from TNF-$\alpha^{-/-}$ mice and those from WT mice. We have previously demonstrated that LPS (ultra-pure grade) or P3C (a synthetic TLR2 ligand) alone induced negligible production of IL-10 in BMDCs, while the simultaneous treatment with these ligands results in the vigorous production of IL-10 [34]. Thus, DCs were stimulated with LPS plus P3C to evaluate the ability for the IL-10 production.

BMDCs from WT or TNF-$\alpha^{-/-}$ mice were treated with TLR-L (1 μg/ml LPS plus 100 ng/ml P3C) for 24 h, and levels of IL-10, IL-12 p40, and TNF-α in the culture supernatants were determined by ELISA (Fig. 1A). Consistent with our previous study, TLR-L induced substantial level of IL-10 production by WT DCs. Notably, IL-10 production by TNF-$\alpha^{-/-}$ DCs stimulated with TLR-L was significantly suppressed as compared to that by WT DCs (Fig. 1A, left). In contrast, both WT DCs and TNF-$\alpha^{-/-}$ DCs vigorously produced IL-12 p40 in response to TLR-L and no significant difference was detected in this cytokine production between these types of DCs (Fig. 1A, center). WT DCs markedly produced TNF-α in response to TLR-L, while TNF-$\alpha^{-/-}$ DCs showed no TNF-α production irrespective of the TLR stimulation (Fig. 1A, right). We also analyzed IL-12 p70 production by WT and TNF-$\alpha^{-/-}$ DCs upon TLR stimulation. However, no IL-12 p70 production was detected in any cultures tested (<30 pg/ml, data not shown). No significant difference was detected in the cell viability between WT and TNF-$\alpha^{-/-}$ DCs after 24 h of culture (data not shown).

3.2. The effect of exogenous TNF-α in IL-10 production by DCs upon TLR stimulation

Above findings (Fig. 1A) suggest that DC production of TNF-α lead to the IL-10 production by these DCs in response to TLR ligands. We next examined whether addition of exogenous TNF-α during the TLR stimulation recovered the impaired ability of TNF-$\alpha^{-/-}$ DCs to produce IL-10.

BMDCs from WT or TNF-$\alpha^{-/-}$ mice were stimulated with TLR-L in the presence or absence of TNF-α 100 ng/ml for 24 h, and levels of IL-10 and IL-12 p40 in the culture supernatants were determined by ELISA (Fig. 1B). TNF-α alone never induced IL-10 production by both types of DCs (Fig. 1B left). Again, TLR-L induced vigorous production of IL-10 by WT DCs but not by TNF-$\alpha^{-/-}$ DCs. Addition of TNF-α restored the TLR-mediated IL-10 production by TNF-$\alpha^{-/-}$ DCs to the level of that by WT DCs. In contrast, TNF-α showed no significant effect on TLR-L mediated IL-10 production by WT DCs. Thus, TNF-α produced by WT DCs may be necessary to induce maximal IL-10 production by the DCs in response to TLR-L.

TLR-L markedly induced IL-12 p40 production by WT DCs and TNF-$\alpha^{-/-}$ DCs, and no significant difference was detected in the level of IL-12 p40 production between these types of DCs (Fig. 1B, middle). Exogenous TNF-α never affected the TLR-mediated IL-12 p40 production by WT DCs. Although TNF-α slightly increased the TLR-mediated IL-12 p40 production by TNF-$\alpha^{-/-}$ DCs, the effect was statistically not significant.

3.3. Cell surface expressions of maturation markers on TLR-stimulated DCs

We next analyzed the cell surface expression of several maturation markers on WT and TNF-$\alpha^{-/-}$ DCs. WT and TNF-$\alpha^{-/-}$ DCs were treated with TLR-L for 24 h and the cell surface expressions of CD40, CD86, and I-A^b were determined by flow cytometry (Fig. 2). After the TLR stimulation, WT and TNF-$\alpha^{-/-}$ DCs exhibited mature phenotype, high expression of CD86, CD40, and I-A^b. No significant difference was detected in the expression level of these maturation markers between WT and TNF-$\alpha^{-/-}$ DCs, although the proportion of CD86 positive cells was increased in TNF-$\alpha^{-/-}$ DCs compared to WT DCs (Fig. 2). Addition of TNF-α during the TLR stimulation showed no effect on the level of CD86, CD40, and I-A^b expressions in both types of DCs (data not shown). From these results, TNF-α may be dispensable for the phenotypic maturation of DCs in response to TLR stimulation.

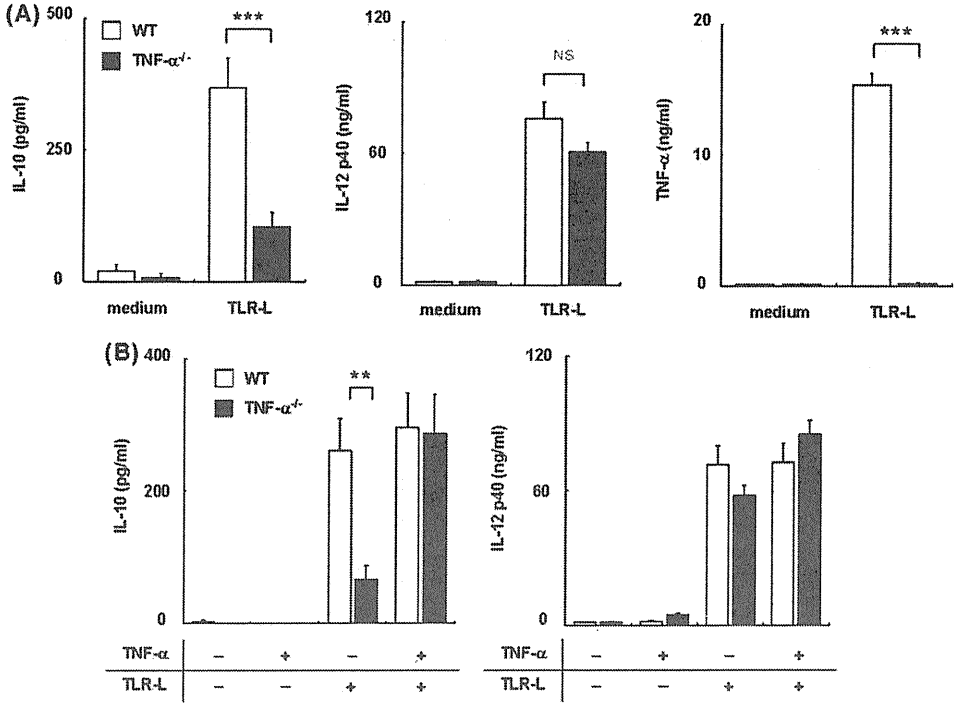

Fig. 1. Cytokine production by WT and TNF-$\alpha^{-/-}$ DCs upon TLR stimulation. (A) BMDCs from WT or TNF-$\alpha^{-/-}$ mice were stimulated with 1 μg/ml LPS plus 100 ng/ml P3C (TLR-L) for 24 h. (B) BMDCs from WT or TNF-$\alpha^{-/-}$ mice were stimulated with TLR-L in the presence or absence of TNF-α (100 ng/ml) for 24 h. The amount of cytokines in the culture supernatants was measured by ELISA. Each column represents the mean ± SE of 11 (A) or nine (B) independent experiments. Statistical significance was calculated by Student's *t*-test (**$p < 0.01$; ***$p < 0.001$; NS, not significant).

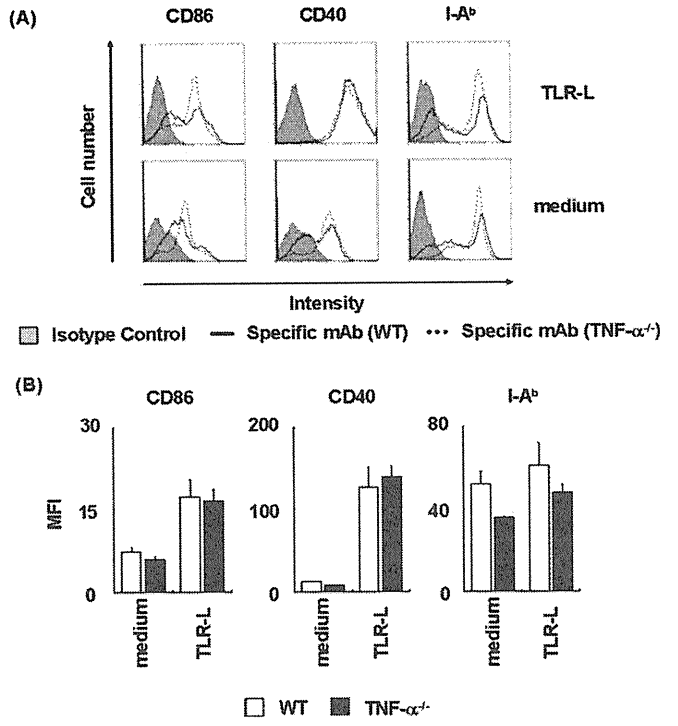

Fig. 2. Expression of surface molecules on WT and TNF-$\alpha^{-/-}$ DCs upon TLR stimulation. BMDCs from WT or TNF-$\alpha^{-/-}$ mice were stimulated with TLR-L for 24 h. Expressions of CD86, CD40, and I-A^b were analyzed by flow cytometry. (A) Representative histogram of the each molecule on WT and TNF-$\alpha^{-/-}$ DCs. (B) Each column represents the mean ± SE of three independent experiments. MFI, mean fluorescence intensity.

3.4. The effect of TNF-α on activation of Akt and MAPKs in DCs upon TLR stimulation

PI3K/Akt and MAPK pathways are responsible for production of various cytokines following TLR stimulation [36]. It has been reported that TNF-α is capable of activating these intracellular pathways [37,38]. TNF-α promoted IL-10 production in TNF-$\alpha^{-/-}$ DCs but not in WT DCs (Fig. 1). To analyze the molecular mechanism responsible for the TNF-α-mediated promotion of IL-10 production seen in TNF-$\alpha^{-/-}$ DCs, we examined the effect of TNF-α on activation of Akt and MAPKs (ERK1/2, p38 MAPK, and JNK1/2) in the TNF-$\alpha^{-/-}$ DCs upon TLR stimulation.

BMDCs from TNF-$\alpha^{-/-}$ mice were stimulated with TNF-α and/or TLR-L for indicated time periods, and intracellular protein levels of phospho-Akt (pAkt), phospho-ERK1/2 (pERK1/2), phospho-p38 MAPK (pp38 MAPK), and phospho-JNK1/2 (pJNK1/2) were determined by immunoblotting (Fig. 3).

TNF-α markedly increased the level of pERK1/2 in TNF-$\alpha^{-/-}$ DCs at 7 min, while showed only slight effect at 15–30 min (Fig. 3A and B). On the other hand, TLR-L induced slight phosphorylation of ERK1/2 in TNF-$\alpha^{-/-}$ DCs at 7 min, but markedly increased the level at 15 min. The effect was decreased at 30 min. The pERK1/2 in TNF-$\alpha^{-/-}$ DCs at 7 min after treatment with both TLR-L and TNF-α showed same level as that in TNF-$\alpha^{-/-}$ DCs treated with TNF-α alone. Thus, the ERK1/2 activation at 7 min seemed to be largely dependent on TNF-α. At 15 and 30 min no difference was detected in the pERK1/2 level between TLR-L-treated and TLR-L plus TNF-α-treated TNF-$\alpha^{-/-}$ DCs.

