Antibacterial mechanism of compound K in activated microglia and its neuroprotective effect on experimental stroke in mice

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Running Title Page

Running title: Anti-inflammatory and neuroprotective effects of compound K

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Abbreviations:
AP-1, activator protein-1; ARE, antioxidant response element; CRE, cyclic-AMP responsive element; CREB, CRE-binding protein; ERK, extracellular signal-regulated kinase; GR, glucocorticoid receptor; HO-1, heme oxygenase-1; IL-6, interleukin-6; iNOS, inducible nitric oxide synthase; JNK, c-Jun N-terminal kinase; LPS, lipopolysaccharide; MAPK, mitogen-activated protein kinase; MCP, monocyte chemotactic protein-1; MMP, matrix metalloproteinase; NADPH, nicotinamide adenine dinucleotide phosphate; NF-κB, nuclear factor-κB; Nrf2, nuclear factor E2-related factor-2; ROS, reactive oxygen species; TNF, tumor necrosis factor

Section: Neuropharmacology
Abstract

Microglial activation plays a pivotal role in the pathogenesis of various neurologic disorders, such as cerebral ischemia, Alzheimer’s disease and Parkinson’s disease. Thus, controlling microglial activation is a promising therapeutic strategy for such brain diseases. In the present study, we found that a ginseng saponin metabolite, compound K, inhibited the expressions of inducible nitric oxide synthase, proinflammatory cytokines, monocyte chemotactic protein-1, and matrix metalloproteinase-3 and -9 in lipopolysaccharide (LPS)-stimulated BV2 microglial cells and primary cultured microglia. Subsequent mechanistic studies revealed that compound K suppressed microglial activation via inhibiting reactive oxygen species, mitogen-activated protein kinases, and NF-κB/AP-1 activities with enhancement of HO-1/ARE signaling. To address the anti-inflammatory effects of compound K in vivo, we used two brain disease models of mice: sepsis (systemic inflammation) and cerebral ischemia. Compound K reduced the number of Iba1-positive activated microglia and inhibited the expressions of tumor necrosis factor-alpha and interleukin-1 beta in the LPS-induced sepsis brain. Furthermore, compound K reduced the infarct volume of ischemic brain induced by middle cerebral artery occlusion, and suppressed microglial activation in the ischemic cortex. The results collectively suggest that compound K is a promising agent for prevention and/or treatment of cerebral ischemia and other neuroinflammatory disorders.
Introduction

Microglia are major immune cells in the central nervous system, which are readily activated following brain injury or during neurodegenerative processes, and secrete growth factors, pro-/anti-inflammatory cytokines, reactive oxygen species (ROS), nitric oxide (NO), and glutamate (Block and Hong, 2005; Stolp and Dziegielewska, 2009). While microglial activation is necessary and important for host defense, overactivation of microglia is neurotoxic. Microglia are also activated after ischemic stroke and produce cytokines, triggering neuronal death in response to ischemic injury (Wang et al., 2007). Within 3 days of a stroke, various inflammatory molecules are concomitantly up-regulated in the brain, cerebrospinal fluid (CSF), and blood, and thus continuous brain loss is expected during that time. If inflammation can be suppressed, progressive brain loss following a stroke may be prevented and the clinical outcome improved (Wang et al., 2007). Thus, development of agents that reduce microglial activation and their proinflammatory responses are considered to be an important therapeutic strategy for neuroinflammatory disorders such as cerebral ischemia, Alzheimer’s disease, and Parkinson’s disease (Block and Hong, 2005; Stolp and Dziegielewska, 2009; Wang et al., 2007).

Compound K (20-O-D-glucopyranosyl-20(S)-protopanaxadiol) is one of the major metabolites of ginseng, which are formed by the intestinal bacteria after oral administration of ginseng extract in humans and rats. The ginseng saponin metabolite, compound K, is absorbed from the gastrointestinal tract to the blood (Akao et al., 1998). Compound K has a variety of pharmacological activities, including anti-tumor, anti-diabetic, anti-allergic and anti-inflammatory effects (Jia et al., 2009; Radad et al., 2010). Our group has recently reported that compound K suppresses glioma invasion via
inhibition of MMP-9 expression (Jung et al., 2006). Compound K also suppressed inflammation in colitic mice via inhibition of interleukin-1 receptor-associated kinase-1 (IRAK-1) activation (Joh et al., 2011).

