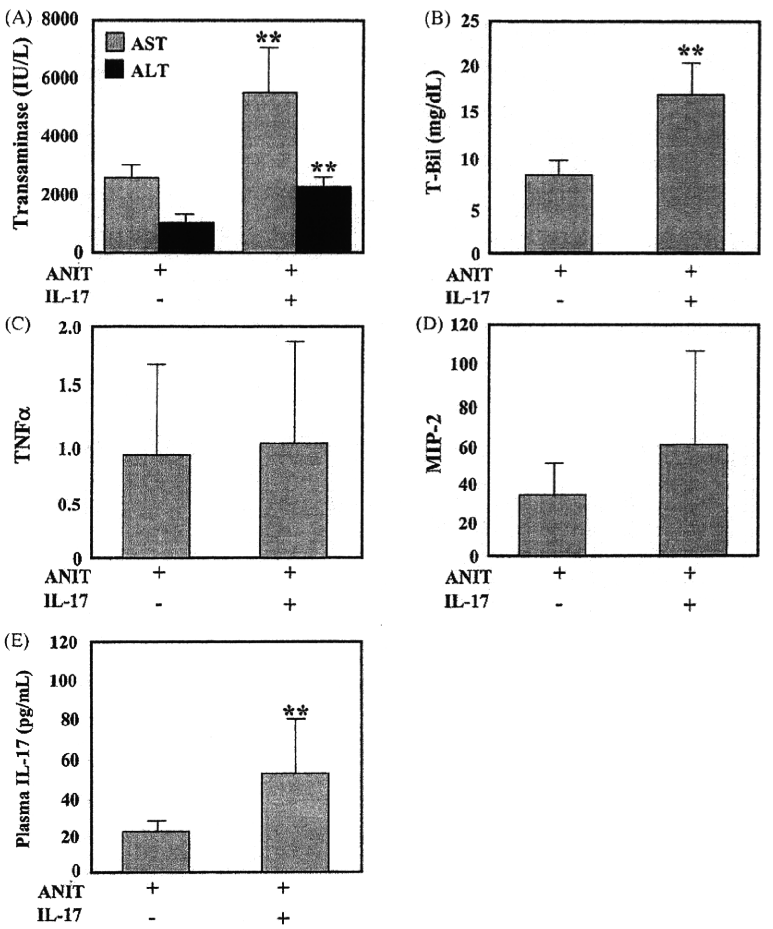

Fig. 7. Effect of recombinant mouse IL-17 on plasma AST, ALT and T-Bil, hepatic mRNA expression of TNFα and MIP-2 and plasma IL-17 levels in ANIT-administered mice. Immediately after the ANIT administration, recombinant mouse IL-17 (1 μg per mouse, i.p.) was injected. Twenty-four hours after ANIT administration, plasma for the AST, ALT and T-Bil analyses was collected (A and B). Relative expressions of hepatic TNFα (C) and MIP-2 (D) mRNA were measured by real-time RT-PCR and normalized to GAPDH mRNA. The plasma IL-17 level was measured using ELISA (E). Data are mean ± SD of 6 mice. Significantly different from ANIT-administered group (**$P < 0.01$).

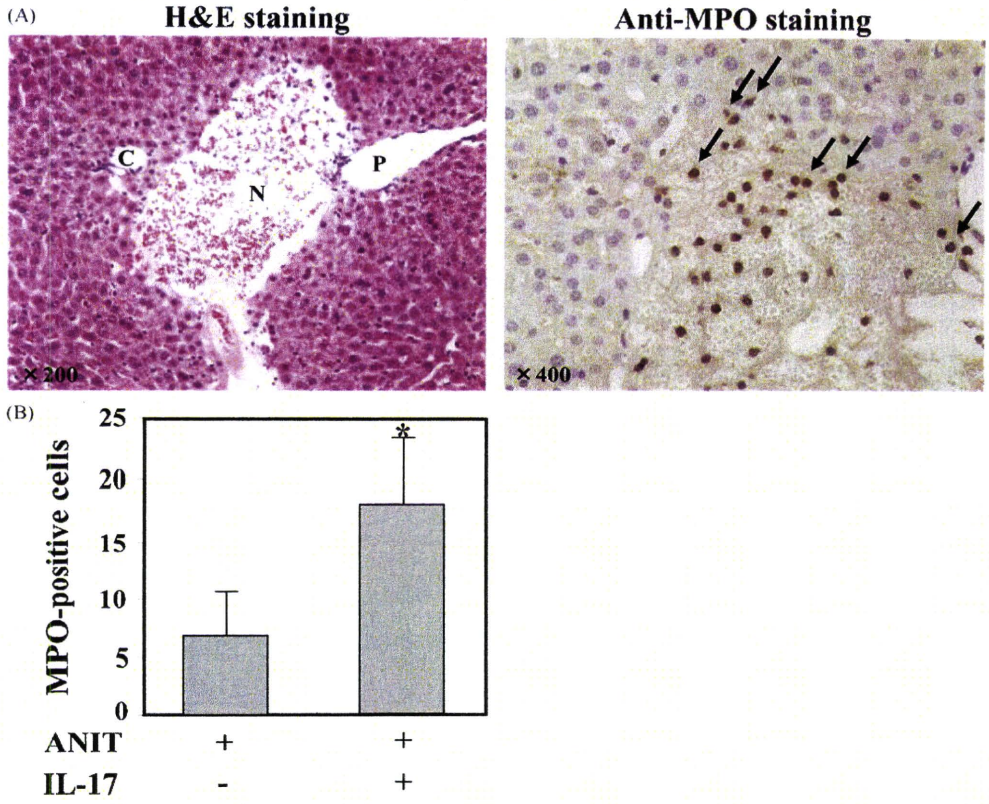

Fig. 8. Effect of recombinant mouse IL-17 on histopathological changes of liver injury in ANIT-administered mice and number of hepatic MPO-positive cells.
Immediately after the ANIT administration, recombinant mouse IL-17 (1 μg per mouse, i.p.) was injected. Liver specimens were sampled 24 h after the ANIT administration. The liver tissue sections were stained with H&E or immunostained with anti-MPO antibody (A). Arrows indicated MPO-positive cells. C, central vein; N, necrotic area; P, portal vein.
The number of MPO-positive mononuclear cells was counted from five pictures of each specimen. The total number of MPO-positive cells from five randomly selected visual fields was compared with mice administered ANIT alone (B). Significantly different from ANIT-administered group ($^*P < 0.05$).

atic changes including a lack of hepatocytes and the destruction of the interlobular bile ducts around the portal area were observed to be more severe in the recombinant IL-17-injected group. Furthermore, the increase of the number of MPO-positive cells was observed in the recombinant IL-17-treated mice (Fig. 8A and B) compared with the mice-administered ANIT alone (Fig. 1C). From these results, recombinant IL-17 exacerbated the hepatotoxic effect in ANIT-induced liver injury.

4. Discussion

ANIT causes severe cholestatic liver injury and is used in rodents as a model of human intrahepatic cholestasis. Dahm et al. (1991) suggested that the inflammatory reaction plays an important role in the expression of ANIT-induced liver injury using an animal model with depletion of circulating neutrophils. In this study, we investigated whether immune-mediated factors play an important role in the ANIT-induced liver injury.

A number of MPO positive cells had infiltrated in mouse liver 24 h after the ANIT administration in the immunohistochemical analysis with anti-MPO antibody (Fig. 1C), suggesting that neutrophil infiltration occurred in the ANIT-administered mouse liver. We examined the hepatic expression of transcriptional factors and cytokine genes in ANIT-administered mice. The hepatic mRNA expression level of RORγt, which is a master regulator in Th17 cells, and MIP-2, which is a CXC chemokine, significantly increased after the ANIT administration (Figs. 2F and 3B). These results suggested that Th17 cells and MIP-2 might be involved in ANIT-induced liver injury.

Th17 cells have been associated with the pathology in autoimmune disease, and it has been thought that Th17 cells increase inflammation by recruiting cells, particularly neutrophils, to the peripheral tissues for pathogen clearance (Roark et al., 2008). The plasma level of IL-17, produced in Th17 cells, significantly increased after the ANIT administration (Fig. 4). IL-17 is known to stimulate the production of CXC chemokines (MIP-2 and keratinocyte-derived chemokine) and plays an important role in the neutrophil activity (Zhu and Paul, 2008). These lines of evidence prompted us to investigate further the involvement of IL-17 in ANIT-induced liver injury.

In the present study, we demonstrated that the plasma IL-17 level was increased after the ANIT administration (Fig. 4) and neutralization of IL-17 using anti-mouse IL-17 antibody. In our previous study using a halothane-induced liver injury model (Kobayashi et al., 2009), we found the appropriate dose of anti-IL-17 antibody as 100 μg/body and the timing of anti-IL-17 injection as 9 h after halothane administration to suppress the hepatotoxic effect. Neutralization of IL-17 significantly inhibited the increase of the plasma AST, ALT and T-Bil levels (Fig. 5A and B). In addition, the neutralization study demonstrated that the increase of hepatic MIP-2 mRNA was related to IL-17 (Fig. 5D and E). Subsequently, recombinant IL-17 injection study was performed to further investigate whether IL-17 is involved in ANIT-induced liver injury. The appropriate dose of recombinant IL-17 (1 μg/body) and the timing of IL-17 injection to exacerbate the hepatotoxic effect were also determined accord-

ing to our previous study (Kobayashi et al., 2009). The injection of recombinant IL-17 caused a remarkable increase of the plasma AST, ALT and T-Bil levels (Fig. 7A and B) resulting in an exacerbation of the hepatotoxic effect of ANIT. However, hepatic MIP-2 mRNA was not significantly increased after the recombinant IL-17 injection (Fig. 7D). In the recombinant IL-17 injection study, the hepatic IL-10 mRNA expression level was significantly increased in recombinant IL-17-treated mice compared with mice administered ANIT alone (data not shown). IL-10, one of the anti-inflammatory cytokines, inhibits inflammatory cytokines (Glimcher and Murphy, 2000) and promotes the degradation of mRNA for the proinflammatory cytokines (Opal and DePalo, 2000). Therefore, it is suggested that IL-10 might inhibit MIP-2 production in recombinant IL-17 treated mice. From these lines of evidence, it is suggested that IL-17 is involved in the pathogenesis or exacerbation of ANIT-induced liver injury.