The levels of pp38 MAPK and pAkt in TNF-$\alpha^{-/-}$ DCs were markedly increased at 7 min, and then gradually reduced at 15–30 min after TNF-α stimulation (Fig. 3A, C, and E). In contrast, TLR-L increased the levels of these molecules slightly at 7 min, but markedly at 15 and 30 min. Treatment of these DCs with both TNF-α and TLR-L considerably increased the levels of pp38 MAPK and pAkt at 7 min as compared with those in DCs treated with TLR-L alone. Thus, exogenous TNF-α was responsible for an early (7 min) activation of p38 MAPK and Akt.

The level of pJNK1/2 in TNF-$\alpha^{-/-}$ DCs was modestly increased at 7 to 15 min and then decreased at 30 min after TNF-α stimulation (Fig. 3A and D). In contrast, TLR-L increased the level of pJNK1/2 modestly at 7 min and markedly at 15 and 30 min. Exogenous TNF-α, however, showed no significant effect on the TLR-L-mediated phosphorylation of pJNK1/2 at all time periods tested.

3.5. The effect of ERK1/2, p38 MAPK, or PI3K inhibition on IL-10 and IL-12 p40 production by TNF-$\alpha^{-/-}$ DCs upon TNF-α plus TLR-L stimulation

ERK1/2, p38 MAPK, and Akt activation in TNF-$\alpha^{-/-}$ DCs upon TLR stimulation was significantly enhanced by addition of TNF-α at an early time point (Fig. 3). We thus examined the role of ERK1/2, p38 MAPK, and Akt in IL-10 production by TNF-$\alpha^{-/-}$ DCs upon stimulation with TLR-L plus TNF-α using U0126, a specific inhibitor of MEK-ERK pathway, SB203580, a specific inhibitor of p38 MAPK, and LY294002, a specific inhibitor of PI3K.

TNF-$\alpha^{-/-}$ DCs were pretreated with U0126, SB203530, LY294002, or vehicle alone (0.1% DMSO) for 1 h and then stimulated with TNF-α and/or TLR-L for 24 h in the presence of each inhibitor. The amount of IL-10 and IL-12 p40 in the culture supernatant was quantitated by ELISA (Fig. 4). Again, stimulation with TLR-L plus TNF-α induced vigorous production of IL-10 and IL-12 p40. U0126 modestly inhibited the IL-10 production and increased the IL-12 p40 production by TNF-$\alpha^{-/-}$ DCs. Notably, both SB203580 and LY294002 markedly inhibited the IL-10 production by TNF-$\alpha^{-/-}$ DCs upon TLR-L plus TNF-α stimulation, while showing no significant effect on the IL-12 p40 production. Thus, the TNF-α-mediated early activation of ERK1/2, p38 MAPK, and PI3K/Akt may be responsible for the promotion of IL-10 production by TNF-$\alpha^{-/-}$ DCs upon TLR stimulation.

4. Discussion

TLR ligands induce vigorous production of pro-inflammatory cytokines by macrophages and DCs. These TLR-mediated innate immune responses are crucial to initiates acquired immunity. TLR ligands also induce production of IL-10, an anti-inflammatory cytokine, which may suppress undesirable and/or exceeded inflammatory responses. Although transcription factors and signal transduction pathways for production of pro-inflammatory cytokines have been well identified, those of anti-inflammatory cytokines such as IL-10 have been elusive. In the present study, we examined the role of TNF-α in DC production of IL-10 upon TLR4 and TLR2 stimulation (TLR4,2 stimulation) and pursued mechanism underlying the TNF-α-mediated regulation of IL-10 production. We demonstrated herein that TNF-α was involved in DC production of IL-10 but not IL-12 p40 upon TLR4,2 stimulation. It was also shown that the TNF-α-mediated activation of MAPK and PI3K/Akt pathways may be responsible for the TNF-α-mediated regulation of IL-10 production.

First, we compared productions of IL-10 and IL-12 p40 between WT and TNF-$\alpha^{-/-}$ DCs in response to TLR-L (LPS plus P3C). Upon TLR4,2 stimulation, TNF-$\alpha^{-/-}$ DCs produced lower level of IL-10 than those by WT DCs. In contrast, no significant differences were noted in the TLR-mediated IL-12 p40 production between these types of DCs. Addition of TNF-α during the TLR stimulation recovered the impaired ability of TNF-$\alpha^{-/-}$ DCs for IL-10 production, although TNF-α alone exerted negligible effect on the IL-10

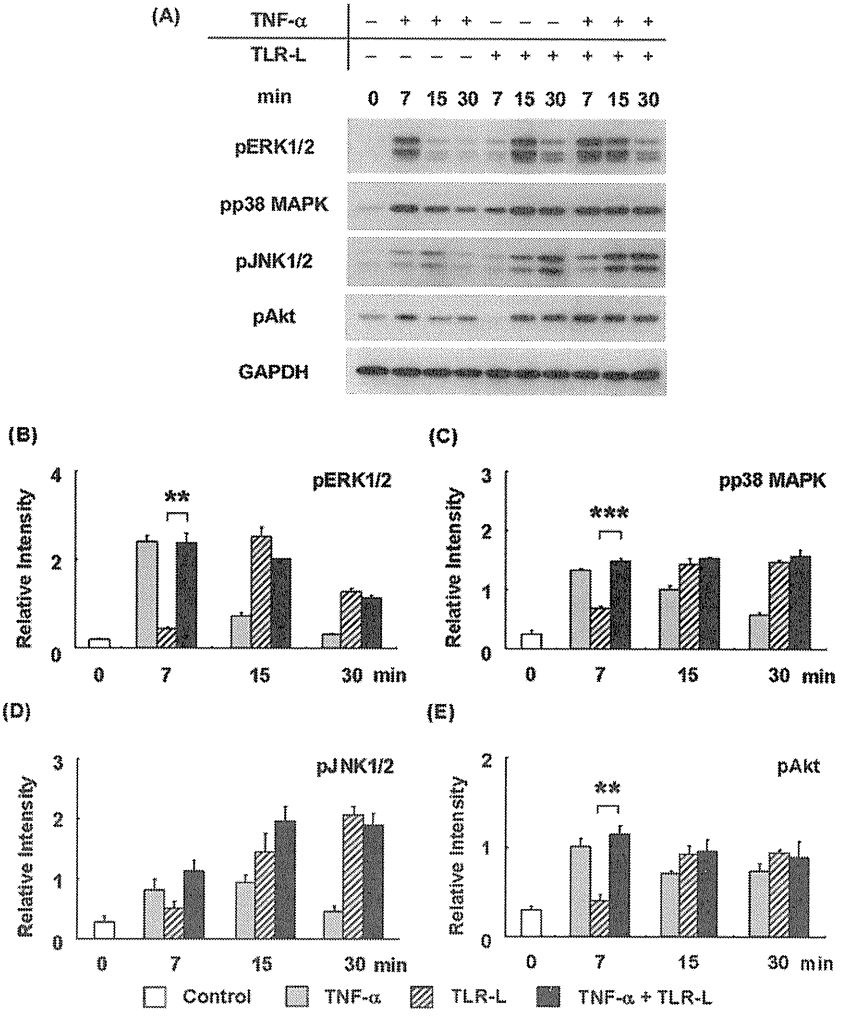

Fig. 3. Activation of ERK1/2, p38 MAPK, JNK1/2, and Akt in TNF-$\alpha^{-/-}$ DCs upon stimulation with TNF-α and TLR-L. BMDCs were treated with TNF-α (100 ng/ml) and/or TLR-L for 7, 15, or 30 min, and whole cell lysates were prepared. Levels of phospho-ERK1/2 (pERK1/2), phospho-p38 MAPK (pp38 MAPK), phospho-JNK1/2 (pJNK1/2), and phospho-Akt (pAkt) in the cell lysates were determined by immunoblotting. GAPDH level was determined as an internal control for each sample. (A) Representative immunoblot is shown. (B) The relative intensity of the specific band is shown. Each column represents the mean ± SE of three independent experiments. Statistical significance was calculated by Student's *t*-test (**$p < 0.01$; ***$p < 0.001$).

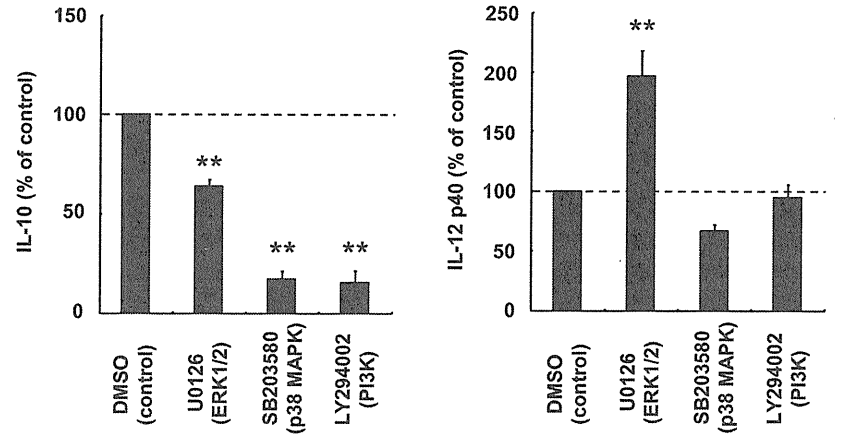

Fig. 4. The effect of ERK1/2, p38 MAPK, or PI3K inhibition on IL-10 and IL-12 production by TNF-$\alpha^{-/-}$ DCs stimulated with TNF-α plus TLR-L. BMDCs were pretreated with 10 μM U0126 (a MEK1/2 inhibitor), 30 μM SB203530 (a p38 MAPK inhibitor), 10 μM LY294002 (a PI3K inhibitor), or vehicle alone (0.1% DMSO) for 1 h and then stimulated with TNF-α (100 ng/ml) plus TLR-L for 24 h in the presence of each inhibitor. The amount of IL-10 and IL-12 in the culture supernatants was measured by ELISA. Each column represents the mean ± SE of five independent experiments. Statistical significance was calculated by Dunnett's test (**$p < 0.01$).

production. It seems that TNF-α is involved in the enhancement of TLR-mediated production of IL-10, while this cytokine-mediated signaling alone is insufficient to induce a substantial level of IL-10 production by DCs.

We also analyzed the expression of maturation markers, CD86, CD40, and I-A^b, on WT and TNF-$\alpha^{-/-}$ DCs upon TLR4,2 stimulation. No significant difference was detected in the level of mean fluorescence intensity of these expressions between WT and TNF-$\alpha^{-/-}$ DCs. However, the proportion of CD86 positive cells was increased in TNF-$\alpha^{-/-}$ DCs compared to WT DCs. Thus, TNF-α may play a role in the regulation of CD86 expression on DCs.

MAPKs and PI3K/Akt are involved in activation of various transcription factors that promote the IL-10 synthesis in macrophages/monocytes and DCs upon TLR stimulation [36,39,40]. Recently, we demonstrated that MAPK and PI3K/Akt pathways were responsible for the promotion of IL-10 production by BMDCs upon TLR stimulation [34]. It has been reported that TNF-α also activates MAPK and PI3K signaling pathways via TNFR1 [1,2,5–7,37,38]. To explore the mechanism underlying the TNF-α-mediated regulation of IL-10 production by DCs, we analyzed effect of TNF-α on the activity of MAPKs and PI3K in TNF-$\alpha^{-/-}$ DCs upon TLR stimulation. TNF-α markedly enhanced activities of ERK, p38 MAPK, and Akt in TNF-$\alpha^{-/-}$ DCs upon TLR4,2 stimulation at an early phase (at 7 min). Blocking the activation of ERK, p38 MAPK, or PI3K significantly inhibited IL-10 production by TNF-$\alpha^{-/-}$ DCs upon stimulation with TNF-α plus TLR-L. Thus, TNF-α appears to facilitate the TLR-mediated IL-10 production through the activation of ERK, p38 MAPK, and PI3K/Akt pathways in DCs.