We have previously reported that ginseng extracts and total saponins exert anti-inflammatory effects in lipopolysaccharide (LPS)- and/or β-amyloid-stimulated microglial cells (Park et al., 2009). Among the individual ginsenosides tested, compound K suppressed LPS-induced NO production. However, the anti-inflammatory effects of compound K in activated microglia and its’ underlying molecular mechanisms have not been clearly demonstrated. In the present study, we examined the effects of compound K on various inflammatory molecules in LPS-stimulated microglial cells and analyzed the detail molecular mechanisms. Subsequently, we demonstrated the anti-inflammatory and/or neuroprotective effects of compound K in brain disease models of mice such as sepsis (systemic inflammation) and cerebral ischemia.
Methods

Reagents

Compound K (20-O-D-glucopyranosyl-20(S)-protopanaxadiol) was prepared as previously described (Joh et al., 2011). In brief, protopanaxadiol-type ginsenosides were incubated with Bacteroides JY-6, a human intestinal bacterium in a general anaerobic medium for 24 h at 37°C. The incubated medium was extracted with BuOH. The supernatant was concentrated in vacuum and was processed using silica gel column chromatography with CHCl₃-MeOH-H₂O (65:35:10 [v/v]). The isolated compound K was characterized by mass spectroscopy and ¹H-and ¹³C-nuclear magnetic resonance (NMR) spectrometry. The chemical structure of compound K is shown in Fig. 1. All reagents used for cell culture were purchased from Gibco BRL (Grand Island, NY, USA). Antibodies against MAP kinases or HO-1 were purchased from Cell Signaling Technology (Beverly, MA, USA). All other chemicals were obtained from Sigma-Aldrich (St. Louis, MO, USA), unless otherwise stated.

Microglial cell cultures

Immortalized murine BV2 microglial cells (Bocchini et al., 1992) were grown and maintained in Dulbecco’s modified Eagle’s medium supplemented with 10 % heat-inactivated FBS, streptomycin (10 μg/ml), and penicillin (10 U/ml) at 37°C. Primary microglial cells were cultured from the cerebral cortices of 1-2-day-old Sprague-Dawley rat pups, as described previously (Park et al., 2009). The purity of microglial cultures was > 95%, which was determined by isolectin B4 staining (data not shown).

Measurement of cytokine, nitrite, and intracellular ROS levels
Microglial cells (1 x 10^5 cells per well in a 24-well plate) were pre-treated with compound K (25, 50, 75 μM) for 30 min and stimulated with LPS (0.1 μg /ml). The supernatants of the cultured microglia were collected 24 h after LPS stimulation and the concentrations of TNF-α and IL-1β were measured by an enzyme-linked immunosorbent assay (ELISA). Accumulated nitrite was measured in the cell supernatant using the Griess reagent (Promega, Madison, WI, USA). The intracellular accumulation of ROS was measured with H_2DCF-DA (Sigma-Aldrich) by modifying a previously reported method (Qin et al., 2005).

**RT-PCR**

BV2 cells (7.5 x 10^5 cells on a 6-cm dish) and rat primary microglia (7 x 10^6 cells on a 6-cm dish) were treated with LPS in the presence of compound K (25, 50, 75 μM) and total RNA was extracted with TRI reagent (Sigma-Aldrich). For RT-PCR, total RNA (1 μg) was reverse-transcribed in a reaction mixture containing 1 U RNase inhibitor, 500 ng random primers, 3 mM MgCl_2, 0.5 mM dNTP, 1 X RT buffer, and 10 U reverse transcriptase (Promega). The synthesized cDNA was used as a template for the PCR reaction using GoTaq polymerase (Promega) and primers, as below (Table).

<table>
<thead>
<tr>
<th>Gene</th>
<th>Forward Primer (5’→3’)</th>
<th>Reverse Primer (5’→3’)</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>iNOS</td>
<td>CCCTTCGAAGTTTCTGGCAGCAGC</td>
<td>GCCTGTCAAGGCTGCTGCTTTGG</td>
<td>450 bp</td>
</tr>
<tr>
<td>TNF-α</td>
<td>CCTATGTCTCAGCCTCTTTCT</td>
<td>CCTGTTAGATGCAAT</td>
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<tr>
<td>IL-1β</td>
<td>GGCAACTGTTCCTGAACTCAACTG</td>
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<tr>
<td>IL-6</td>
<td>CCACATTCAAGTCGGAGGCTT</td>
<td>CCAGCTTATCTGTGAGGAGGA</td>
<td>395 bp</td>
</tr>
<tr>
<td>MCP-1</td>
<td>ACTGAAGCCAGCTCCTCTTCTTCTC</td>
<td>TTTCTTGGGTCAGCAGCACAG</td>
<td>276 bp</td>
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<tr>
<td>MMP-3</td>
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<td>CCATTGGAAGTCTTACGTCCTAC</td>
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<tr>
<td>MMP-9</td>
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<td>GAAGCCATACGTTCTCTACTG</td>
<td>352 bp</td>
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<tr>
<td>GAPDH</td>
<td>ATGTACGTAGCCATCCAGGC</td>
<td>AGGAAGGAAGGCTGGAGAG</td>
<td>420 bp</td>
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</table>
Electrophoretic mobility shift assay (EMSA)