Neutrophils have been reported to mediate liver injury in a number of experimental animal models such as ischemia-reperfusion injury (Jaeschke et al., 1990), alcoholic hepatitis (Bautista, 2002; Jaeschke, 2002), obstructive cholestasis (Gujral et al., 2003) and acetaminophen toxicity (Liu et al., 2006). You et al. (2006) demonstrated the role of neutrophils in the pathogenesis of halothane-induced liver injury. IL-17 can induce many inflammatory and immunological responses such as neutrophil recruitment and activation (Zhu and Paul, 2008; Kolls and Linden, 2004). In the present study, the changes of the plasma IL-17 levels demonstrated the attenuation and exacerbation of ANIT-induced liver injury. It is suggested that IL-17 plays an important role in ANIT-induced liver injury in mice. Furthermore, the present study supported the usefulness of the plasma IL-17 level for monitoring the severity of acute hepatic injury in human (Yasumi et al., 2007).

In the present study, it was demonstrated that IL-17 might play an important role in drug-induced liver injury, especially immune-mediated liver injury. Furthermore, IL-17 might be a general mechanism responsible for neutrophil infiltration and subsequent liver damage.

Conflict of interest

None of the authors has any conflicts of interest related to this manuscript.

Acknowledgments

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Terbinafine stimulates the pro-inflammatory responses in human monocytic THP-1 cells through an ERK signaling pathway

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ABSTRACT

Aims: Oral antifungal terbinafine has been reported to cause liver injury with inflammatory responses in a small percentage of patients. However the underlying mechanism remains unknown. To examine the inflammatory reactions, we investigated whether terbinafine and other antifungal drugs increase the release of pro-inflammatory cytokines using human monocytic cells.

Main methods: Dose- and time-dependent changes in the mRNA expression levels and the release of interleukin (IL)-8 and tumor necrosis factor (TNF)α from human monocytic THP-1 and HL-60 cells with antifungal drugs were measured. Effects of terbinafine on the phosphorylation of extracellular signal-regulated kinase (ERK)1/2, p38 mitogen-activated protein (MAP) kinase and c-Jun N-terminal kinase (JNK) 1/2 were investigated.

Key findings: The release of IL-8 and TNFα from THP-1 and HL-60 cells was significantly increased by treatment with terbinafine but not by fluconazole, suggesting that terbinafine can stimulate monocytes and increase the pro-inflammatory cytokine release. Terbinafine also significantly increased the phosphorylation of ERK1/2 and p38 MAP kinase in THP-1 cells. Pretreatment with a MAP kinase/ERK kinase (MEK)1/2 inhibitor U0126 significantly suppressed the increase of IL-8 and TNFα levels by terbinafine treatment in THP-1 cells, but p38 MAPK inhibitor SB203580 did not. These results suggested that an ERK1/2 pathway plays an important role in the release of IL-8 and TNFα in THP-1 cells treated with terbinafine.

Significance: The release of inflammatory mediators by terbinafine might be one of the mechanisms underlying immune-mediated liver injury. This in vitro method may be useful to predict adverse inflammatory reactions that lead to drug-induced liver injury.

Introduction

Drug-induced hepatotoxicity is one of the major causes of liver injury and is classified into intrinsic and idiosyncratic types. Idiosyncratic drug reactions do not occur in most patients at any dose and they are often referred to as rare, with a typical incidence of from 1/100 to 1/100,000 (Uetrecht 1999). It has been hypothesized that inflammatory stress might be caused by some xenobiotics leading to an adverse drug reaction. The sporadic occurrence of acute inflammatory episodes could explain the onset of some idiosyncratic reactions during clinical drug therapy (Ganey et al. 2004; Roth et al. 2003; Tafazoli et al. 2005). Inflammatory reactions in liver are induced by the activation of immune cells, such as monocytes, macrophages and Kupffer cells. Activated monocytes and macrophages release large amounts of pro-inflammatory cytokines and chemokines, including interleukin (IL)-1, tumor necrosis factor (TNF)α, and IL-8. TNFα triggers the release of a cascade of other cytokines that recruit and activate immune cells, including lymphocytes and macrophages (Bradham et al. 1998). IL-8 exhibits multiple effects on neutrophils, including the induction of lysosomal enzyme release, the increase in the expression of adhesion molecules, and rapid infiltration (Leonard et al. 1991; Baggiolini et al. 1994). In several rodent models, it was shown that the production of TNFα and neurtophil infiltration in liver play a critical role in immune-mediated liver injury by drugs such as acetaminophen, non-steroidal anti-inflammatory drugs, and antibiotics (Jaeschke 2005; Deng et al. 2009).

Recently, it has been reported that human monocytic cell lines were useful to examine inflammatory responses mediated by drugs withdrawn from the market. In human monocytic THP-1 cells, the mRNA expression levels and/or the release of pro-inflammatory cytokines and chemokines were increased by the treatment with troglitazone or ximelagatran (Edling et al. 2008; Edling et al. 2009).

Terbinafine is an oral antifungal drug of the allylamine class and is effective for the treatment of onychomycosis and dermatophytosis (Gupta and Shear 1997). A postmarketing surveillance study showed that mild to severe gastrointestinal, skin, and taste disturbances are the most common adverse events related to oral terbinafine

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treatment (Hall et al. 1997). In addition, terbinafine has been also reported to cause liver injury in a small percentage of patients. Teribnafine-induced hepatic injury is classified into a mixed hepatocellular and cholestatic pattern. Liver biopsies of some patients revealed mixed cellular infiltration in portal tracts, including mononuclear cells, lymphocytes, and neutrophils (Mallat et al. 1997; Fernandes et al. 1998; Zapata Garrido et al. 2003). Moreover, some case reports showed that terbinafine-induced hepatic injury occurred in combination with hypersensitivity reactions, including fever, rash, and lymphadenopathy (Gupta and Porges 1998).

The estimated reporting incidence for the development of clinically significant signs and symptoms of hepatobiliary dysfunction for which no other cause was apparent is approximately 1:45,000–1:54,000 (Gupta et al. 1997; García Rodríguez et al. 1999). These backgrounds suggested that terbinafine-induced hepatic injury might be caused by an idiosyncratic rather than a direct hepatotoxic reaction (van't Wout et al. 1994). However, adverse reactions associated with the use of oral antifungal agents are usually mild, transient, and reversible after discontinuation. From these reasons, terbinafine was not withdrawn from the market. Routine hepatic monitoring when the duration of therapy exceeds 6 weeks could be replaced by the requirement to monitor only if symptoms or signs suggestive of hepatic injury (Gupta et al. 1997). If the underlying mechanisms of terbinafine-induced hepatic injury will be clarified, patient with high risk for hepatic injury will be predicted by using immune-related biomarkers.

Considering the reports of terbinafine-induced hepatic injury, we hypothesized that terbinafine stimulates inflammatory responses that may result in immune-mediated hepatic injury. The purpose of this study is to investigate whether terbinafine stimulates the release of pro-inflammatory cytokines and chemokines from human monocytic cells and to clarify the involvement of cell signaling in the release of pro-inflammatory cytokines and chemokines from THP-1 cells.

Materials and methods

Materials

Terbinafine hydrochloride, butenafine hydrochloride, and fluconazole were purchased from Wako Pure Chemical Industries (Osaka, Japan). Primers were commercially synthesized at Hokkaido System Sciences (Sapporo, Japan). The monoclonal antibodies of anti-Thr202/Tyr204 phosphorylated extracellular signal-regulated kinase (ERK) 1/2, anti-Thr180/Tyr182 phosphorylated p38 mitogen-activated protein (MAP) kinase, and anti-Thr183/Tyr185 phosphorylated c-Jun N-terminal kinase (JNK) 1/2 were purchased from Cell Signaling Technology (Beverly, MA). The monoclonal antibodies against ERK1/2 and JNK1/2 and the polyclonal antibody against p38 MAP kinase were also purchased from Cell Signaling Technology. Lipopolysaccharide (LPS) used only for positive control and plymyxin B to check the LPS contamination in antifungal drugs was purchased from Sigma-Aldrich (St. Louis, MO). Cell Counting Kit-8 (CCK-8) for MTT ((3-(4,5-dimethylthiazol-2-yl)-2,5-dephenyltetrazolium bromide) assay was purchased from Dojindo Laboratories (Kumamoto, Japan). All other reagents were of the highest grade commercially available.

Cell culture

Human monocytic leukemia cell line THP-1 was obtained from Riken Gene Bank (Tsukuba, Japan). HL-60 and KG-1 cells were obtained from American Type Culture Collection (Manassas, VA). THP-1 cells were cultured in RPMI 1640 medium (Nissui Pharmaceutical, Tokyo, Japan) supplemented with 10% fetal bovine serum (FBS; Invitrogen, Carlsbad, CA). HL-60 and KG-1 cells were cultured in RPMI 1640 medium supplemented with 20% FBS. These cells were maintained at 37 °C under an atmosphere of 5% CO_2.

Drug treatment of human monocytic cell lines

THP-1, HL-60, and KG-1 cells were seeded at a density of 1×10^6 cells/well in 24-well plates with the medium containing the indicated concentration of antifungal drugs, and then incubated at 37 °C. The final concentration of dimethyl sulfoxide (DMSO) in medium was 0.1% in all experiments. Cells were not activated with LPS. In experiments using MAP kinase inhibitors, cells were pretreated with MAP kinase/ERK kinase (MEK) 1/2 inhibitor U0126 (Wako Pure Chemical Industries), p38 MAP kinase inhibitor SB203580 (Wako Pure Chemical Industries), or JNK1/2 inhibitor SP600125 (Calbiochem, Los Angeles, CA) for 1 h, and then treated with the antifungal drugs. Supernatants were separated from cell cultures by centrifugation and stored at -70 °C until assayed. For immunoblot analysis, the cells were suspended in TGE buffer (10 mM Tris–HCl, 20% glycerol, 1 mM EDTA, pH 7.4) and disrupted by freeze-thawing three times.