It has been reported that p38 MAPK and Akt are activated via RIP1, while JNK was activated via TRAF2 in TNF-α-mediated cellular responses [6]. Thus, we speculate that RIP1 is crucial for the TNF-α-mediated effect on IL-10 production in TNF-$\alpha^{-/-}$ DCs. On the other hand, Vivarelli et al. showed that RIP1 is also involved in TLR4-mediated activation of PI3K-Akt pathway [41]. Thus, TNF-α- and TLR-mediated signaling pathways appear to share the RIP1. Consequently, we could not clarify whether the decrease in IL-10 production in response to MAPK and PI3K inhibitors (Fig. 4) is due to specific inhibition of the TNF-α-mediated signaling. Nonetheless, we believe that our present findings are important to understand a regulation system of IL-10 in DCs in response to TLR stimulation.

Recently, several studies also showed that MAPK- or PI3K-mediated signal is involved in IL-10 production and autocrine IL-10 negatively regulated IL-12 production upon TLR stimulation in macrophages and DCs [40–43]. On the other hand, we have previously reported that LY294002 (a PI3K specific inhibitor) decreases IL-10 production, but shows no effect on IL-12 p40 production upon TLR-stimulation in BMDCs [34]. At present, decrease in IL-10 production by inhibiting PI3K activity showed no significant effect on IL-12 p40 production by TNF-$\alpha^{-/-}$ DCs stimulated with TLR-L plus TNF-α (Fig. 4). The discrepancy between above studies in the autocrine inhibitory effect of IL-10 on IL-12 p40 production may be attributable to the differences in cell types and/or culture conditions such as cell density and stimuli.

We performed the blocking study using anti-TNF-α mAb (clone: MP6-XT22), anti-TNFR1 mAb (clone: 55R-170), and anti-TNFR2 mAb (clone: TR75-54.7). TNF-α-induced increase in CD86 expression on BC1 cells [35] was completely inhibited by treatment with the anti-TNFR1 mAb or the anti-TNF-α mAb (data not shown). However, these mAbs failed to exert significant effects on the IL-10 production by DCs upon the TLR stimulation (data not shown). As a possible explanation for the discrepant results, attenuated TNF-α signal in the presence of the mAb might be enough to enhance the TLR-mediated IL-10 production. Alternatively, a constitutive weak TNF-α signaling before the antibody treatment might be sufficient to facilitate IL-10 production upon TLR stimulation.

We also analyzed production of IL-23, a member of the IL-12 cytokine family, in WT and TNF-$\alpha^{-/-}$ DCs upon TLR stimulation. TLR ligands induced substantial production of IL-23 in WT and TNF-$\alpha^{-/-}$ DCs. The IL-23 production by TNF-$\alpha^{-/-}$ DCs was higher than that by WT DCs (data not shown). In contrast, the IL-12 p40 production upon the TLR stimulation slightly decreased in TNF-$\alpha^{-/-}$ DCs compared to WT DCs (Fig. 1). Thus, the level of IL-12 p40 production did not reflect to that of IL-23 production in our culture system. It has been shown that IL-12 p40 expression was not parallel to IL-23 p19 expression in DCs [44]. It seems to us that this point should be carefully analyzed in future studies.

We demonstrated herein that TNF-α signaling to promote DC production of anti-inflammatory cytokine, IL-10, but not inflammatory cytokine, IL-12, upon TLR stimulation. Thus, TNF-α may be a key molecule to regulate the balance between anti-inflammatory versus inflammatory cytokines in DCs. However, the precise mechanism underlying the TNF-α-mediated regulation of IL-10 production remains to be unclear. Thus, we would like to identify the molecular mechanisms responsible for the TNF-α-mediated regulation system in the future studies. Since the balance between IL-10 and IL-12 production by DCs is crucial to induce appropriate immune responses, further elucidation of the TNF-α-mediated immune regulation may lead to the development of clinical applications for the treatment of various immune disorders.

Acknowledgments

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ORIGINAL RESEARCH

Non-phosphorylated FTY720 Induces Apoptosis of Human Microglia by Activating SREBP2

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Abstract A synthetic analog of sphingosine named FTY720 (Fingolimod), phosphorylated by sphingosine kinase-2, interacts with sphingosine-1-phosphate (S1P) receptors expressed on various cells. FTY720 suppresses the disease activity of multiple sclerosis (MS) chiefly by inhibiting S1P-dependent egress of autoreactive T lymphocytes from secondary lymphoid organs, and possibly by exerting anti-inflammatory and neuroprotective effects directly on brain cells. However, at present, biological effects of FTY720 on human microglia are largely unknown. We studied FTY720-mediated apoptosis of a human microglia cell line HMO6. The exposure of HMO6 cells to non-phosphorylated FTY720 (FTY720-non-P) induced apoptosis in a dose-dependent manner with IC50 of 10.6 ± 2.0 μM, accompanied by the cleavage of caspase-7 and caspase-3 but not of caspase-9. The apoptosis was inhibited by Z-DQMD-FMK, a caspase-3 inhibitor, but not by Pertussis toxin, a Gi protein inhibitor, suramin, a S1P3/S1P5 inhibitor, or W123, a S1P1 competitive antagonist, although HMO6 expressed S1P1, S1P2, and S1P3. Furthermore, both phosphorylated FTY720 (FTY720-P) and SEW2871, S1P1 selective agonists, did not induce apoptosis of HMO6. Genome-wide gene expression profiling and molecular network analysis indicated activation of transcriptional regulation by sterol regulatory element-binding protein (SREBP) in FTY720-non-P-treated HMO6 cells. Western blot verified activation of SREBP2 in these cells, and apoptosis was enhanced by pretreatment with simvastatin, an activator of SREBP2, and by overexpression of the N-terminal fragment of SREBP2. These observations suggest that FTY720-non-P-induced apoptosis of HMO6 human microglia is independent of S1P receptor binding, and positively regulated by the SREBP2-dependent proapoptotic signaling pathway.

Keywords Apoptosis · Cholesterol · FTY720 · Microglia · S1P1 · SREBP2

Abbreviations

CNS	Central nervous system
DAVID	Database for Annotation, Visualization, and Integrated Discovery
EDG	Endothelial differentiation gene
FTY720-non-P	Non-phosphorylated form of FTY720
FTY720-P	Phosphorylated form of FTY720
G3PDH	Glyceraldehyde-3-phosphate dehydrogenase
GPCR	G-protein-coupled receptor
INSIG1	Insulin-induced gene 1
LDLR	Low density lipoprotein receptor

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MS	Multiple sclerosis
OPC	Oligodendroglial progenitor cell
S1P	Sphingosine-1-phosphate
SPHK2	Sphingosine kinase-2
SREBP	Sterol regulatory element-binding protein
PARP	Poly-ADP-ribose-polymerase
PTX	Pertussis toxin

Introduction

FTY720 (Fingolimod) is a synthetic analog of sphingosine generated by chemical modification of myriocin, a natural product of the fungus *Isaria sinclairii*. FTY720, phosphorylated by endogenous sphingosine kinase-2 (SPHK2), is converted into the biologically active form FTY720-P that binds to sphingosine-1-phosphate (S1P) receptors expressed on various cells (Brinkmann et al. 2010). S1P receptors belong to the endothelial differentiation gene (EDG) receptor family of G-protein-coupled receptors (GPCRs). FTY720-P interacts with S1P1, S1P3, S1P4, and S1P5 but not with S1P2. S1P1, S1P2, and S1P3 are distributed widely in the immune system, cardiovascular system, and the central nervous system (CNS), and S1P4 expression is more restricted to the lung, spleen, and thymus, while S1P5 is located chiefly on the skin, spleen, and brain. FTY720-P not only serves as an agonist for S1P receptors, but also acts as a functional antagonist for S1P1 by downregulating the receptor expression via internalization, ubiquitination, and proteasomal degradation (Mullershausen et al. 2009). The latter induces unresponsiveness to endogenous S1P.

Recent clinical trials indicate that FTY720 has promising therapeutic effects on multiple sclerosis (MS), a human demyelinating disease affecting exclusively the CNS white matter (Brinkmann et al. 2010). Oral administration of FTY720 reduces the number of gadolinium-enhanced lesions on MRI and decreased annual relapse rate in the patients with relapsing-remitting MS (Kappos et al. 2006). Consequently, US Food and Drug Administration (FDA) approved FTY720 as the first oral medication for MS in September 2010. FTY720-mediated immunomodulatory effects on the disease activity of MS are chiefly attributable to inhibition of S1P-dependent egress of autoreactive T lymphocytes from secondary lymphoid organs (Brinkmann et al. 2010).

Increasing evidence indicates that FTY720, capable of passing the blood–brain barrier due to its lipophilicity, exerts anti-inflammatory and neuroprotective effects within the CNS by interacting with a battery of S1P receptors expressed on neural cells (Dev et al. 2008). Reactive astrocytes in active MS lesions show a robust increase in S1P1 and S1P3 expression, where FTY720-P inhibits production of proinflammatory cytokines from astrocytes (Van Doorn et al. 2010). FTY720-P persistently downregulates S1P1 expression on astrocytes, and thereby attenuates the disease activity of experimental autoimmune encephalomyelitis (EAE), an animal model of MS (Choi et al. 2011). FTY720-P induces rapid phosphorylation of ERK1/2 and activates the PI3-kinase/Akt pathway in rat oligodendrocyte progenitor cells (OPCs), and subsequently protects OPCs from apoptosis caused by proinflammatory mediators (Coelho et al. 2007). FTY720-P promotes process extension of human OPCs and enhances their survival (Miron et al. 2008).

Microglia, acting as antigen-presenting cells and proinflammatory effector cells in the CNS, play a central role in development of demyelinating lesions in MS (Jack et al. 2005). Therefore, it is possible that FTY720 acts directly on microglia at the site of inflammation in MS brains. S1P1-expressing cells positive for CD68, a marker of microglia/macrophages, are accumulated in MS lesions (Van Doorn et al. 2010). Rat microglial cells express mainly S1P1 and S1P3 (Dev et al. 2008). In mouse organotypic cerebellar cultures affected with lysolecithin-induced demyelination, FTY720-P induces proliferation of microglia (Miron et al. 2010), while FTY720 reduces the accumulation of reactive microglia/macrophages in the lesions of traumatic brain injury (Zhang et al. 2007). FTY720 reduces the lesion size of cerebral infarct in mice with middle cerebral artery (MCA) occlusion and improves neurological deficits, accompanied by a decrease in the number of activated microglia/macrophages and apoptotic neurons (Wei et al. 2011). FTY720-P does not affect the global cytokine production by cultured human microglia (Durafourt et al. 2011). However, at present, immunomodulatory effects of FTY720 on human microglia remain largely unknown. The aim of the present study is to investigate biological effects of FTY720 on a human microglial cell line HMO6.