Nuclear extracts from treated microglia were prepared, as described previously (Woo et al., 2003). The double-stranded DNA oligonucleotides containing the NF-κB, AP-1, ARE, or CRE consensus sequences (Promega) were end-labeled by \([\gamma^{32}\text{P}]\text{ATP}\). EMSA was performed using 30,000 to 50,000 cpm of labeled probe and nuclear proteins (5 μg) in a final volume of 20 μl of 12.5% glycerol and (in mM): 12.5 HEPES (pH 7.9), 4 Tris-HCl (pH 7.9), 60 KCl, 1 EDTA, and 1 DTT with 1 μg of poly(dI-dC) as nonspecific competitor. The reaction was incubated at room temperature for 20 min. The DNA-protein was resolved on high ionic strength, nondenaturing 6% polyacrylamide gel followed by autoradiography with an intensifying screen. For the supershift assay, antibodies to the p65 or p50 subunits of NF-κB (Santa Cruz, CA) were co-incubated with the nuclear protein in the reaction mixture for 30 min at 4°C prior to adding the radiolabeled probe.

Transient transfection and luciferase assay

Transfection of the reporter genes into BV2 cells was performed using Geneporter\textsuperscript{TM} 2 transfection reagent (Gene Therapy Systems, San Diego, CA, USA). The NF-κB reporter plasmid contains three copies of the κB−binding sequence fused to the firefly luciferase gene (Clontech, Mountain View, CA, USA). The ARE-luciferase (ARE-Luc) reporter plasmid contains enhancer 2 (E2) and a minimal promoter sequence of the mouse HO-1 gene fused to the luciferase gene (So et al., 2006). BV2 cells (2 \times 10\textsuperscript{5} cells per well in a 12-well plate) were transfected with 1 μg of the reporter construct mixed with Geneporter. After 48 h, cells were harvested and luciferase assay was performed, as previously described (Woo et al., 2003). To determine the effect of
compound K on reporter gene activity, cells were pre-treated with the agent before treating with LPS (0.1 μg/ml) and incubated for 6 h prior to harvesting cells.

**In vivo administration of compound K**

Experiments were performed in male C57BL/6 mice (10-11 weeks old; Orient Bio Inc., Seongnam, Republic of Korea). All experiments were performed in accordance with the NIH and Ewha Womans University guidelines for Laboratory Animals Care and Use, and the study was approved by the Institutional Animal Care and Use Committee in the Medical School of Ewha Womans University. Compound K was dissolved in 3% cremophore (Sigma-Aldrich) in normal saline. Mice were randomly divided into control and treatment groups, and vehicle (3% cremophore in normal saline) or compound K (30 mg/kg ip) was administered 4 days before LPS (5 mg/kg ip) treatment or transient MCAO. The doses of LPS and compound K were based on a previous study (Park et al., 2009).

**Transient middle cerebral artery occlusion (MCAO)**

Procedures for transient MCAO have been established and published previously (Shin et al., 2009). Briefly, mice were anesthetized and a fiber optic probe was attached to the right parietal bone (2 mm posterior and 5 mm lateral to the bregma) and connected to a laser-Doppler flowmeter (Periflux System 5010; Perimed, Sweden). Cerebral blood flow (CBF) was continuously recorded during MCAO and reperfusion periods using a computer-based data acquisition system (Perisoft, Perimed). A 6-0 silicon-coated black monofilament surgical suture (Doccol Cooperation, Redlands, CA, USA) was inserted into the exposed right external carotid artery, advanced into the
internal carotid artery, and wedged into the circle of Willis to obstruct the origin of the MCA. The filament was left in place for 30 min, then withdrawn to re-establish CBF. Only animals that exhibited a reduction in CBF >85% during MCA occlusion and in which CBF recovered by >80% after 10 min of reperfusion were included in the study.

Infarct volume measurement

Infarct volume was measured according to procedures described previously (Lin et al., 1993). Mice were sacrificed 3 days after MCAO, and brains were removed, frozen, and sectioned (30 µm thick) using a cryostat. Brain sections were collected serially at 600-µm intervals, and stained with cresyl violet. Infarct volume was determined using an image analyzer (Axiovision LE 4.1; Carl Zeiss, Jena, Germany). Values were reported after correcting for post-ischemic swelling, as previously described (Lin et al., 1993).