Enzyme-linked immunosorbent assay (ELISA)

The pro-inflammatory cytokine TNFα and the chemokine IL-8 in cell supernatants were measured by Human TNFα ELISA Ready-SET-GO!™ (eBioscience, San Diego, CA) and Human IL-8 ELISA MAX™ (Biolegend, San Diego, CA), respectively, according to the manufacturer's instructions.

Real-time reverse transcription-polymerase chain reaction (RT-PCR)

Total RNA was extracted from THP-1 cells with RNAiso (Takara Bio, Shiga, Japan) according to the protocol supplied by manufacturer. Reverse transcription was performed with ReverTra Ace (Toyobo, Tokyo, Japan) according to the manufacturer's protocol. For quantitative analysis, real-time RT-PCR was performed for inflammatory cytokine mRNA using an MX3000P real-time PCR system (Stratagene, La Jolla, CA). The primers used in this study were human IL-8 (forward: 5′-CAGCCTTCCTGATTTCTCTGCAG-3′, reverse: 5′-AGACAGAGCTCTCTTCCATCAG-3′) and human TNFα (forward: 5′-CTTCTGCCTGCTGCACTTTGGAG-3′, reverse: 5′-GGCTACAGGCTTGTCACTCGG-3′). A 1 μl portion of the reverse-transcribed mixture was added to a PCR mixture containing 10 pmol of each primer and 10 μl of SYBR Premix ExTaq solution in a final volume of 20 μl. After an initial denaturation at 95 °C for 30 s, the amplification was performed by denaturation at 94 °C for 20 s and annealing and extension at 64 °C for 20 s for 45 cycles. The IL-8 and TNFα mRNA levels were normalized with human glyceraldehyde 3-phosphate dehydrogenase (GAPDH) mRNA (forward: 5′-CCATGAGAAGTATGACAACAGCC-3′, 5′-TGGGTGGCAGTGATGGCATGGA-3′).

Immunoblot analysis

SDS-polyacrylamide gel electrophoresis and immunoblot analysis were performed according to Laemmli (1970). Cell sources (25 μg) were separated on 10% polyacrylamide gels and electrotransferred onto polyvinylidene difluoride membrane, Immobilon-P (Millipore Corporation, Billerica, MA). The membranes were probed with the monoclonal antibodies of anti-Thr202/Tyr204 phosphorylated ERK1/2, anti-Thr180/Tyr182 phosphorylated p38 MAP kinase, and anti-Thr183/Tyr185 phosphorylated JNK1/2, and the corresponding fluorescent dye-conjugated second antibody and an Odyssey Infrared Imaging system (LI-COR Biosciences, Lincoln, NE) were used for the detection. The relative expression level was quantified using ImageQuant TL Image Analysis software (GE Healthcare, Little Chalfont, Buckinghamshire, UK).

Cell viability assay

For the cell viability assay, THP-1 cells were seeded at a density of 1×10^5 cells/well in 96-well plates with the medium containing the indicated concentration of the antifungal drug, and then incubated at 37 °C. The final concentration of DMSO in medium was 0.1%. After 6 h-incubation, MTT assay was performed by Cell counting Kit-8 using water-soluble [2-(2-methoxy-4-nitrophenyl)-3-(4-mitrophenyl)-5-2,4-disulfophenyl]-2H-tetrazlium monosodium salt] (WST-8). WST-8 produces a water-soluble formazan dye upon reduction in the presence of an electron carrier coupling with mitochondrial dehydrogenases. The fluorescence (excitation: 338 nm, emission: 458 nm) was detected by using a luminometer 1420 ARVO MX (Wallac, Turku, Finland).

Statistical analysis

Data are expressed as mean ± SD of triplicate determinations. Comparison of 2 groups was made with an unpaired, two-tailed student's *t*-test. Comparison of multiple groups was made with ANOVA followed by Dunnett or Tukey test. A value of $P<0.05$ was considered statistically significant.

Results

Comparative effect of antifungal drugs on human monocytic cell lines

To investigate whether antifungal drugs increased the release of IL-8 and TNFα from human monocytic cells, cells were treated with 100 μM of the antifungal drugs for 6 h and then the release of IL-8 and TNFα in the cell supernatants was measured by ELISA (Fig. 1). Butenafine was used as a drug structurally similar to terbinafine, although it used as ointment, and has never been administered orally. Fluconazole was used because it is assumed to have a lower risk of adverse events leading to treatment discontinuation compared with other antifungal drugs, including terbinafine (Chang et al. 2007). The IL-8 and TNFα release from THP-1 and HL-60 cells was significantly increased by treatment with terbinafine or butenafine but not by fluconazole compared with control (0.1% DMSO) (Fig. 1A–D). These results suggested that terbinafine and its structural similar drugs have the ability to increase the release of pro-inflammatory cytokines and chemokines from monocytes that activate the inflammatory responses. In contrast, IL-8 and TNFα release from KG-1 cells was not increased by the three antifungal drugs (Fig. 1E and F). In addition, antifungal drugs were incubated with 50 μM plymyxin B to check the potential LPS contamination. As a result, no change was observed by the addition of polymyxin B, indicating no LPS contamination (data not shown). For the subsequent analyses, THP-1 cells were used because it showed the highest sensitivity for the TNFα release.

Time-dependent changes in the mRNA expression levels and the release of IL-8 and TNFα in THP-1 cells treated with terbinafine

Time-dependent changes of the IL-8 and TNFα levels in THP-1 cells were investigated. By the treatment with 100 μM terbinafine, the mRNA expression levels of IL-8 and TNFα in THP-1 cells were significantly increased for 1.5 to 24 h compared with control and were mostly increased at a 3 h-treatment (Fig. 2A and B). In addition, terbinafine significantly increased IL-8 release from THP-1 cells in a time-dependent manner and the highest IL-8 release was 7.0-fold at

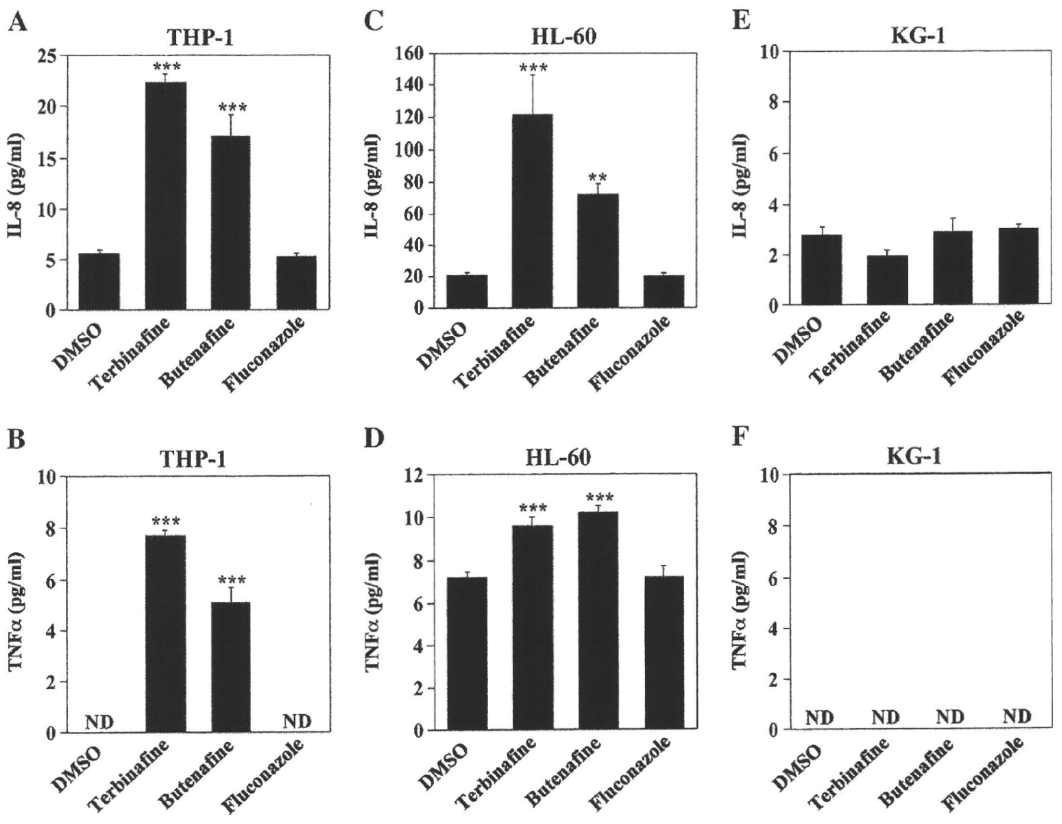

Fig. 1. Effects of antifungal drugs on the release of IL-8 and TNFα from human monocytic cell lines. Human monocytic cell lines including THP-1 (A and B), HL-60 (C and D), and KG-1 (E and F) were treated with 100 μM of the antifungal drugs for 6 h. The release of IL-8 (A, C, and E) and TNFα (B, D, and F) in the supernatant was measured by ELISA. Data represent the mean ± SD of triplicate determinations. **, $P<0.01$, ***, $P<0.001$, compared with control (0.1% DMSO). ND, not detectable.