Methods

Human Microglia Cell Line HMO6

The HMO6 cell line was established by immortalizing cultured microglia isolated from human embryonic telencephalon tissues with a retroviral vector PASK1.2 encoding v-myc oncogene (Nagai et al. 2001). HMO6 cells express the markers of the microglia/macrophage lineage cells, including CD11b, CD68, CD86, HLA-ABC, HLA-DR, and ricinus communis agglutinin lectin-1 (RCA), serving as a model of human microglia both in

vitro and in vivo (Narantuya et al. 2010). The cells were maintained in Dulbecco's Modified Eagle's medium (DMEM; Invitrogen, Carlsbad, CA, USA) supplemented with 10% fetal bovine serum (FBS), 100 U/ml penicillin and 100 μg/ml streptomycin (feeding medium). Human neural and non-neural cell lines other than HMO6 were described elsewhere. LDH release from cultured cells was assessed by using a LDH cytotoxicity detection kit (Takara Bio, Shiga, Japan).

Chemicals

Non-phosphorylated FTY720 (FTY720-non-P; Calbiochem, Darmstadt, Germany) and *(S)*-FTY720 phosphate (FTY720-P; Echelon Biosciences, Salt Lake City, UT, USA) were usually dissolved in dimethyl sulfoxide (DMSO), providing the stock solution at the concentration of 10 mM. For negative controls, the inclusion of DMSO at the concentration of 0.1% v/v (1:1000 dilution) was applied. We found that the solvent alone never induces apoptosis of HMO6 at any incubation time. Sphingosine 1-phosphate (S1P) was obtained form Sigma, St. Louis, MO, USA. SEW2871, a selective S1P1 agonist and W123, a competitive S1P1 antagonist were obtained from Cayman Chemical, Ann Arbor, MI, USA. Suramin, a S1P3/S1P5 inhibitor, Z-DQMD-FMK, a caspase-3 inhibitor, and simvastatin, a HMG-CoA reductase inhibitor were obtained from Calbiochem. Pertussis toxin (PTX), a Gi protein inhibitor, was obtained form Seikagaku Biobusiness, Tokyo, Japan.

RT-PCR Analysis

Total cellular RNA was extracted by using TRIZOL (Invitrogen). RNA treated with DNase I was processed for cDNA synthesis using oligo$(dT)_{20}$ primers and SuperScript II reverse transcriptase (Invitrogen). Then, cDNA was amplified by PCR using HotStar Taq DNA polymerase (Qiagen, Valencia, CA, USA) and a panel of sense and antisense primer sets following: 5′aagcgctctttacttggtcgc tgg3′ and 5′tgatctccacccttcccagtgcat3′ for an 189 bp product of S1P1; 5′ccacagacctgggtgatgttg3′ and 5′tccccttaaatgctgcc tgcc3′ for a 200 bp product of S1P2; 5′actttgggctccagagtct ttc3′ and 5′cattctacgcacaggaaatgtagtg3′ for an 193 bp product of S1P3; 5′gttgcagtcttgcgtgtggatgg3′ and 5′ggtgac catgggaagcccatttg3′ for an 183 bp product of S1P4; 5′aggaatggcatgcgcaaag3′ and 5′cttctatggctcccacctcactc3′ for a 200 bp product of S1P5; and 5′ccatgttcgtcatgggtgtgaacca3′ and 5′gccagtagaggcagggatgatgttc3′ for a 251 bp product of the glyceraldehyde-3-phosphate dehydrogenase (G3PDH) gene.

For quantitative real-time RT-PCR (qPCR) analysis, cDNA was amplified by PCR in LightCycler ST300 (Roche Diagnostics, Tokyo, Japan) using SYBR Green I and a panel of sense and antisense primer sets with the following: 5′tgatcgttccagaagtggccttgg3′ and 5′aactgtcgtc ctatgttccccacc3′ for an 186 bp product of insulin-induced gene 1 (INSIG1) and 5′ctgggggtcttccttctatggaag3′ and 5′cacgtcatcctccagactgaccat3′ for an 168 bp product of low density lipoprotein receptor (LDLR). The expression levels of target genes were standardized against the levels of G3PDH, an internal control, detected in corresponding cDNA samples. All the assays were performed in triplicate.

Microarray Analysis

For microarray analysis, total cellular RNA was isolated by using the TRIZOL Plus RNA Purification kit (Invitrogen). The quality of total RNA was evaluated on Agilent 2100 Bioanalyzer (Agilent Technologies, Palo Alto, CA, USA). One hundred ng of total RNA was processed for cRNA synthesis, fragmentation, and terminal labeling with the GeneChip Whole Transcript Sense Target Labeling and Control Reagents (Affymetrix, Santa Clara, CA, USA). Then, it was processed for hybridization at 45°C for 17 h with Human Gene 1.0 ST Array that contains 28,869 genes (Affymetrix). The arrays were washed in the GeneChip Fluidic Station 450 (Affymetrix), and scanned by the GeneChip Scanner 3000 7G (Affymetrix). The raw data were expressed as CEL files and normalized by the robust multiarray average (RMA) method with the Expression Console software version 1.1 (Affymetrix). The annotation was studied by searching genes on the Database for Annotation, Visualization, and Integrated Discovery (DAVID) (david.abcc.ncifcrf.gov) (da Huang et al. 2009).

Molecular Network Analysis

KeyMolnet is a comprehensive knowledgebase that contains the contents on 123,000 relationships among human genes and proteins, small molecules, diseases, pathways and drugs, regularly updated, and curated by expert biologists (Satoh et al. 2009). By importing the list of Entrez Gene IDs derived from microarray data, KeyMolnet automatically provides corresponding molecules as a node on networks. Among various network-searching algorithms, the "neighboring" network-search algorithm selected one or more molecules as starting points to generate the network of all kinds of molecular interactions around starting molecules, including direct activation/inactivation, transcriptional activation/repression, and the complex formation within the designated number of paths from starting points. The generated network was compared side by side with 430 human canonical pathways of the KeyMolnet library. The algorithm counting the number of overlapping molecular relations between the extracted network and the

canonical pathway makes it possible to identify the canonical pathway showing the most significant contribution to the extracted network. The significance in the similarity between both is scored following the formula, where O = the number of overlapping molecular relations between the extracted network and the canonical pathway, V = the number of molecular relations located in the extracted network, C = the number of molecular relations located in the canonical pathway, T = the number of total molecular relations, and the X = the sigma variable that defines coincidence.

$$\text{Score} = -\log_2(\text{Score(p)}) \quad \text{Score (p)} = \sum_{x=O}^{Min(C,V)} f(x)$$

$$f(x) = {}_{C}C_{x} \cdot {}_{T-C}C_{V-x} / {}_{T}C_{V}$$

Transient Expression of SREBP2

To transiently overexpress sterol regulatory element-binding protein-2 (SREBP2), the gene encoding the N-terminal fragment of SREBP2 spanning amino acid residues 1–484 was amplified by PCR using PfuTurbo DNA polymerase (Stratagene, La Jolla, CA) and a sense and antisense primer set of 5′gcgatggacgacagcggcgagctg3′ and 5′tcacagaagaatccg tgagcggtc3′, and cloned in the expression vector pEF6 (Invitrogen). The vector was transfected into HMO6 cells by X-tremeGENE HP DNA transfection reagent (Roche Diagnostics). At 24 h after transfection, the cells were processed for western blot analysis. For the control, V5-tagged LacZ cloned in the pEF6 vector was transfected into sister cultures.

Western Blot Analysis

To prepare total protein extract, the cells were homogenized in RIPA buffer supplemented with a cocktail of protease inhibitors (Sigma). The protein extract was centrifuged at 12,000 rpm for 5 min at room temperature (RT). The protein concentration was determined by a Bradford assay kit (BioRad Hercules, CA, USA). The mixture of the supernatant and a 2× Lammeli loading buffer was boiled and separated on SDS-PAGE gels ranging from 8 to 12%. After gel electrophoresis, the protein was transferred onto nitrocellulose membranes, and immunolabeled at RT overnight with rabbit anti-poly-ADP-ribose-polymerase (PARP) antibody (#11835238001; Roche Diagnostics), rabbit anti-cleaved caspase-3 (Asp175) antibody (#9661; Cell Signaling Technology, Danvers, MA, USA), mouse anti-caspase-7 antibody (#9494; Cell Signaling Technology), rabbit anti-caspase-9 antibody (#9502; Cell Signaling Technology), rabbit anti-S1P1 antibody (sc-25489, EDG-1, H-60; Santa Cruz Biotechnology, Santa Cruz, CA), or goat anti-SREBP2 antibody (sc-8151, N-19; Santa Cruz Biotechnology). Then, the membranes were incubated at RT for 60 min with HRP-conjugated anti-mouse IgG, anti-rabbit IgG, or anti-goat IgG (Santa Cruz Biotechnology). The specific reaction was visualized by exposing the membranes to a chemiluminescent substrate (Thermo Scientific, Rockford, IL, USA).

In some experiments, the antibodies were stripped by incubating the membranes at 50°C for 30 min in stripping buffer, composed of 62.5 mM Tris-HCl, pH 6.7, 2% SDS, and 100 mM 2-mercaptoethanol. Then, the membranes were processed for relabeling with goat anti-heat shock protein HSP60 antibody (sc-1052, N-20; Santa Cruz Biotechnology) used for an internal control of protein loading, followed by incubation with HRP-conjugated anti-goat IgG.

Results

S1P Receptor Expression on Human Microglia Cell Line HMO6

The expression of five S1P receptor mRNAs in a panel of human neural cells and tissues was determined by RT-PCR. All the cells and tissues examined, including the human cerebrum (CBR), fetal astrocytes (AS), neuronal progenitor (NP) cells, NTera2 teratocarcinoma-derived neurons, SK-N-SH neuroblastoma, IMR-32 neuroblastoma, U-373MG astroglioma, and the microglia cell line HMO6, expressed varying levels of S1P1, S1P2, and S1P3 mRNAs, except for Y79 retinoblastoma that did not express S1P1 (Fig. 1a–c, lanes 2–10). In contrast, the levels of G3PDH, a housekeeping gene, were almost constant in the cells and tissues examined (Fig. 1f, lanes 2–10). Although discernible levels of S1P4 and S1P5 mRNAs were identified in the human cerebrum (CBR), both of these mRNAs were almost undetectable in HMO6 (Fig. 1d, e, lanes 2 and 10). No products were amplified when the reverse transcription step is omitted (Fig. 1a–f, lane 1). We verified S1P1 protein expression in HMO6 by western blot (not shown).