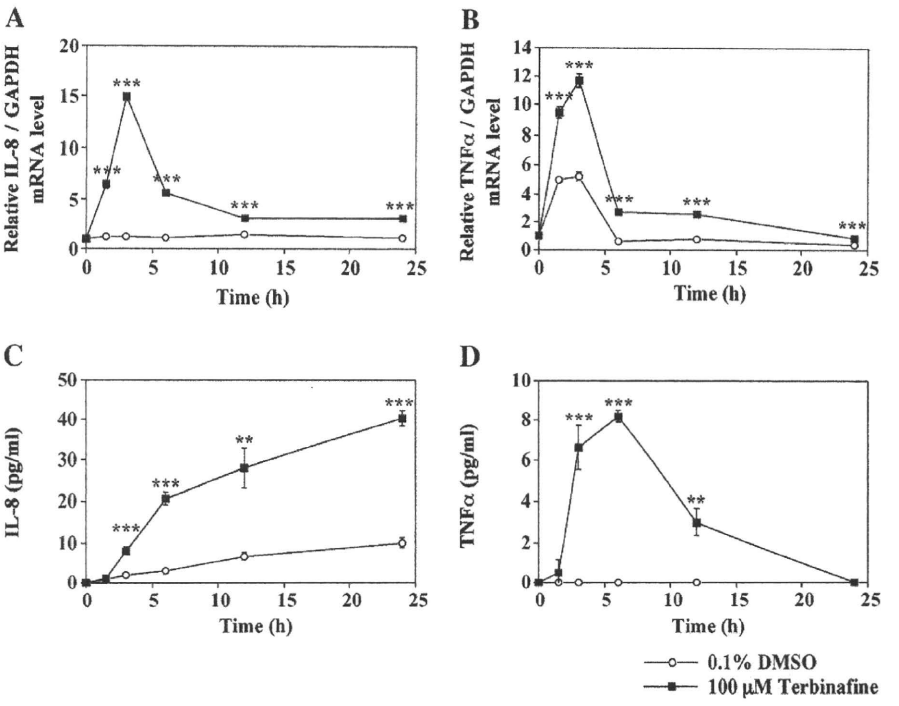

Fig. 2. Time-dependent changes in the mRNA expression levels and the release of IL-8 and TNFα in THP-1 cells treated with terbinafine. THP-1 cells were treated with 100 μM terbinafine for various durations. The mRNA expression levels of IL-8 (A) and TNFα (B) in THP-1 cells were measured by real-time RT-PCR analysis. The release of IL-8 (C) and TNFα (D) in the supernatant was measured by ELISA. Data represent the mean ± SD of triplicate determinations. **, $P<0.01$; ***, $P<0.001$, compared with control (0.1% DMSO) of each time point.

6 h-incubation compared with control (Fig. 2C). In contrast, TNFα release from THP-1 cells was transiently increased and the highest increase was detected at 6 h-incubation with terbinafine (Fig. 2D). Then, the incubation times of 3 h and 6 h were selected for further assay to measure the mRNA expression levels and the release of IL-8 and TNFα, respectively. To investigate whether there were cytotoxic effects on THP-1 cells caused by the leakage of intercellular cytokines and chemokines, a cell viability assay in THP-1 cells was performed. At 6 h-incubation, at the peak of IL-8 and TNFα release from THP-1 cells, the three antifungal drugs had no cytotoxic effects on THP-1 cells (data not shown).

Dose-dependent changes in the mRNA expression levels and the release of IL-8 and TNFα in THP-1 cells treated with antifungal drugs

To investigate whether antifungal drugs at a lower concentration can also change the IL-8 and TNFα levels in THP-1 cells, THP-1 cells were treated with antifungal drugs at the indicated concentration and then the mRNA expression levels and the release of IL-8 and TNFα were measured after 3 h- and 6 h-incubation, respectively. As shown in Fig. 3, terbinafine and butenafine increased the IL-8 and TNFα levels. In addition, at least 25 μM terbinafine was required to increase the mRNA expression levels and the release of IL-8 in THP-1 cells. Although the TNFα mRNA levels in THP-1 cells were significantly increased at 10 μM terbinafine, TNFα release was significantly increased from 50 μM.

Activation of MAP kinase signaling pathway in THP-1 cells treated with terbinafine

MAP kinases, including ERK1/2, p38 MAP kinase, and JNK1/2, are important components for many intracellular signaling pathways. Phosphorylation of MAP kinases, which are required for the enzyme activity, activate signaling cascades, the down stream effects of which have been linked to the regulation of the inflammatory response (DeFranco et al. 1998). To clarify the role of MAP kinase signaling pathway in the activation of THP-1 cells, the phosphorylation of ERK1/2 (44/42 kDa), p38 MAP kinase (43 kDa), and JNK1/2 (46/54 kDa) in cell lysates was assessed by immunoblot analysis. A sample treated with 2 μg/ml LPS was used as a positive control of the phosphorylation of MAP kinases. As shown in Fig. 4, terbinafine treatment for 1 h significantly increased phosphorylation of ERK1/2 and p38 MAP kinase but not JNK1/2 in THP-1 cells. These results suggested that terbinafine activated ERK1/2 and p38 MAP kinase pathways in THP-1 cells. In addition, to confirm the effects of MAP kinase inhibitors on the phosphorylation of ERK1/2, p38 MAP kinase, and JNK1/2, THP-1 cells were pretreated for 1 h with various concentrations of MEK1/2 inhibitor U0126, p38 MAP kinase inhibitor SB203580, or JNK1/2 inhibitor SP600125 (English and Cobb 2002) before the treatment with 100 μM terbinafine. As shown in Fig. 4, the phosphorylation of ERK1/2 and p38 MAP kinase was significantly suppressed by the pretreatment with each specific inhibitor U0126 and SB203580, respectively.

Effects of MAP kinase inhibitors on the IL-8 and TNFα levels in THP-1 cells treated with antifungal drugs

To clarify which MAP kinase signaling pathway is mainly involved in the increase of IL-8 and TNFα, the effects of MAP kinase inhibitors on the increase of IL-8 and TNFα in THP-1 cells treated with terbinafine were investigated. As shown in Fig. 5, the increased mRNA expression levels and the release of IL-8 and TNFα by terbinafine treatment in THP-1 cells were significantly suppressed in a dose-dependent manner by the pretreatment with U0126, suggesting that an ERK1/2 pathway plays an important role in the increase of IL-8 and TNFα by terbinafine treatment. In contrast, the pretreatments with SB203580 and SP600125 did not suppress the increase of IL-8 and TNFα by terbinafine treatment in THP-1 cells. Interestingly, the increase of IL-

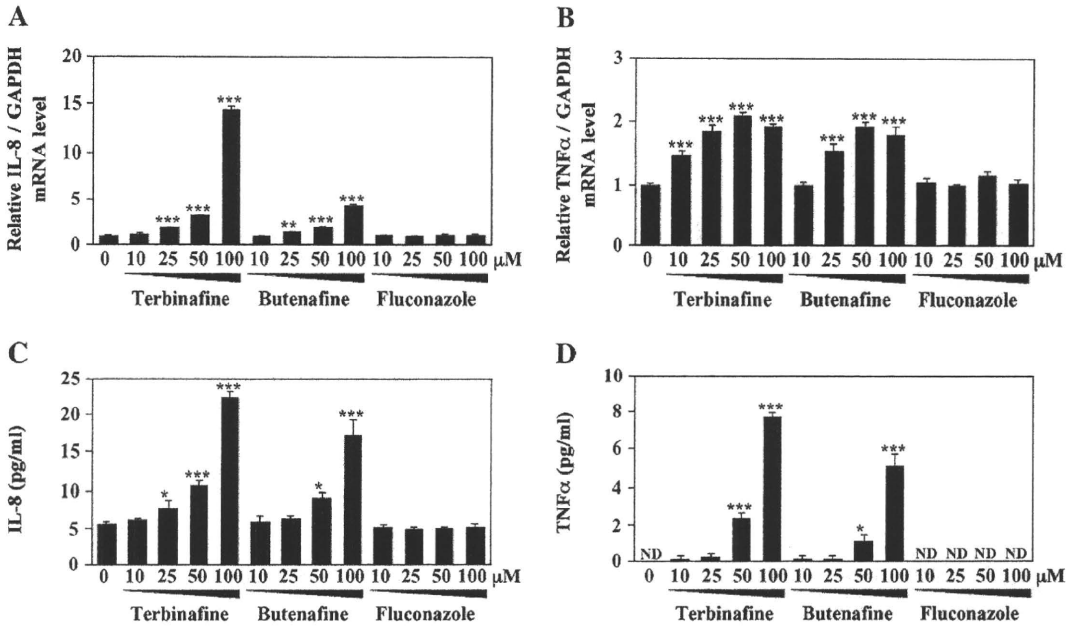

Fig. 3. Dose-dependent changes in the mRNA expression levels and the release of IL-8 and TNFα in THP-1 cells treated with antifungal drugs. THP-1 cells were treated with the indicated concentrations of the antifungal drugs. After incubation for 3 h, the mRNA expression levels of IL-8 (A) and TNFα (B) in THP-1 cells were measured by real-time RT-PCR analysis. After incubation for 6 h, the release of IL-8 (C) and TNFα (D) in supernatant was measured by ELISA. Data represents the mean ± SD of triplicate determinations. *, $P<0.05$; **, $P<0.01$; ***, $P<0.001$, compared with control (0.1% DMSO). ND, not detectable.

8 and TNFα was enhanced by the pretreatment with SB203580 at the higher concentration. The pretreatment with SB202190, a p38 MAP kinase inhibitor, also enhanced IL-8 and TNFα levels increased by terbinafine (data not shown).

We investigated the effects of MAP kinase inhibitors on the mRNA expression levels and the release of IL-8 and TNFα in THP-1 cells treated with other antifungal drugs. As shown in Fig. 6, with butenafine and terbinafine treatment, the pretreatment with U0126 remarkably

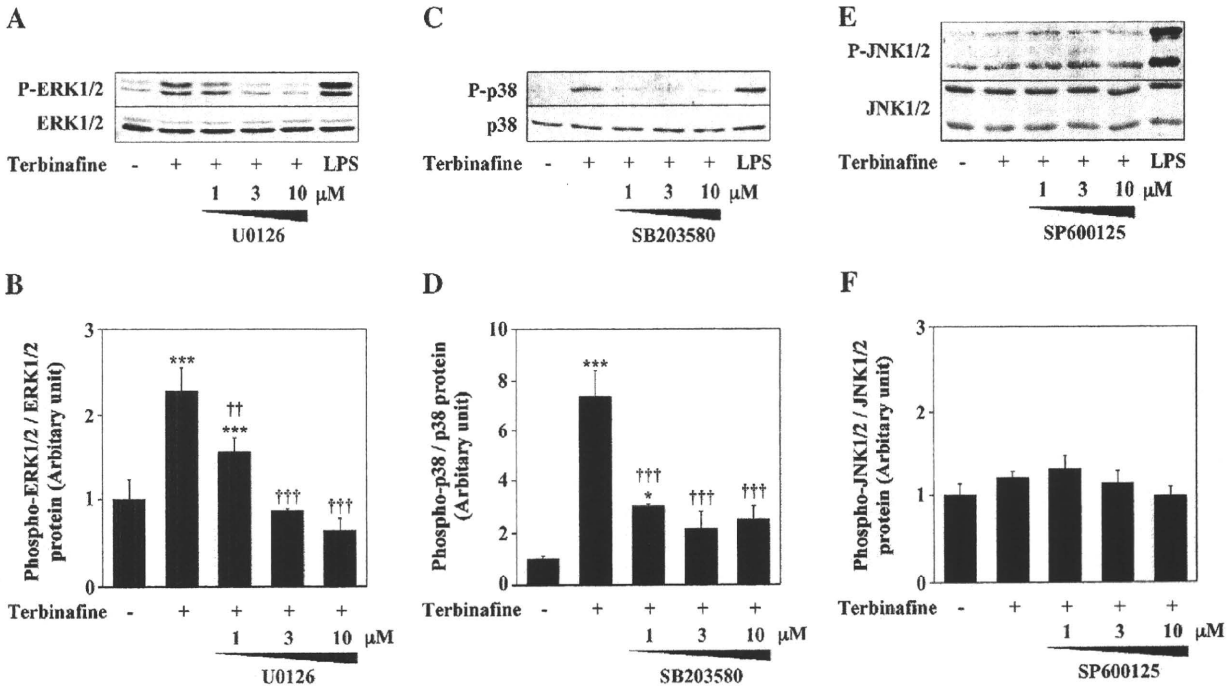

Fig. 4. Activation of MAP kinase signaling pathways in THP-1 cells treated with terbinafine. Immunoblot analyses of MAP kinase proteins in THP-1 cells were performed (A, C, and E) and quantified (B, D, and F). Before the treatment with 100 μM terbinafine, THP-1 cells were pretreated with the indicated concentrations of MAP kinase inhibitors for 1 h. U0126, SB203580, and, SP600125 were used as specific inhibitors of MEK1/2, p38 MAP kinase, and, JNK1/2, respectively. After 1 h-incubation with terbinafine, cell lysates were subjected to immunoblot analyses using antibodies of anti-Thr202/Tyr204 phosphorylated ERK1/2 (A and B), anti-Thr180/Tyr182 phosphorylated p38 MAP kinase (C and D), and anti-Thr183/Tyr185 phosphorylated JNK1/2 (E and F). The same sample treated with 2 μg/ml LPS was used as a positive control. Data represent the mean ± SD of triplicate determinations. *, $P<0.05$; ***, $P<0.001$, compared with control (0.1% DMSO). †, $P<0.01$; †††, $P<0.001$, compared with terbinafine only.

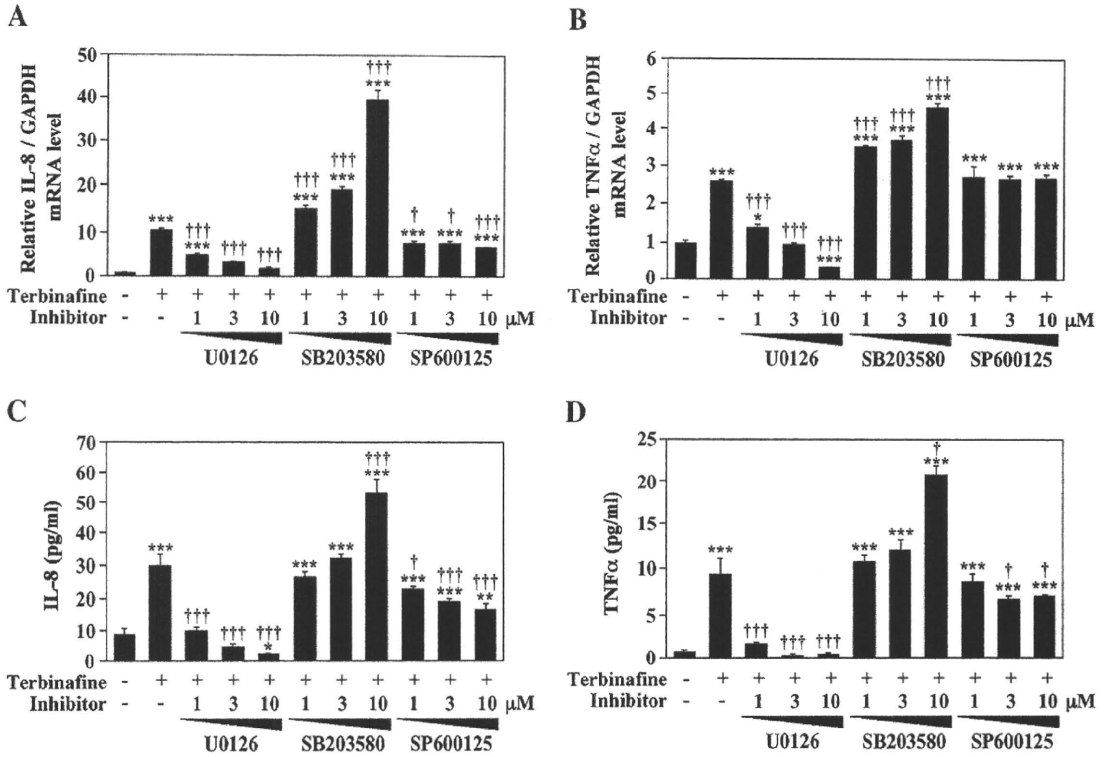

Fig. 5. Effects of MAP kinase inhibitors on the IL-8 and TNFα levels in THP-1 cells treated with terbinafine. Before the treatment with 100 μM terbinafine, THP-1 cells were pretreated with the indicated concentrations of MAP kinase inhibitors for 1 h. After 3 h-incubation with terbinafine, the mRNA expression levels of IL-8 (A) and TNFα (B) in THP-1 cells were measured by real-time RT-PCR analysis. After 6 h-incubation with terbinafine, the release of IL-8 (C) and TNFα (D) in supernatant was measured by ELISA. Data represent the mean ± SD of triplicate determinations. *, $P<0.05$; **, $P<0.01$; ***, $P<0.001$, compared with control (0.1% DMSO). †, $P<0.05$; †††, $P<0.001$, compared with terbinafine only.

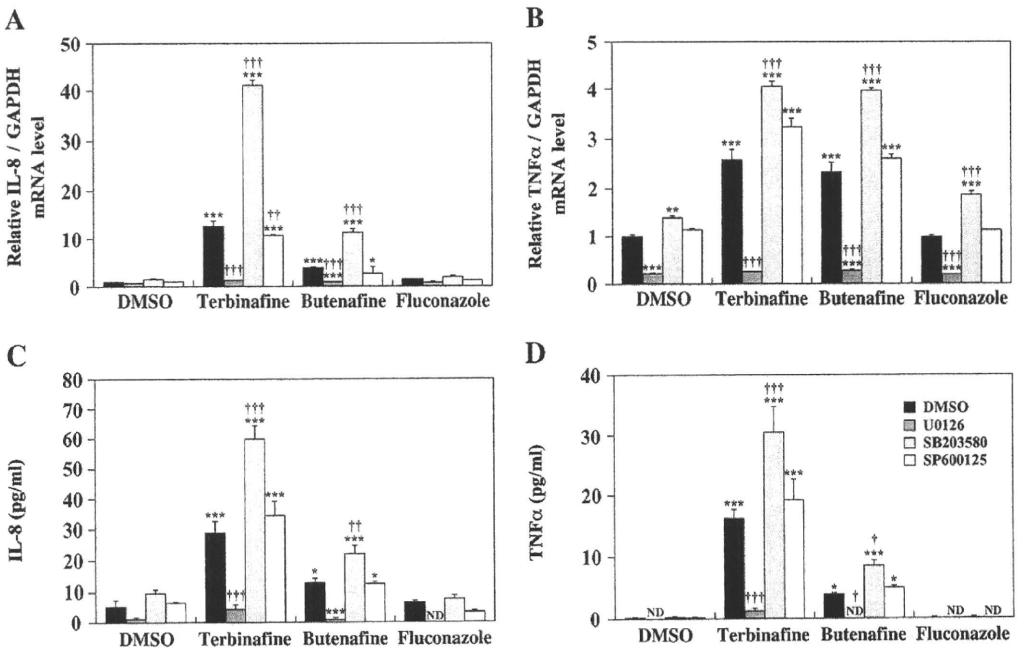

Fig. 6. Effects of MAP kinase inhibitors on the IL-8 and TNFα levels in THP-1 cells treated with antifungal drugs. Before the incubation with 100 μM antifungal drugs, THP-1 cells were pretreated with 10 μM MAP kinase inhibitors for 1 h. After 3 h-incubation with antifungal drugs, the mRNA expression levels of IL-8 (A) and TNFα (B) in THP-1 cells were measured by real-time RT-PCR analysis. After 6 h-incubation with antifungal drugs, the release of IL-8 (C) and TNFα (D) in the supernatant was measured by ELISA. Data represent the mean ± SD of triplicate determinations. *, $P<0.05$; **, $P<0.01$; ***, $P<0.001$, compared with control (0.1% DMSO). †, $P<0.05$; ††, $P<0.01$; †††, $P<0.001$, compared with an antifungal drug only. ND, not detectable.

suppressed the increase of IL-8 and TNFα in THP-1 cells and those of SB203580 and SP600125 had no suppressive effects. These results suggested that an ERK1/2 pathway also plays an important role in the increase of IL-8 and TNFα by butenafine treatment. In contrast, even for the control, the basal IL-8 and TNFα levels in THP-1 cells were suppressed by the pretreatment with U0126 and were increased by the pretreatment with SB203580, suggesting that the basal IL-8 and TNFα levels in THP-1 cells were affected by the MAP kinase inhibitors. In the case of fluconazole, a negative control, the effects of MAP kinase inhibitors on the IL-8 and TNFα levels in THP-1 cells were similar to those of the control (0.1% DMSO). In addition, the levels of ERK1/2 and phospho-ERK1/2 were measured by Western blotting in the presence of polymyxin B to check the potential contamination of LPS. The levels of phospho-ERK1/2 did not change by the addition of polymyxin B (data not shown).