Non-Phosphorylated FTY720 Induced Apoptosis of HMO6

A 6 h-exposure of non-phosphorylated FTY720 (FTY720-non-P) induced LDH release from HMO6 cells and cell death in a dose-dependent manner with IC50 of 10.6 ± 2.0 μM (Fig. 2a, c). It is worthy to note that the concentration of FTY720-non-P at lower than 5 μM was completely ineffective in inducing cell death of HMO6 (Fig. 2a). Generally, LDH release did not discriminate apoptotic and necrotic cell death. The exposure of FTY720-non-P at a concentration of 10 μM mediated the cleavage of PARP in the incubation time longer than 4 h,

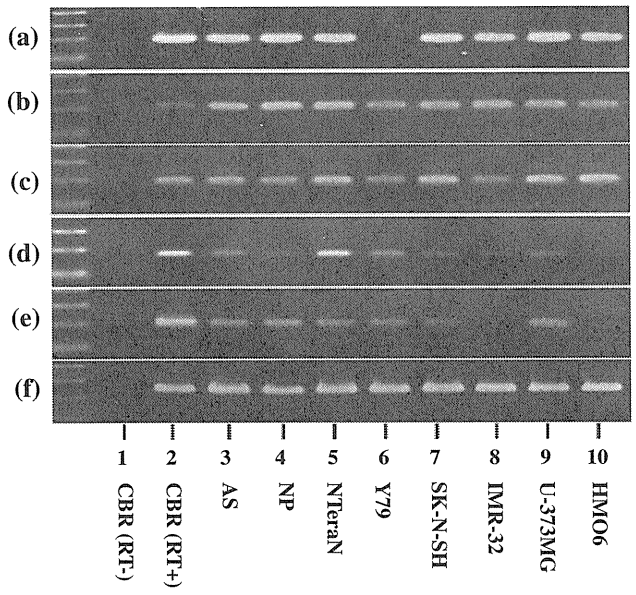

Fig. 1 S1P receptor expression in human neural cell lines. The expression of five S1P receptor mRNAs was studied by RT-PCR. **a** S1P1, **b** S1P2, **c** S1P3, **d** S1P4, **e** S1P5, and **f** G3PDH. The lanes (*1–10*) represent (*1*) the human frontal cerebral cortex (CBR) without inclusion of the reverse transcription (RT) step, (*2*) CBR with inclusion of the RT step, (*3*) cultured astrocytes (AS), (*4*) cultured neuronal progenitor (NP) cells, (*5*) NTera2 teratocarcinoma-derived neurons (NTera2N), (*6*) Y79 retinoblastoma, (*7*) SK-N-SH neuroblastoma, (*8*) IMR-32 neuroblastoma, (*9*) U-373MG astrocytoma, and (*10*) HMO6 microglia. The 100 bp ladder marker is shown on the left

indicating that FTY720-non-P induced cell death of HMO6 via apoptosis (Fig. 2d, lanes 7–10).

FTY720-non-P-induced apoptosis of HMO6 was accompanied by the cleavage of caspase-7 and caspase-3 (Fig. 3b, c, lane 2) but not of caspase-9 (Fig. 3e, lane 4), suggesting that the mitochondrial pathway of apoptosis that usually activates caspase-9 did not play a major role. Furthermore, Z-DQMD-FMK, a caspase-3-specific inhibitor, completely blocked FTY720-non-P-induced apoptosis of HMO6 (Fig. 3g, h, lane 10).

FTY720-Induced Apoptosis of HMO6 was Independent of S1P Receptor Binding

Because FTY720, when phosphorylated, binds to S1P1, S1P3, S1P4, and S1P5, all of which are G protein-coupled receptors (GPCR), we utilized Pertussis toxin (PTX), a Gi protein inhibitor, suramin, a S1P3/S1P5 inhibitor, and W123, a S1P1 competitive antagonist to block the ligand-receptor interaction. However, none of these receptor blockers could inhibit FTY720-induced apoptosis of HMO6 (Fig. 4a, lanes 4, 6, 8). Furthermore, SEW2871, a S1P1 selective agonist, and phosphorylated FTY720 (FTY720-P) at a concentration of 10 μM each did not induce apoptosis of HMO6 during the incubation time of 12 h (Fig. 4c, lanes 11 and 12). In addition, the combined administration of FTY720-P (10 μM) and FTY720-non-P (10 μM) did not inhibit apoptosis of HMO6, and treatment with sphiongosine-1 phosphate (S1P) (10–50 μM) did not induce apoptosis of HMO6 (data not shown). These results suggest that FTY720-non-P-induced apoptosis of HMO6 was independent of S1P receptor binding, and both FTY720-P and S1P were incapable of inducing apoptosis of HMO6.

FTY720 Induced SREBP-Responsive Genes

To investigate the molecular mechanism responsible for triggering FTY720-non-P-induced apoptosis of HMO6, we studied the genome-wide gene expression profile by microarray analysis. We identified 30 genes with an over 2-fold increase in HMO6 cells treated for 2 h with 10 μM FTY720-non-P versus those exposed to the vehicle (DMSO) (Table 1). Among them, the DAVID program categorized seven genes as a group of the genes associated with steroid and/or sterol metabolism (Table 1). None of apoptosis initiator and executor genes were induced in HMO6 cells at 2 h after initiation of the treatment. Upregulated expression of INSIG1 and LDLR in FTY720-non-P-treated HMO6 cells was validated by qPCR analysis (Fig. 5a, b).

Next, we imported the list of Entrez Gene IDs of the 30 genes upregulated in FTY720-non-P-treated HMO6 cells into KeyMolnet, a tool for analyzing molecular interactions on the comprehensive knowledgebase. KeyMolnet generated the molecular network, presenting with the most significant relationship with transcriptional regulation by sterol regulatory element-binding protein (SREBP) (the score = 69.719 with the *P*-value = 1.029E−21) (Fig. 5c). These results suggest that in HMO6 cells, FTY720-non-P activates SREBP proteins, either SREBP1 or SREBP2, belonging to the bHLH-Zip transcription factor family that promotes the synthesis of enzymes involved in cholesterol and fatty acid biosynthesis. To exclude a direct effect of vehicle (DMSO), in which FTY720-non-P was dissolved, on gene expression, we performed an additional set of microarray experiment by exposing HMO6 cells to FTY720-non-P dissolved in ethanol. We again identified the similar gene expression profile composed of upregulation of key SREBP-target genes, regardless of the solvent (See Table 1 in Electronic Supplementary Material).

SREBP2 is primarily involved in cholesterol synthesis, while SREBP1 chiefly regulates fatty acid synthesis (Sato 2010). INSIG1 identified by microarray analysis encodes an ER protein that plays a pivotal role in regulating intracellular cholesterol levels by interacting with SREBP cleavage-activating protein (SCAP) having the sterol-sensing domain activated by reduced cellular cholesterol levels. Thereafter, we have focused on SREBP2 expression

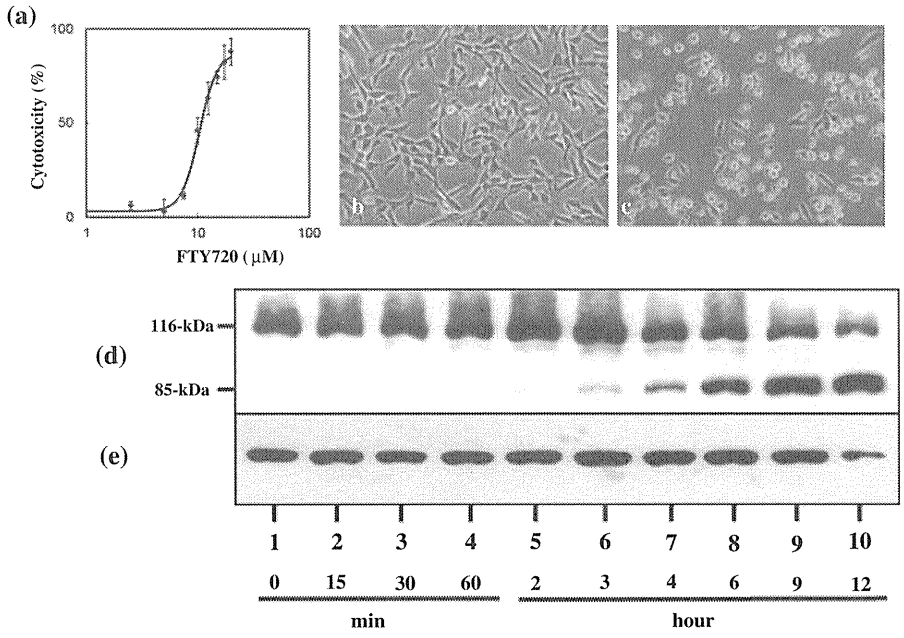

Fig. 2 Non-phosphorylated FTY720 induced apoptosis of HMO6 cells. HMO6 cells were exposed for various time periods to varying concentrations of non-phosphorylated FTY720 (FTY720-non-P). **a** LDH release assay, **b** the phase contrast photomicrograph of the cells exposed for 6 h to vehicle (DMSO), **c** the phase contrast photomicrograph of the cells exposed for 6 h to 10 μM FTY720-non-P, **d** western blot of PARP (an 116-kDa uncleaved form and an 85-kDa cleaved form), and **e** western blot of HSP60, an internal control of protein loading. The lanes (*1–10*) represent (*1*) untreated HMO6 cells, and HMO6 cells treated for (*2*) 15 min, (*3*) 30 min, (*4*) 1 h, (*5*) 2 h, (*6*) 3 h, (*7*) 4 h, (*8*) 6 h, (*9*) 9 h, and (*10*) 12 h with 10 μM FTY720-non-P

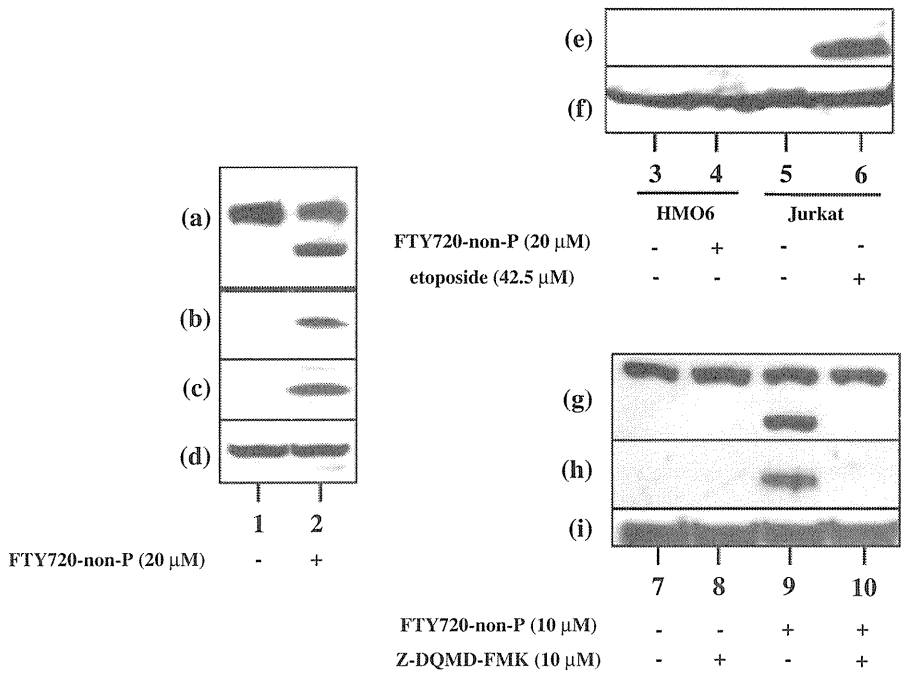

Fig. 3 FTY720-induced apoptosis of HMO6 was accompanied by activation of caspases 3 and 7. HMO6 cells were exposed for various time periods to varying concentrations of FTY720-non-P. For the positive control of caspase-9 activation, Jurkat cells were exposed to etoposide, an apoptosis-inducing agent. **a–i** indicate western blot of **a**, **g** PARP, **b** caspase-7 (a 20-kDa cleaved form), **c**, **h** caspase-3 (a 19-kDa cleaved form), **e** caspase-9 (a 37-kDa cleaved form), and **d**, **f**, **i** HSP60, an internal control of protein loading. The lanes (*1–10*) indicate HMO6 cells treated with (*1*, *3*) vehicle (DMSO) and (*2*, *4*) 20 μM FTY720-non-P for 9 h, and Jurkat cells treated with (*5*) vehicle (DMSO) and (*6*) 42.5 μM etoposide for 6 h, and (*7*) untreated HMO6 cells, and HMO6 cells treated with (*8*) 10 μM Z-DQMD-FMK, (*9*) 10 μM FTY720-non-P, and (*10*) a combination of 10 μM Z-DQMD-FMK and 10 μM FTY720-non-P for 12 h