Discussion

THP-1, HL-60, and KG-1 cells are classified as human monocytic cell lines and are useful for studying the differentiation and the activation of immune cells, such as monocytes, macrophages, and immature myelocytes. In the present study, by the treatment with the antifungal drugs terbinafine and butenafine, IL-8 and TNFα release from THP-1 and HL-60 cells was significantly increased compared with the control (Fig. 1A–D). This suggested that terbinafine and butenafine have the ability to stimulate the release of pro-inflammatory cytokines from monocytes, leading to the activation of the inflammatory reaction. In contrast, fluconazole, used as a negative control of terbinafine, had no effects on the cytokine release in THP-1 and HL-60 cells. This result was supported to the previous report that fluconazole had a lower risk of adverse events leading to treatment discontinuation compared with terbinafine (Chang et al. 2007). On the other hand, the cytokine release from KG-1 cells was not increased by the three antifungal drugs (Fig. 1E and F). However, it was reported that even potent inducers, such as LPS, did not increase the cytokine release from KG-1 cells (Teobald et al. 2008).

In our study, at least 25 to 50 μM terbinafine was required to significantly increase IL-8 and TNFα release from THP-1 cells (Fig. 3C and D). It has been reported that the peak plasma concentrations of 3.9 μM appeared at 2 h after a single oral administration of 250 mg terbinafine in humans (Kovarik et al. 1992). Median duration of terbinafine treatment was 12 weeks in 25091 patients of onychomycosis (Hall et al. 1997). Terbinatine was considered a possible or probable cause of 11 (0.04%) serious adverse events. Most likely, the terbinafine-associated hepatic injury in these patients was caused by an idiosyncratic rather than a direct hepatotoxic reaction (van't Wout et al. 1994, Hall et al. 1997). However, immune response-related adverse reactions in human are remained totally unknown. Further study will be necessary to clarify whether oral administration of terbinafine stimulates the release of pro-inflammatory cytokines and chemokines in vivo.

We found that terbinafine stimulates the release of pro-inflammatory cytokines and chemokines from human monocytic cells. The activation of inflammatory responses might be one of the mechanisms underlying the immune-mediated liver injury by terbinafine. On the other hand, the activation of human monocytic cells by other drugs, such as ximelagatran and troglitazone, has been reported recently, although these drugs have been already withdrawn from the market due to idiosyncratic hepatic injury. Ximelagatran increased the release of chemokines from THP-1 cells but the types of released cytokines and the time course of the cytokine release by the drug treatment were different from the case of terbinafine (Edling et al. 2008). In addition, troglitazone increased the mRNA expression levels of pro-inflammatory cytokines and chemokines in THP-1 cells, and some of them were affected by co-culture with human hepatoma Huh-7 cells (Edling et al. 2009). Therefore, measurement of the release of pro-inflammatory cytokines and chemokines from human monocytic cells may be useful to predict adverse reactions to drugs involving immune-mediated hepatic injury.

As reported by Iverson and Uetrecht (2001), the main reactive metabolite of tervinafine is an N-dealkylated product, 7,7-dimethylhept-2-ene-4-ynal (TBF-A). We could not obtain the TBF-A standard chemical in this study. Terbinafine is mainly metabolized by P450s, such as CYP3A4, CYP2C8 and CYP2C9, in the liver, and the TBF-A will covalently bind to hepatic protein and/or concentrate in the bile. Studies on metabolism-mediated immune responses will be our future subjects.

The activation of MAP kinases such as ERK1/2, p38 MAP kinase, and JNK1/2 is important in mediating many macrophage functions, including the activation of various transcription factors and the production of pro-inflammatory cytokines (Payne et al. 1991; DeFranco et al. 1998). In this study, terbinafine activated ERK1/2 and p38 MAP kinase pathways in THP-1 cells (Fig. 4). To determine the involvement of MAP kinases in transcriptional and translational regulation of terbinafine-induced IL-8 and TNFα release, blocking studies were performed using specific inhibitors of MAP kinases, including U0126, SB203580, and SP600125 (English and Cobb 2002). The mRNA expression levels and the release of IL-8 and TNFα increased by terbinafine were significantly suppressed by the pretreatment by U0126 but not by SB203580 (Fig. 5). These results suggested that an ERK pathway is mainly involved in IL-8 and TNFα release from THP-1 cells at the transcriptional level. In addition, the increase of IL-8 and TNFα in THP-1 cells was enhanced by the pretreatment with SB203580 (Fig. 5). It was demonstrated that SB203580 activated members of the ERK cascade, c-Raf, MEK, and ERK, in THP-1 cells. The activation of these kinases was sustained for at least 24 h after SB203580 treatment (Ishii et al. 2001; Numazawa et al. 2003). SB203580 activates the ERK cascades without transducing the signal into the nucleus. When cells are treated with stimulants, such as drugs, the impaired ERK signal transduction caused by the inhibitor may turn over and lead to synergistic enhancement of ERK cascade-dependent gene expression (Numazawa et al. 2003). Thus, care should be taken when applying P38 MAP kinase inhibitors to evaluate the inflammation reactions. THP-1 cells also have been reported to show enhance of ERK cascade by SB202190 (another p38 MAP kinase inhibitor), resulting in the increase of cell growth (Hirosawa et al. 2009). In this study, we confirmed that the effects of SB202190 in this study were the same as those of SB203580 (data not shown). Considering these reports, the increase of IL-8 and TNFα levels in THP-1 cells by SB203580 would be due to the activation of an ERK pathway.

Conclusion

In this study, we found that terbinafine stimulates human monocytic THP-1 cells resulting in IL-8 and TNFα release. It is suggested that terbinafine increases the pro-inflammatory cytokine release from monocytes and macrophages and activates the inflammatory response, which might result in immune-mediated hepatic injury. The findings presented here provide important insight concerning terbinafine-induced liver injury.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

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MOLECULAR TOXICOLOGY

Stimulation of pro-inflammatory responses by mebendazole in human monocytic THP-1 cells through an ERK signaling pathway

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Abstract Oral helminthic mebendazole (MBZ) has been reported to cause liver injury with inflammatory responses. However, the underlying mechanism remains unknown. To examine the inflammatory reactions, we investigated whether MBZ and other helminthic drugs increase the release of pro-inflammatory cytokines and chemokines using human monocytic cells. The release of interleukin (IL)-8 and tumor necrosis factor (TNF) α from human monocytic THP-1 cells was significantly increased by treatment with MBZ, albendazole (ABZ), fenbendazole (FBZ), or oxibendazole (OBZ), but not by albendazole sulfoxide or praziquantel, suggesting that MBZ and structurally similar drugs can stimulate monocytes and increase the release of pro-inflammatory cytokines. MBZ also significantly increased the phosphorylation of extracellular signal-regulated kinase (ERK) 1/2 and c-Jun N-terminal kinase (JNK) 1/2 in THP-1 cells. Pretreatment with the MAP kinase/ERK kinase 1/2 inhibitor U0126 significantly suppressed the increase of IL-8 and TNFα levels by MBZ, ABZ, FBZ, or OBZ treatment in THP-1 cells, but the p38 mitogen-activated protein kinase inhibitor SB203580 or JNK1/2 inhibitor SP600125 did not. These results suggested that an ERK1/2 pathway plays an important role in the release of IL-8 and TNFα in THP-1 cells treated with MBZ and structurally similar drugs. In conclusion, the release of inflammatory mediators by MBZ might be one of the mechanisms underlying immune-mediated liver injury. This in vitro method may be useful to predict adverse inflammatory reactions that lead to hepatotoxicity.

Keywords Mebendazole · THP-1 cell · Hepatotoxicity · IL-8 · TNFα

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Introduction

Drug-induced liver injury is the most frequent reason for the withdrawal of an approved drug from the market and for failures in drug development in pharmaceutical companies. Because of significant adverse drug reactions associated with hepatotoxicity, several drugs have been removed from the pharmaceutical market (Holt and Ju, 2006). Inflammatory stress might be caused by xenobiotics or drugs leading to idiosyncratic adverse drug reactions. The sporadic occurrence of acute inflammatory episodes could explain the onset of some idiosyncratic reactions during clinical drug therapy (Ganey et al. 2004; Roth et al. 2003; Tafazoli et al. 2005). Inflammatory reactions in liver are induced by the activation of immune cells, such as monocytes, macrophages and Kupffer cells. Activated monocytes and macrophages release large amounts of pro-inflammatory cytokines and chemokines, including interleukin (IL)-1, tumor necrosis factor (TNF) α, and IL-8. TNFα triggers the release of a cascade of other cytokines and recruits activated immune cells, including lymphocytes and macrophages (Bradham et al. 1998). IL-8 exhibits multiple effects on neutrophils, including the induction of lysosomal enzyme release, the increase in the expression of adhesion molecules, and rapid infiltration (Leonard et al. 1991; Baggiolini et al. 1994). In several rodent models, it was shown that the production of TNFα and neurtophil infiltration in liver play a critical role in immune-mediated

liver injury by drugs such as acetaminophen, non-steroidal anti-inflammatory drugs, and antibiotics (Jaeschke 2005; Deng et al. 2009).

Recently, it has been reported that human monocytic cell lines were useful to examine the inflammatory responses mediated by drugs withdrawn from the market. In human monocytic THP-1 cells, the mRNA expression levels and/or the release of pro-inflammatory cytokines and chemokines were increased by the treatment with troglitazone or ximelagatran (Edling et al. 2008, 2009).