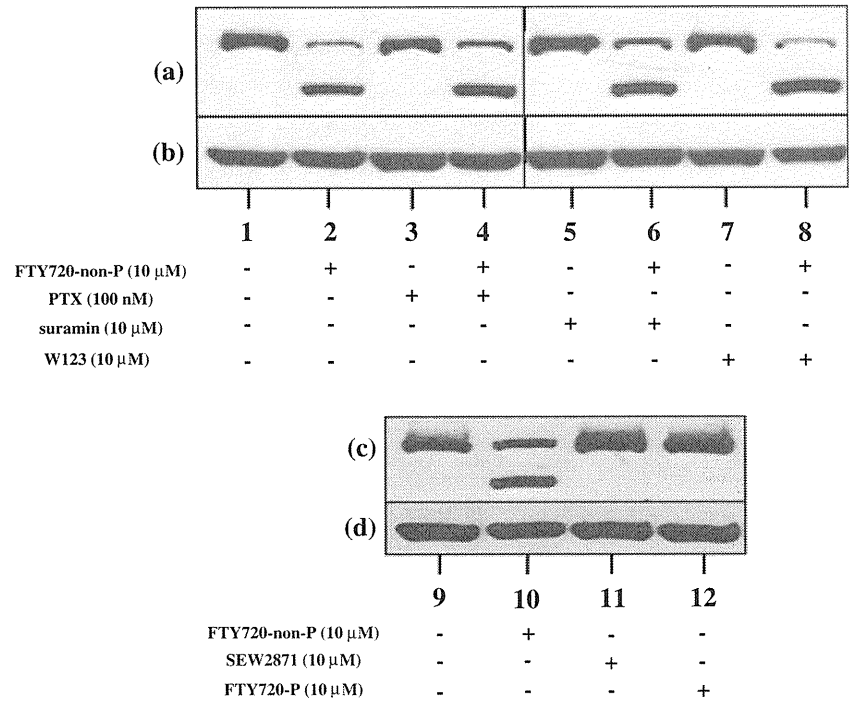

Fig. 4 FTY720-induced apoptosis of HMO6 was independent of S1P receptor binding. HMO6 cells were exposed for 12 h to 10 μM FTY720-non-P with or without inclusion of various S1P receptor agonists and antagonists. Pretreatment started at 30 min before exposure to FTY720-non-P. **a–d** indicate western blot of **a**, **c** PARP and **b**, **d** HSP60, an internal control of protein loading. The lanes (*1–12*) indicate (*1*, *9*) untreated HMO6 cells, and HMO6 cells treated with (*2*, *10*) 10 μM FTY720-non-P exposure alone, (*3*) 100 nM pertussis toxin (PTX) pretreatment alone, (4) 100 nM PTX pretreatment and 10 μM FTY720-non-P exposure, (*5*) 10 μM suramin pretreatment alone, (*6*) 10 μM suramin pretreatment and 10 μM FTY720-non-P exposure, (*7*) 10 μM W123 pretreatment alone, (*8*) 10 μM W123 pretreatment and 10 μM FTY720-non-P exposure, and HOM6 cells treated with a 12 h-exposure to (*11*) 10 μM SEW2871 or (*12*) 10 μM phosphorylated FTY720 (FTY720-P)

in HMO6 cells. The N-terminal fragment of SREBP2 is cleaved, dimerized, and translocated to the nucleus in response to the activating stimuli (Sato 2010). We identified the cleaved form of SREBP2 in HMO6 cells following an 1 h-exposure to FTY720-non-P ranging from 10 to 20 μM or by treatment with 3 μM simvastatin, a HMG-CoA reductase inhibitor capable of activating SREBP2 (Fig. 6a, lanes 2–4). Neither FTY720-non-P nor simvastatin alone at a concentration of 5 μM each induced apoptosis of HMO6 (Fig. 2a; Fig. 6b, lanes 7, 8). In contrast, a 12 h-pretreatment with 5 μM simvastatin enhanced FTY720-non-P-induced apoptosis of HMO6 cells, suggesting a proapoptotic effect mediated by SREBP2 activation following simvastatin treatment (Fig. 6b, lane 10).

A recent study showed that statins activate SREBP2, which positively controls the expression of caspase-7, resulting in induction of apoptosis of human gastric cancer cells (Gibot et al. 2009). When the N-terminal fragment of SREBP2 was overexpressed in HMO6 cells, the cleavage of PARP and caspase-3 was greatly enhanced, compared with the cells with overexpression of LacZ (Fig. 6c, f, lane 12), while the levels of procaspase-7 and cleaved caspase-7 were unaltered (Fig. 6g, lane 12).

Discussion

The present study revealed that non-phosphorylated FTY720 (FTY720-non-P) induced apoptosis of human microglia HM06 in a time- and dose-dependent manner with IC50 of 10.6 ± 2.0 μM. The apoptosis was inhibited by Z-DQMD-FMK, a caspase-3 inhibitor, but not by Pertussis toxin, a Gi protein inhibitor, suramin, a S1P3/S1P5 inhibitor, or W123, a S1P1 competitive antagonist, although HMO6 expressed S1P1, S1P2, and S1P3. Furthermore, both phosphorylated FTY720 (FTY720-P) and SEW2871, S1P1 selective agonists, did not induce apoptosis of HMO6. These observations suggest that FTY720-non-P-induced apoptosis of HMO6 cells is independent of S1P receptor binding.

Supporting these observations, FTY720, serving as a potential anti-cancer agent, induces apoptosis of various human cancer cell lines derived from liver, kidney, pancreas, and breast, multiple myeloma and leukemia cells, which is often mediated by S1P receptor-independent mechanisms (Matsuoka et al. 2003; Lee et al. 2004; Liu et al. 2010; Nagaoka et al. 2008). The concentrations required to induce apoptosis of tumor cells in vitro are about

Table 1 Upregulated genes in HMO6 following treatment with FTY720-non-P

Rank	Fold change	Entrez gene ID	Gene symbol	Gene name
1	5.75	25774	GSTTP1	Glutathione S-transferase theta pseudogene 1
2	3.16	150527	LOC150527	Hypothetical LOC150527
3	2.78	728380	RPL7P26	Ribosomal protein L7 pseudogene 26
4	2.74	3638	INSIG1	Insulin induced gene 1
5	2.72	158160	HSD17B7P2	Hydroxysteroid (17-beta) dehydrogenase 7 pseudogene 2
6	2.70	3157	HMGCS1	3-hydroxy-3-methylglutaryl-coenzyme A synthase 1 (soluble)
7	2.68	346007	EYS	Eyes shut homolog (Drosophila)
8	2.48	26834	RNU4-2	RNA, U4 small nuclear 2
9	2.46	163720	CYP4Z2P	Cytochrome P450, family 4, subfamily Z, polypeptide 2 pseudogene
10	2.44	54541	DDIT4	DNA-damage-inducible transcript 4
11	2.41	6351	CCL4	Chemokine (C–C motif) ligand 4
12	2.39	3949	LDLR	Low density lipoprotein receptor
13	2.37	6307	SC4MOL	Sterol-C4-methyl oxidase-like
14	2.34	286359	LOC286359	Hypothetical LOC286359
15	2.30	391003	PRAMEF18	PRAME family member 18
16	2.29	23175	LPIN1	Lipin 1
17	2.25	54897	CASZ1	Castor zinc finger 1
18	2.16	3156	HMGCR	3-hydroxy-3-methylglutaryl-coenzyme A reductase
19	2.16	196335	OR56B4	Olfactory receptor, family 56, subfamily B, member 4
20	2.10	3283	HSD3B1	Hydroxy-delta-5-steroid dehydrogenase, 3 beta- and steroid delta-isomerase 1
21	2.09	8553	BHLHE40	Basic helix-loop-helix family, member e40
22	2.07	10517	FBXW10	F-box and WD repeat domain containing 10
23	2.06	256892	OR51F1	Olfactory receptor, family 51, subfamily F, member 1
24	2.05	4598	MVK	Mevalonate kinase
25	2.04	196074	METT5D1	Methyltransferase 5 domain containing 1
26	2.04	901	CCNG2	Cyclin G2
27	2.03	439927	C1orf180	Chromosome 1 open reading frame 180
28	2.01	10551	AGR2	Anterior gradient homolog 2 (Xenopus laevis)
29	2.01	91074	ANKRD30A	Ankyrin repeat domain 30A
30	2.00	1831	TSC22D3	TSC22 domain family, member 3

HMO6 cells were exposed to non-phosporylated FTY720 (10 μM) or vehicle (DMSO) for 2 h. The genome-wide transcriptome was studied on Human Gene 1.0 ST array. The genes with an over 2-fold increase in FTY720-non-P-treated HMO6 cells are listed. The genes associated with steroid and/or sterol metabolism annotated by the DAVID program are underlined

two orders of magnitude greater than the blood concentration in the clinical setting, i.e., 5.4 ng/ml in plasma (Brinkmann et al. 2001, 2010). FTY720 has a half-life of approximately 10 days in vivo, and is cleared predominantly by a metabolic pathway requiring cytochrome P450 4F2 (CYP4F2) (Jin et al. 2011). The enzymatic activity of CYP4F2 is inhibited by certain drugs like ketoconazole, and the gene encoding CYP4F2 has a variety of single nucleotide polymorphisms (SNPs) (www.ncbi.nlm.nih.gov/snp). Therefore, in poor metabolizers of FTY720 receiving a CYP4F2 inhibitor, if they exist, the blood concentration of FTY720 could increase up to the range of toxic levels.

FTY720-non-P goes through the plasma membrane without requirement of the receptor binding, and targets directly key intracellular enzymes involved in sphingolipid metabolism, such as sphingosine kinases, phospholipase A2, and S1P lyase (Bandhuvula et al. 2005). FTY720 also inhibits ceramide synthases, resulting in a decrease in cellular levels of ceramide, dihydroceramide, shingosine, and S1P, and an increase in dihydrosphingosine and dihydroshingosine-1-phosphate, all of which alter the endogenous balance between survival and apoptotic signals (Berdyshev et al. 2009). FTY720-non-P promotes phosphorylation of 14-3-3zeta on Ser58 that disrupts 14-3-3 dimer formation, resulting in releasing proapototic mediators (Woodcock et al. 2010). FTY720, phosphorylated by SPHK2 located inside the plasma membrane, is transported outside the cells via the S1P transporter named spinster

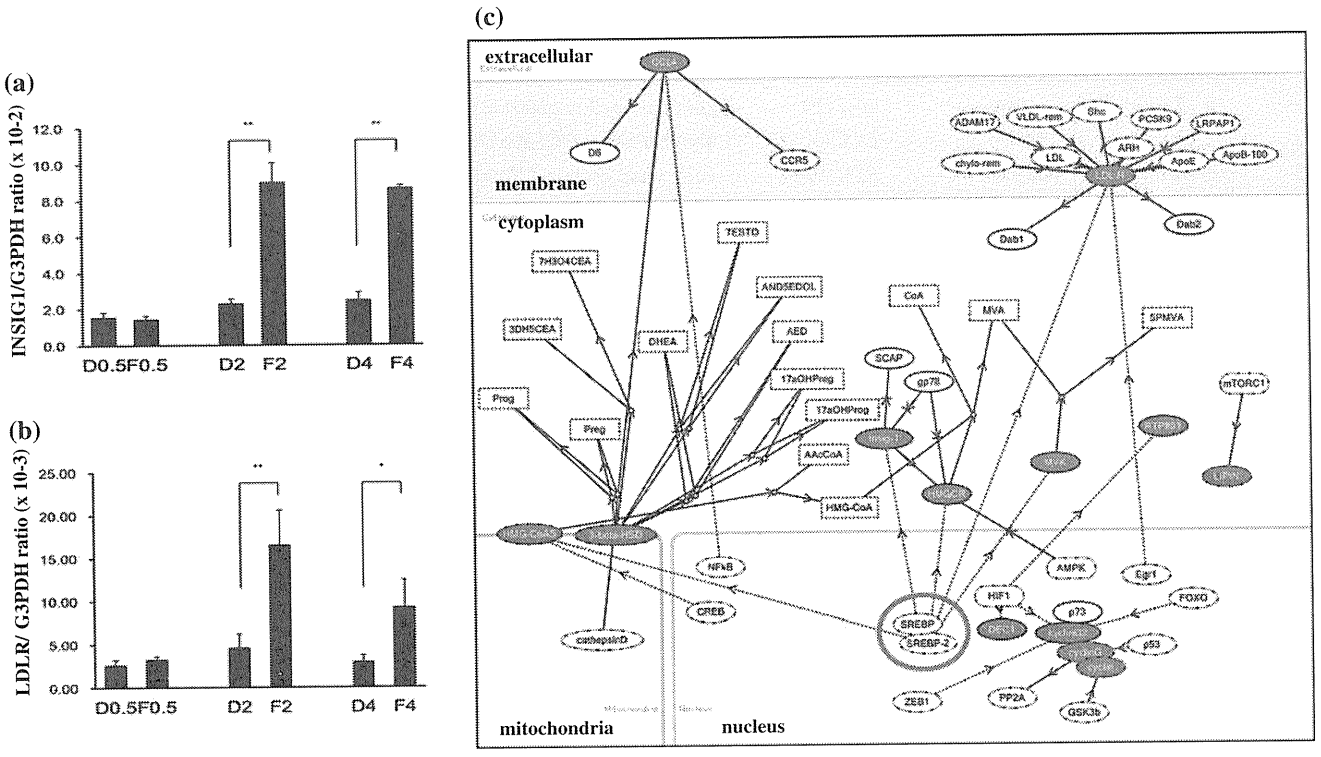

Fig. 5 FTY720 Induced SREBP-Responsive Genes. HMO6 cells were exposed for 2 h to 10 μM FTY720-non-P or vehicle (DMSO). Then, total RNA was processed for the genome-wide gene expression profiling on a microarray, followed by molecular network analysis by KeyMolnet and validation by qPCR. We identified 30 upregulated genes in FTY720-non-P-treated HMO6 cells (Table 1). **a–c** indicate qPCR of **a** INSIG1 and **b** LDLR, and **c** molecular network of FTY720-non-P-induced genes. Abbreviations: D, vehicle (DMSO); F, FTY720-non-P; 0.5, 30 min; 2, 2 h; and 4, 4 h. In **c**, red filled nodes represent FTY720-non-P-induced genes, whereas white open nodes exhibit additional nodes extracted automatically from the core contents of KeyMolnet to establish molecular connections. The molecular relation is indicated by solid line with arrow (direct binding or activation), solid line with arrow and stop (direct inactivation), solid line without arrow (complex formation), dash line with arrow (transcriptional activation), and dash line with arrow and stop (transcriptional repression). The transcription factor SREBP (SREBP2) is highlighted by a red thick circle

homolog 2 (SPNS2), and then the phosphorylated FTY720 binds to S1P receptors expressed on the surface of the plasma membrane (Hisano et al. 2011).

Being consistent with our observations, FTY720-non-P but not FTY720-P induces apoptosis of human breast and colon cancers (Nagaoka et al. 2008). FTY720 inhibits cytosolic phospholipase A2 ($cPLA_2$) in a manner independent of S1P receptor binding (Payne et al. 2007). FTY720-non-P but not FTY720-P inhibits PKC activation, which is associated with cell-surface expression of S1P1 (Sensken and Gräler 2010). Furthermore, FTY720-P counteracts FTY720-non-P-induced apoptosis of human fibroblasts by activating Bcl-2 (Potteck et al. 2010).

Several previous studies showed that FTY720-induced apoptosis is often accompanied by activation of a series of caspases (Wang et al. 1999). We found activation of both caspase-3 and caspase-7 during FTY720-non-P-induced apoptosis of HMO6. Furthermore, FTY720-induced apoptosis also involves various mechanisms, such as dephosphorylation of protein kinase B (Akt) (Matsuoka et al. 2003; Lee et al. 2004), deregulation of mitogen-activated protein kinases (MAPKs), focal adhesion kinase (FAK), and Rho-GTPase (Matsuda et al. 1999; Sonoda et al. 2001), and activation of protein phosphatase 2A (PP2A) (Liu et al. 2010). Here, we for the first time showed that FTY720-non-P-induced apoptosis of HMO6 cells is positively regulated by the SREBP2-dependent signaling pathway.

A recent study showed that statins induce apoptosis of human gastric cancer cells by activating SREBP1 and SREBP2, both of which transcriptionally upregulate caspase-7 (Gibot et al. 2009). Statin-dependent apoptosis is prevented by replenishment of mevalonate, the immediate product by the HMG-CoA reductase activity (Xia et al. 2001). A previous study showed that activation of caspase-3 releases SREBP proteins from ER membrane in a proteolytic reaction distinct from the sterol-regulated cleavage, resulting in nuclear transport of SREBP and transcriptional activation of sterol-regulatory genes (Higgins and Ioannou 2001). However, during FTY720-non-P-induced apoptosis of HMO6 cells, we identified activation of SREBP2 as early as at 1 h after initiation of the treatment, which is long before detection of the PARP cleavage, suggesting that

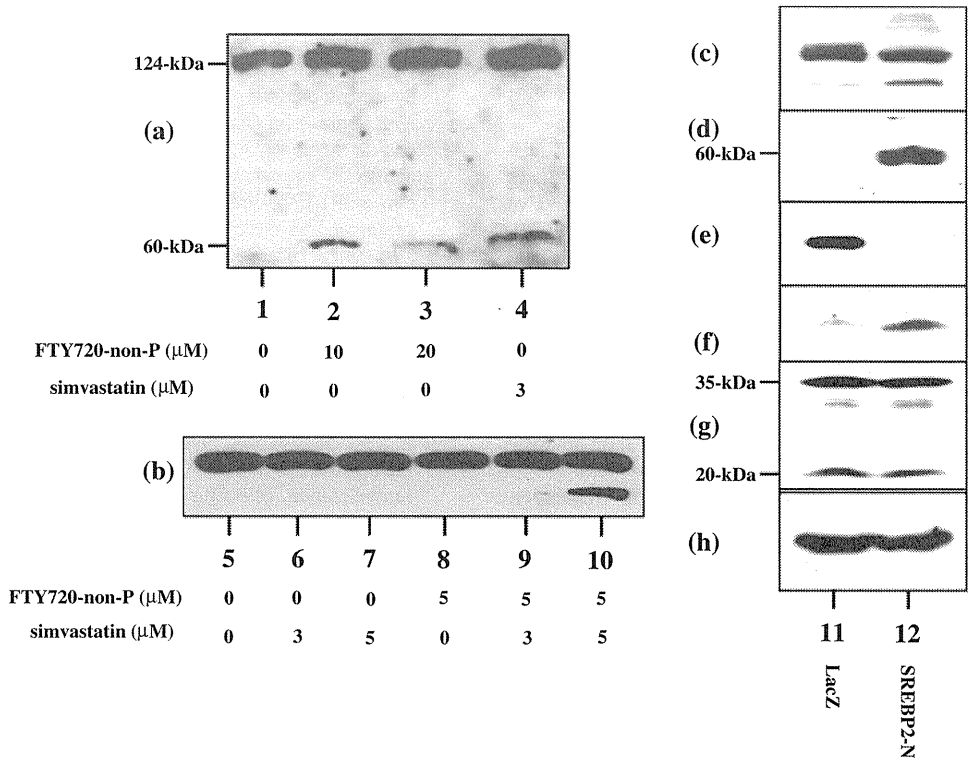

Fig. 6 Activation of SREBP2 by FTY720-non-P in HMO6 cells. HMO6 cells were exposed to FTY720-non-P or simvastatin, or transfected with the vector expressing the N-terminal fragment of SREBP2 (SREBP2-N) or LacZ. **a–h** indicate western blot of **a**, **d** SREBP2, **b**, **c** PARP, **e** V5, **f** cleaved caspase-3, **g** caspase-7 (a 35-kDa proform and a 20-kDa cleaved form), and **h** HSP60. The lanes *1–12* represent (*1*, *5*) untreated HMO6 cells, and HMO6 cells treated for 1 h with (*2*) 10 μM FTY720-non-P, (*3*) 20 μM FTY720-non-P, (*4*) 3 μM simvastatin, and HMO6 cells pretreated for simvastatin starting at 12 h before a 6 h-exposure to FTY720-non-P, whose conditions are composed of (*6*) 3 μM simvastatin pretreatment alone, (*7*) 5 μM simvastatin pretreatment alone, (*8*) no simvastatin pretreatment and 5 μM FTY720-non-P exposure, (*9*) 3 μM simvastatin pretreatment and 5 μM FTY720-non-P exposure, and (*10*) 5 μM simvastatin pretreatment and 5 μM FTY720-non-P exposure, and HMO6 cells with overexpression of (*11*) V5-tagged LacZ or (*12*) SREBP2-N

SREBP activation is not a secondary phenomenon following caspase-3 activation. Furthermore, we found that activation of SREBP2 by overexpression of the N-terminal fragment of SREBP2 in HMO6 cells enhances the cleavage of PARP and caspase-3 in the absence of FTY720. Moreover, we found that pretreatment with simvastatin enhanced FTY720-non-P-induced apoptosis of HMO6 cells. Statins activate SREBP2 and induce apoptosis of various cells (Xia et al. 2001; Gibot et al. 2009). All of these observations suggest that the SREBP2-dependent signaling pathway is intrinsically proapoptotic, when it is aberrantly regulated.

A recent study showed that FTY720 inhibits intracellular transport of cholesterol to ER in human macrophages, being independent of S1P1 binding, indicating that FTY720-non-P certainly affects the cellular cholesterol processing (Blom et al. 2010). Importantly, cholesterol interacts specifically with sphingosine in human intestinal epithelial cells under physiological conditions (Garmy et al. 2005). S1P is intracellularly generated by sphingosine kinases SPHK1 and SPHK2 from sphingosine, a breakdown product of the cell membrane constituent sphingomyelin (Chi 2011). S1P and its synthetic analog FTY720-P share S1P1, S1P3, S1P4, and S1P5 expressed on the plasma membrane. All of these observations propose a possible scenario that excessive amounts of intracellular FTY720-non-P disturb the complex metabolic network of cholesterols and sphingolipids, resulting in activation of the SREBP2-dependent proapoptotic signaling pathway.