Many benzimidazoles have been launched on the market and used in clinical drug therapy. Mebendazole (MBZ) and other structurally related drugs are used for the therapy of various helminthic infections as well as for the treatment of hydatid disease and alveolar echinococcosis (Ammann and Eckert 1996). However, MBZ has been reported to cause hepatic injury. Bekhti and Pirotte (1987) described a case of acute hepatocellular injury in a patient treated with MBZ 600 mg/day for echinococcosis. Colle et al. (1999) reported a case of granulomatous hepatitis with eosinophilia after the administration of MBZ. Seitz et al. (1983) and Junge and Mohr (1983) reported MBZ-induced hepatic injury, and the liver biopsy of the patient revealed hepatocytic necrosis and portal inflammation with eosinophils during long-term (49–60 days) and high-dose (2–3.5 g/day) therapy with MBZ. Recently, MBZ has been carefully used in clinical drug therapy, thus case reports of severe hepatic injury are very rare (Bagheri et al. 2004). Chen et al. (2003) reported that MBZ is associated with Steven-Johnson syndrome (SJS)/toxic epidermal necrolysis (TEN), suggesting the involvement of immune-mediated factors. However, the mechanism underlying the hepatic injury by MBZ remains to be clarified.

Considering the case reports of hepatic injury by MBZ, we hypothesized that benzimidazoles stimulate inflammatory responses that may result in immune-mediated hepatic injury. The purpose of this study is to investigate whether benzimidazoles stimulate the release of pro-inflammatory cytokines and chemokines from human monocytic cells and to clarify the involvement of cell signaling in the release of pro-inflammatory cytokines and chemokines from THP-1 cells.

Materials and methods

Materials

ABZ, fenbendazole (FBZ), MBZ, oxibendazole (OBZ), and praziquantel (PZQ) were purchased from Sigma–Aldrich (St. Louis, MO). Albendazole sulfoxide (ABZSO) was purchased from Toronto Reserch Chemicals (Ontario, Canada). Lipopolysaccharide (LPS) was also from Sigma–Aldrich (St. Louis, MO). Primers were commercially synthesized at Hokkaido System Sciences (Sapporo, Japan). The monoclonal antibodies of anti-Thr202/Tyr204 phosphorylated extracellular signal-regulated kinase (ERK) 1/2, anti-Thr180/Tyr182 phosphorylated p38 mitogen-activated protein (MAP) kinase, and anti-Thr183/Tyr185 phosphorylated c-Jun N-terminal kinase (JNK) 1/2 were purchased from Cell Signaling Technology (Beverly, MA). The monoclonal antibodies against ERK1/2 and JNK1/2 and the polyclonal antibody against p38 MAP kinase were also from Cell Signaling Technology. All other reagents were of the highest grade commercially available.

Cell culture

The human monocytic leukemia cell line THP-1 was obtained from Riken Gene Bank (Tsukuba, Japan). HL-60 and KG-1 cells were obtained from American Type Culture Collection (Manassas, VA). THP-1 cells were cultured in RPMI 1640 medium (Nissui Pharmaceutical, Tokyo, Japan) supplemented with 10% fetal bovine serum (FBS; Invitrogen, Carlsbad, CA). HL-60 and KG-1 cells were cultured in RPMI 1640 medium supplemented with 20% FBS. These cells were maintained at 37°C under an atmosphere of 5% CO_2.

Drug treatment of human monocytic cell lines

THP-1, HL-60, and KG-1 cells were seeded at a density of 1×10^6 cells/well in 24-well plates with the medium containing the indicated concentration of helminthic drugs, and then incubated at 37°C. The final concentration of dimethyl sulfoxide (DMSO) in medium was 0.1%. In experiments using MAP kinase inhibitors, cells were pretreated with MAP kinase/ERK kinase (MEK) 1/2 inhibitor U0126 (Wako Pure Chemical Industries), p38 MAP kinase inhibitor SB203580 (Wako Pure Chemical Industries), or JNK1/2 inhibitor SP600125 (Calbiochem, Los Angeles, CA) for 1 h, and then treated with the helminthic drugs. Supernatants were separated from cell cultures by centrifugation and stored at −70°C until assayed. For immunoblot analysis, the cells were suspended in TGE buffer (10 mM Tris–HCl, 20% glycerol, 1 mM EDTA, pH 7.4) and disrupted by freeze-thawing three times.

Enzyme-linked immunosorbent assay (ELISA)

The pro-inflammatory cytokine TNFα and the chemokine IL-8 in cell supernatants were measured by Human TNFα and IL-8 ELISA Ready-SET-GO!™ (eBioscience, San Diego, CA) according to the manufacturer's instructions.

Real-time reverse transcription-polymerase chain reaction (RT–PCR)

Total RNA was extracted from THP-1 cells with RNAiso (Takara Bio, Shiga, Japan) according to the protocol supplied by the manufacturer. Reverse transcription was performed with ReverTra Ace (Toyobo, Tokyo, Japan) according to the manufacturer's protocol. For quantitative analysis, real-time RT–PCR was performed for inflammatory cytokine mRNA using an MX3000P real-time PCR system (Stratagene, La Jolla, CA). The primers used in this study were human IL-8 (forward: 5′-CAGCCTTCCTG ATTTCTCTGCAG-3′, reverse: 5′-AGACAGAGCTCTC TTCCATCAG-3′) and human TNFα (forward: 5′-CTT CTGCCTGCTGCACTTTGGAG-3′, reverse: 5′-GGCTAC AGGCTTGTCACTCGG-3′). An 1 μL portion of the reverse-transcribed mixture was added to a PCR mixture containing 10 pmol of each primer and 10 μL of SYBR Premix ExTaq solution in a final volume of 20 μL. After an initial denaturation at 95°C for 30 s, the amplification was performed by denaturation at 94°C for 20 s and annealing and extension at 64°C for 20 s for 45 cycles. The IL-8 and TNFα mRNA levels were normalized with human glyceraldehyde 3-phosphate dehydrogenase (GAPDH) mRNA (forward: 5′-CCATGAGAAGTATGACAACAGCC-3′, 5′-TG GGTGGCAGTGATGGCATGGA-3′).

Immunoblot analysis

SDS–polyacrylamide gel electrophoresis and immunoblot analysis were performed according to Laemmli (1970). Cell sources (25 μg) were separated on 10% polyacrylamide gels and electrotransferred onto polyvinylidene difluoride membrane, Immobilon-P (Millipore Corporation, Billerica, MA). The membranes were probed with the monoclonal antibodies of anti-Thr202/Tyr204 phosphorylated ERK1/2, anti-Thr180/Tyr182 phosphorylated p38 MAP kinase, and anti-Thr183/Tyr185 phosphorylated JNK1/2, and the corresponding fluorescent dye-conjugated second antibody and an Odyssey Infrared Imaging system (LI-COR Biosciences, Lincoln, NE) were used for the detection. The relative expression level was quantified using ImageQuant TL Image Analysis software (GE Healthcare, Little Chalfont, Buckinghamshire, UK).

Cell viability assay

For the cell viability assay, THP-1 cells were seeded at a density of 1×10^5 cells/well in 96-well plates with the medium containing the indicated concentration of the halminthic drug, and then incubated at 37°C. The final concentration of DMSO in medium was 0.1%. After 6 or 24 h incubation, cell viability was evaluated by 3-(4,5-dimetylthiazol-2-yl)-2, 5-diphenyl tetrazolium bromide (MTT) activities using a CellTiter-Blue Cell Viability Assay (Promega, Medison, WI) according to the manufacturer's protocol. The fluorescence of the generated resorufin was detected fluorometrically (excitation: 338 nm, emission: 458 nm) by using a luminometer (1420 ARVO MX, Wallac, Turku, Finland).

Statistical analysis

Data are expressed as mean ± SD of triplicate determinations. Comparison of 2 groups was made with an unpaired, two-tailed student's *t*-test. Comparison of multiple groups was made with ANOVA followed by Dunnett or Tukey test. A value of $P < 0.05$ was considered statistically significant.

Results

Comparative effect of helminthic drugs on human monocytic cell lines

To investigate whether the helminthic drugs increased the release of IL-8 and TNFα from human monocytic cells, cells were treated with 10 μM of the helminthic drugs for 6 h and then the release of IL-8 and TNFα in the cell supernatants was measured by ELISA. The helminthic drugs used in our study are shown in Fig. 1. ABZSO was the active metabolite of ABZ (Gottschall et al. 1990). FBZ and OBZ were used as drugs structurally similar to MBZ and ABZ, although they have never been administered in humans. PZQ was used because no case of symptomatic hepatic injury has ever been seen so far. The IL-8 and TNFα release from THP-1 cells was significantly increased by treatment with ABZ, FBZ, MBZ, or OBZ but not by ABZSO or PZQ compared with control (0.1% DMSO) (Fig. 2a, b). These results suggested that MBZ and structurally similar drugs have the ability to increase the release of pro-inflammatory cytokines and chemokines from monocytes that activate the inflammatory responses. In addition, MBZ and OBZ also significantly increased the IL-8 release from HL-60 and KG-1 cells and FBZ significantly increased the IL-8 release from KG-1 cells (Fig. 2c, e). In contrast, the TNFα release from HL-60 and KG-1 cells was not increased by these helminthic drugs (Fig. 2d, f). For the subsequent analyses, THP-1 cells were used because they showed the highest sensitivity for the release.

Time-dependent changes in the mRNA expression levels and the release of IL-8 and TNFα in THP-1 cells treated with MBZ

We next investigated the time-dependent changes of the IL-8 and TNFα levels in THP-1 cells. By the treatment

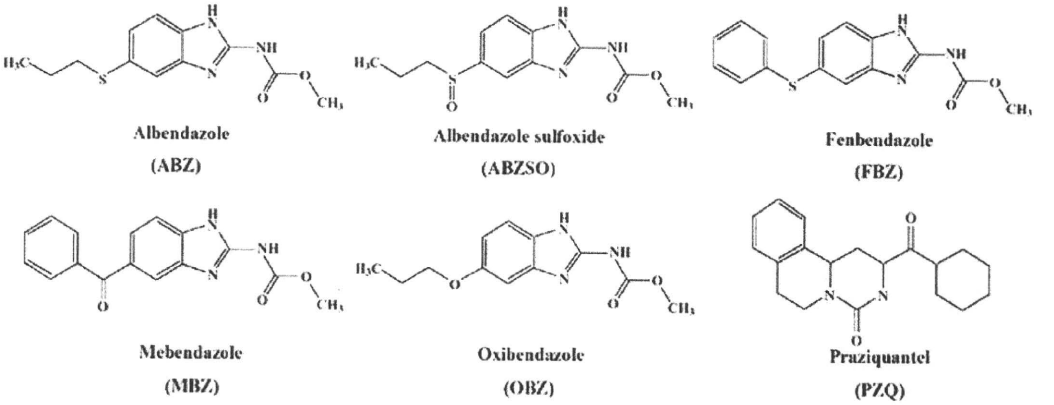

Fig. 1 Chemical structures of the helminthic drugs used in the present study

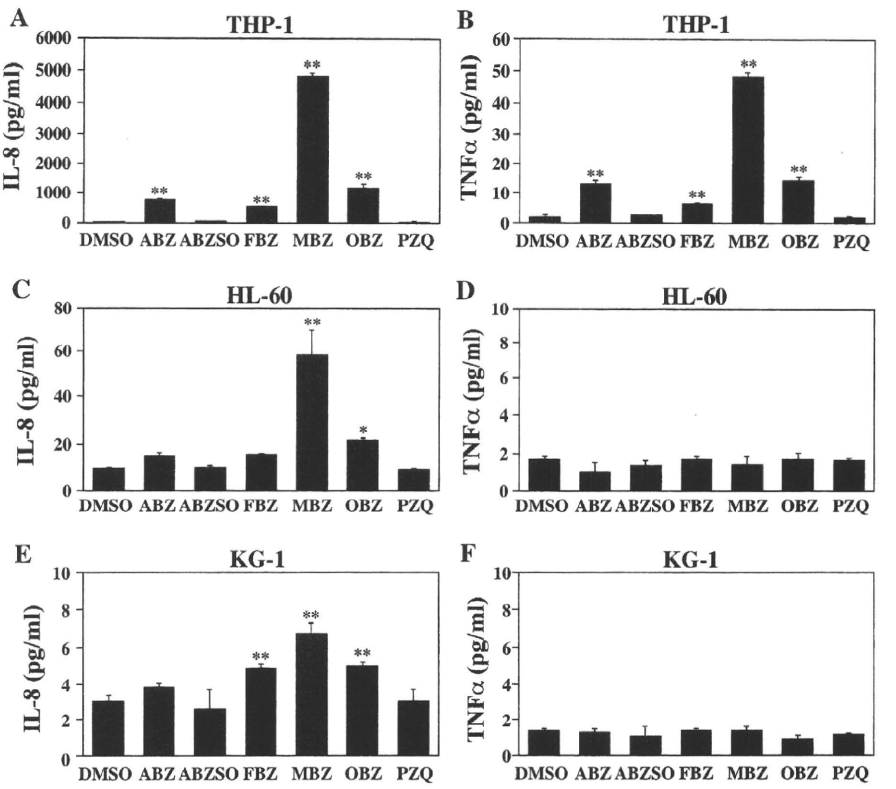

Fig. 2 Effects of helminthic drugs on the release of IL-8 and TNFα from human monocytic cell lines. Human monocytic cell lines including THP-1 (**a** and **b**), HL-60 (**c** and **d**), and KG-1 (**e** and **f**) were treated with 10 μM of the helminthic drugs for 6 h. The release of IL-8 (**a**, **c**, and **e**) and TNFα (**b**, **d**, and **f**) in the supernatant was measured by ELISA. Data represent the mean ± SD of triplicate determinations. $*P < 0.05$; $**P < 0.01$, compared with control (0.1% DMSO)

with 10 μM MBZ, the mRNA expression levels and the release of IL-8 and TNFα in THP-1 cells were significantly increased for 1.5–24 h compared with control (Fig. 3). The mRNA expression levels of IL-8 were mostly increased at 6 h incubation but the increase of IL-8 release was in a time-dependent manner (Fig. 3a, c). The highest increase of the mRNA expression levels and the release of TNFα appeared at 4.5 and 6 h-incubation, respectively (Fig. 3b, d). Therefore, an incubation time of 6 h was selected for further assay to measure the release of IL-8 and TNFα. To investigate whether there were cytotoxic effects on THP-1 cells caused by the leakage of intercellular cytokines and chemokines, a cell viability assay for THP-1 cells was performed. At 24 h-incubation, these helminthic drugs had no cytotoxic effects on THP-1 cells (data not shown).

Dose-dependent changes in the release of IL-8 and TNFα from THP-1 cells treated with helminthic drugs

To investigate whether the helminthic drugs at a lower concentration could also lead to IL-8 and TNFα release in

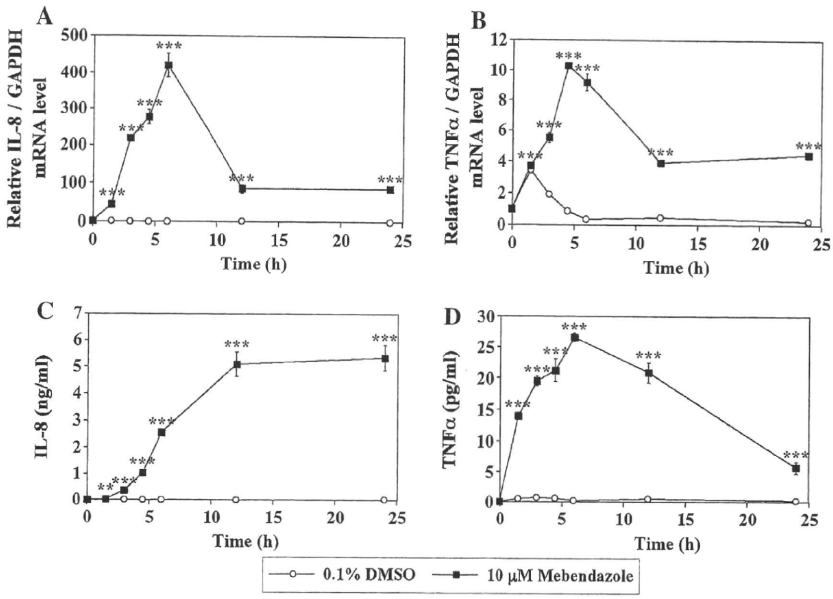

Fig. 3 Time-dependent changes in the mRNA expression levels and the release of IL-8 and TNFα in THP-1 cells treated with MBZ. THP-1 cells were treated with 10 μM MBZ for various durations. The mRNA expression levels of IL-8 (**a**) and TNFα (**b**) in THP-1 cells were measured by real-time RT–PCR analysis. The release of IL-8 (**c**) and TNFα (**d**) in the supernatant was measured by ELISA. Data represent the mean ± SD of triplicate determinations. $^{**}P < 0.01$; $^{***}P < 0.001$, compared with control (0.1% DMSO) of each time point

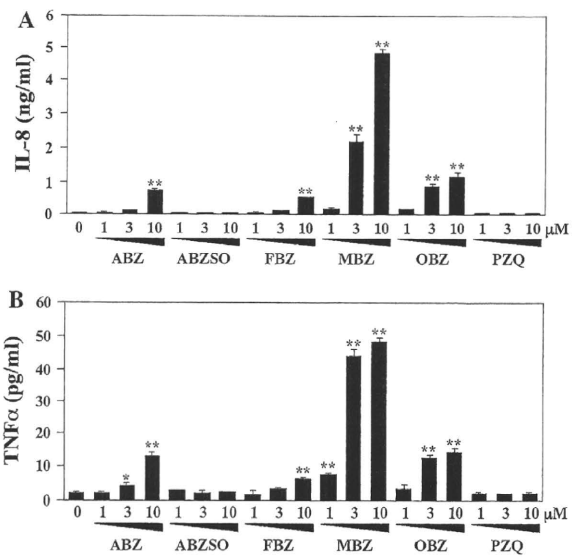

Fig. 4 Dose-dependent changes in the release of IL-8 and TNFα from THP-1 cells treated with helminthic drugs. THP-1 cells were treated with the indicated concentrations of the helminthic drugs. After incubation for 6 h, the release of IL-8 (**a**) and TNFα (**b**) in the supernatant was measured by ELISA. Data represent the mean ± SD of triplicate determinations. $^{*}P < 0.05$; $^{**}P < 0.01$, compared with control (0.1% DMSO)

THP-1 cells, THP-1 cells were treated with helminthic drugs at the indicated concentration for 6 h and then the release of IL-8 and TNFα was measured. As shown in Fig. 4, ABZ, FBZ, MBZ, and OBZ increased the IL-8 and TNFα levels in a dose-dependent manner. In addition, at least 3 μM MBZ was required to increase the release of IL-8 in THP-1 cells. In contrast, the TNFα release was significantly increased at 1 μM MBZ.

Activation of MAP kinase signaling pathway in THP-1 cells treated with MBZ

MAP kinases, including ERK1/2, p38 MAP kinase, and JNK1/2, are major components for many intracellular signaling pathways. The phosphorylation of MAP kinases, which is required for the enzyme activity, activates signaling cascades, the down stream effects of which have been linked to the regulation of the inflammatory response (DeFranco et al. 1998). To clarify the role of MAP kinase signaling pathway in the activation of THP-1 cells, the phosphorylation of ERK1/2 (44/42 kDa), p38 MAP kinase (43 kDa), and JNK1/2 (46/54 kDa) in cell lysates was assessed by immunoblot analysis. A sample treated with 2 μg/ml LPS was used as a positive control for the phosphorylation of MAP kinases. As shown in Fig. 5, MBZ treatment for 1 h significantly increased the phosphorylation of ERK1/2 and JNK1/2 but not p38 MAP kinase in THP-1 cells. These results suggested that MBZ activated ERK1/2 and JNK1/2 pathways in THP-1 cells. In addition, to confirm the effects of MAP kinase inhibitors on the phosphorylation of ERK1/2, p38 MAP kinase, and JNK1/2, THP-1 cells were pretreated for 1 h with various concentrations of MEK1/2 inhibitor U0126, p38 MAP kinase inhibitor SB203580, or JNK1/2 inhibitor SP600125 (English and Cobb, 2002) before the treatment with 10 μM MBZ. As a result, the phosphorylation of ERK1/2 was significantly suppressed by the pretreatment with the specific inhibitor U0126 but not that of JNK1/2 (Fig. 5).