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RESEARCH ARTICLE

International Journal of Geriatric Psychiatry

Relationship between white matter T2 hyperintensity and cortical volume changes on magnetic resonance imaging in healthy elders

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Objective: T2 white matter hyperintensity (WMH) on magnetic resonance imaging (MRI) is associated with brain atrophy. Some previous studies examined the relation between the WMH and cortical atrophy, however, little is known about how the WMHs affect the pattern of cortical atrophy. Recent studies have revealed that patho-physiological role of WMH in affecting cortical atrophy may be different between hyperintensities in basal ganglia and thalami (B&T) and those in other regions. Based on a longitudinal study up to 5 years, we attempt to examine the temporal relation between the WMHs and cortical atrophy with special attention to the hyperintensities in the B&T.

Methods: We evaluated the temporal pattern of cortical atrophy in 74 cognitively normal subjects lacking hyperintensities in B&T (first analysis) and 13 cognitively normal subjects with hyperintensities in B&T (second analysis). The relationship between the baseline WMH severity and the cortical volume change during the observation period (mean: 3.8 years) was voxel basically evaluated on the images.

Results: The first analysis showed fairly axisymmetrical atrophy pattern in parietal, occipital, and precentral cortices, while the findings gained from the second appear to lack such systematic orderliness of the atrophy.

Conclusion: This result shows that WMH may affect atrophy in multiple cerebral cortices even in cognitively normal subjects. Understanding the impact of WMH on the shrinkage shown in the brains of cognitively healthy older individuals is an important base for assessing the temporal pattern of atrophy of the individual with neurodegenerative disorder like AD. Copyright © 2010 John Wiley & Sons, Ltd.

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Introduction

White matter hyper-intensities (WMH) defined as areas with high signal intensities on T2-weighted magnetic resonance imaging (MRI) are commonly found on MRI of older individuals. They have been reported to be related with cognitive impairment and vascular pathology even in the healthy older. The WMH affect cognitive function including the speed of cognitive processes and executive function (Junqué *et al.*, 1990; Schmidt *et al.*, 1993), which is presumably associated with brain atrophy and reduced cerebral blood flow (Mirsen *et al.*, 1991; De Reuck *et al.*, 1992; Du *et al.*, 2005; Mungas *et al.*, 2005; Wen *et al.*, 2006). Pathology of WMH may be attributable to dilatation of periventricular space, peri-vascular demyelination, and gliosis. Several researchers have examined the patho-physiological role of WMH in affecting cortical atrophy of the healthy and pathological brains of the older.

Recently, mild cognitive impairment (MCI) which is a distinct state of abnormal cognition that does not amount to dementia but is distinguishable from

normal cognitive decline associated with aging has attracted an increasing attention, because it may offer opportunities for very early diagnosis of Alzheimer's disease (AD). One study reported that high WMH prevalence strongly predicted the progression from normal to MCI (Smith *et al.*, 2008).

Another study showed difference in the level of WMH between the MCI to AD converter and non-converters (Misra *et al.*, 2009). Although whether the patho-physiology of AD is directly associated with vascular pathological changes remain an open question, it appears that the clinical manifestation of AD is highly correlated with the vascular pathology (Misra *et al.*, 2009). AD patients are likely to have more extensive WMH than age-matched controls (Scheltens *et al.*, 1992).

Taking such information into consideration, it is very important to examine the pattern and mechanism of WMH on cortical atrophy among cognitively healthy individuals is very important for the basis of the assessment for the pattern and mechanism among individuals with pathological conditions including AD.

Most of the previous studies regarding the association between WMH and the cortical atrophy examined the correlation between the load for whole brain WMHs and shrinkage of whole brain gray matter (Mirsen *et al.*, 1991; Du *et al.*, 2005; Mungas *et al.*, 2005), thus little is known about the effect of WMH on the regional cortical atrophy. An exceptional study reported that the WMHs in the frontal lobe were correlated with the change in the volume of frontal cortex (Tullberg *et al.*, 2004). Another study also showed that subjects with WHM loads located mainly in frontal lobe showed bilateral frontal cortical atrophy (Rossi *et al.*, 2006). Furthermore, a study showed the correlation between the cortical change of each lobe and WMHs in its corresponding white matter (Wen *et al.*, 2006). It is of note that all of these studies are cross-sectional design, and no previous study has examined the relation longitudinally.

Recent development of the diffusion tensor imaging technique enabled the depiction of projecting neural fibers non-invasively (Behrens *et al.*, 2003). The development has revealed that basal ganglia and thalami (B&T) mediate communication over widespread areas of the cortex with neural fibers as the central relay station in the brain. The hyperintensity in T2-weighted images of B&T may affect not only volume change of themselves but also the cerebral cortex to which B&T connect. In addition, some researchers have reported that the disturbance of cerebral cortex conversely affects the volume change of basal ganglia (Ogawa *et al.*, 1997; Ota *et al.*, 2007). Therefore, for the accurate estimation of the influence of the WMH on cortical volume loss, it may be appropriate that hyperintensity on T2-weighted images in B&T and that in other regions should be dealt separately. However, previous quantitative studies, automatically calculated the volume of WMHs of the whole brain, thus they did not distinguish hyperintensities on T2-weighted image in B&T from those in other regions. Some studies evaluated the relationship between the regional cortical volume and the WMH loads voxel based on a lobe-to-lobe basis (Rossi *et al.*, 2006; Wen *et al.*, 2006). However, it is known that WMHs in any brain region cause other cortical changes (Tullberg *et al.*, 2004; Rossi *et al.*, 2006; Wen *et al.*, 2006). Additionally, because too many factors are involved in the interaction, it is difficult to evaluate the relationship between the atrophy and the WMHs.

In this study, we have conducted a follow-up brain MRI study for the older individuals participating in a community-based study. In order to easily exclude the subjects with hyperintensities in B&T, we adopted qualitative morphometry based on the grading of local WMHs and identified the subjects without hyperintensities on T2-weighted image in B&T. We examined the correlation between the severity of baseline-scan WMH for whole brain and the atrophy rate of the regional cortex using voxel-based morphometry.

Methods

This study was conducted as a part of a community-based project aiming at prevention of dementia in the older. The details of the project have been reported elsewhere, so the description of the method here will be given in brief (Miyamoto *et al.*, 2009). The protocol for this study was approved by the ethics committee of the University of Tsukuba and all participants gave their informed consent.

At the baseline, between December 2001 and April 2002, 1888 out of the 2698 candidate inhabitants who were 65 years or older underwent the cognitive assessment using a battery of neuropsychological tests (Sasaki *et al.*, 2009); category-cued recall (Grober *et al.*, 1998); set-dependency activity (Sohlberg and Mateer, 1986); category verbal fluency (Monsch *et al.*, 1992); clock-drawing test (Brodaty and Moore, 1997); and Wechsler Adult Intelligence Scale Revised (WAIS-R) (Wechsler, 1981). We regarded the subject who marked score less than 1 SD below the demographically corrected mean on each of the five cognitive domains to fall short of normal limits (Miyamoto *et al.*, 2009).

According to our invitation, 284 self-selected subjects underwent brain MRI scanning. A total of 172 individuals out of the 284 were diagnosed as having normal cognitive function and no abnormal MRI findings such as cortical infarctions, brain tumors, or head injury. We defined infarct as high intensity lesion having a size of ≧3 mm on T2-weighted images and low intensity on T1-weighted images, following the criteria of the Workshop Study (Adachi *et al.*, 2002). They were selected as the participants for the present longitudinal MRI study. Using Fazekas criterion for the severity of WMH, we defined Fazekas 2 or 3 as severe hyperintensity (Wahlund *et al.*, 2001).

Eighty-seven out of the 172 participants were cognitively healthy both at the baseline and the end of the observation period, and underwent annual MRI scanning at least four times. From these 87 participants, we excluded 13 subjects with severe hyperintensity located in B&T on the images of the baseline-scan. For the first analysis, the data from cognitively healthy 74 subjects (39 men, 35 women; mean age, 72.3 ± 3.8 years; mean years of education, 10.9 ± 3.1 years; mean mini-mental state examination (MMSE) score, 28.4 ± 1.8 at the baseline, scan interval = 3.8 ± 0.2) lacking hyperintensities in B&T were used. For the second analysis, the 13 subjects with severe hyperintensities in B&T (4 men, 9 women; mean age, 75.4 ± 4.4 years; mean years of education, 10.4 ± 3.2 years; mean MMSE score, 27.8 ± 2.4 at the baseline, scan interval = 3.8 ± 0.1) were employed.

The clinical characteristics of the subjects are presented in Table 1. We used a pair of MRI data with for each participant.

First, cranial MRI was performed using a 1.5-T Magnetom Symphony system (Siemens, Erlangen, Germany). Conventional axial T2-weighted turbo spin echo images were obtained using the following settings: repetition time (TR), 4000 ms; echo time (TE), 96 ms; slice thickness, 5 mm; intersection gap, 1.5 mm; matrix, 512 × 512; field of view, 230 × 230 mm; number of signals acquired, 2. In addition to T2-weighted imaging, high spatial-resolution, 3-dimensional (3D) T1-weighted imaging was also used for the study. Scans for 3D T1-weighted imaging were made in the sagittal plane using the following settings: TR, 2080 ms; TE, 3.93 ms; flip angle, 12°; effective section thickness, 1.20 mm; slab thickness, 173 mm; matrix, 512 × 512; field of view, 280 × 280 mm; number of signals acquired, 1. This yielded 144 contiguous slices through the head.

To clarify the relationship between the rate of cortical gray matter volume change and the severity of WMH, structural 3D T1-weighted MR images were analyzed using an optimized voxel-based morphometry (VBM) technique. Data were computed using Statistical Parametric Mapping 5 (SPM5) software (Wellcome Department of Imaging Neuroscience, London, UK) running on MATLAB 7.0 (Math Works, Natick, MA). Optimized VBM were processed using SPM5 tool software. Details of this process are described elsewhere (Good *et al.*, 2001). Normalized segmented images were modulated by multiplication with Jacobian determinants of spatial normalization function to encode the deformation field for each subject as tissue density changes in normal space. The atrophy rate of the regional gray matter was computed by comparing the modulated segmented scan image

Table 1 Descriptive characteristics of the study sample without white matter hyperintensities in basal ganglia and thalami (Fazekas <2; (a), $N = 74$) and with hyperintensities in basal ganglia and thalami (Fazekas ≧2; (b), $N = 13$)

The degree of subcortical white matter changes	Age (year) (quartile; median)	Sex	MRI period (year) (quartile; median)	Education (year) (quartile; median)	MMSE (quartile; median)
(a)					
Fazekas = 0	69–73	M: 23; F: 24	3.6–3.8	8–12	27–30
	71		3.7	11	29
Fazekas = 1	69.8–74.5	M: 11; F: 5	3.7–3.8	11–12	27–30
	72		3.7	12	29
Fazekas = 2	75–78	M: 4; F: 5	3.7–3.8	8–12	28–30
	77		3.7	8	30
Fazekas = 3	76–78 (range)	M: 1; F: 1	3.6–3.8 (range)	11–11 (range)	27–30 (range)
(b)					
Fazekas = 0		M: 0; F: 0			
Fazekas = 1	72.5–75.8	M: 1; F: 3	3.8–4.0	8.3–11.5	28.8–30
	74		3.9	9.5	29.5
Fazekas = 2	73.5–78	M: 2; F: 5	3.7–3.8	8–17	25–29.5
	76		3.8	12.5	26
Fazekas = 3	74–76 (range)	M: 1; F: 1	3.8–3.9 (range)	8–17 (range)	25–30 (range)