Immunohistochemistry

Three hours after LPS treatment or 24 h after MCAO, the animals were anesthetized with sodium pentobarbital (120 mg/kg ip) and perfused transcardially with normal saline containing heparin (5 U/ml), followed by 4% formaldehyde in 0.1 M sodium phosphate buffer (pH 7.2). The brains were removed and incubated overnight in fixatives and stored in a 30% sucrose solution. Serial coronal brain sections (20 µm thick, at 600-µm intervals) were collected in a cryostat in regions containing the striatum (between +1.4 and -1.0 mm from the bregma). Brain sections were incubated in TBS containing 0.1% Triton X-100, 5% normal serum, and 1% bovine serum albumin for 1 h, then subsequently incubated with Iba1 antibody (1:500; Wako Pure
Chemical Industries, Osaka, Japan). On the following day, the secondary antibody conjugated to FITC (anti-rabbit, 1:200; Serotec, Raleigh, NC, USA) was applied to sections for 1 h. TBS was used to wash sections between all steps. The sections were mounted with Vectashield mounting medium (Vector Laboratories, Inc., Burlingame, CA, USA), and fluorescence microscopy images were obtained (Axiovert 200; Carl Zeiss). Densely-stained, round, Iba1-positive cells were quantified using the Axiovison LE program (Carl Zeiss). Two serial brain sections from each animal were used, and quantification was performed in three different areas (500 μm² in size) in the lateral cortex and striatum of the right hemisphere per brain section. The mean cell number from six 500 μm² areas per animal was calculated.

**Western blot analysis**

Whole cell protein lysates of BV2 cells were prepared in lysis buffer and protein samples were separated by 12% SDS-PAGE and transferred to nitrocellulose membranes (Amersham, Piscataway, NJ, USA). The membranes were blocked with 5% skim milk in 10 mM Tris-HCl containing 150 mM NaCl and 0.5% Tween 20 (TBST), then incubated with primary antibodies (1:1000) against phospho- or the total form of MAP kinases, HO-1 (Cell Signaling Technology) or p-p47phox [anti-phospho-(Ser345)-p47phox Ab, kindly provided by Dr. J.L. Benna (Universite Paris, France)] (Dang et al., 2006). The cortical tissues from each animal were subjected to simultaneous Western blot hybridization, as previously described (Shin et al., 2010a), and the protein-transferred membrane was incubated overnight with antibodies against IL-1β or TNF-α (1:200; R&D, Minneapolis, MN, USA). After thorough washing with TBST, HRP-conjugated secondary antibodies (1:3000 dilution in TBST; New England Biolabs,
Beverly, MA, USA) were applied and the blots were developed using an enhanced chemiluminescence detection kit (Pierce Biotechnology, Rockford, IL, USA).

**Statistical Analysis**

The data of *in vitro* and *in vivo* studies are expressed as the mean ± S.E.M. Comparisons of *in vivo* data between two groups were analyzed with an unpaired Student’s t-test. Multiple comparisons were evaluated with one-way analysis of variance (ANOVA), followed by a post-hoc Fisher’s protected least significant difference (PLSD) test with Statview (Statview version 5, SAS Institute Inc., Cary, NC, USA). For *in vitro* data, statistical comparisons between groups were performed using one-way ANOVA, followed by Student’s *t*-test. A *p*-value < 0.05 was considered significant.
Results

**Compound K inhibited iNOS, cytokines, MCP-1 and MMP-3/-9 expression in LPS-stimulated microglial cells**

To investigate the anti-inflammatory effects of compound K, BV2 cells and primary microglia were treated with compound K for 30 min before stimulation with LPS. As shown in Fig. 2A, compound K inhibited LPS-induced production of NO, TNF-α, and IL-1β in a dose-dependent manner. Subsequent RT-PCR analysis revealed that compound K suppressed iNOS, TNF-α, and IL-1β expression at the mRNA level (Fig. 2B). Compound K also inhibited the expression of IL-6, MCP-1, MMP-3 and MMP-9, which also play an important role in LPS-induced inflammatory reactions.

**Compound K inhibited NF-κB and AP-1 activities, while it increased nuclear protein binding to CRE**

To investigate the anti-inflammatory mechanism of compound K, we examined the effect of compound K on NF-κB and AP-1, which are important transcription factors modulating cytokines, MMP/MCP-1, and iNOS gene expression in microglia (Lee and Kim, 2009; Smale, 2010). As shown in Fig. 3, stimulation of BV2 cells with LPS resulted in strong NF-κB and AP-1 bindings, which were significantly inhibited by compound K. In addition, compound K inhibited NF-κB-mediated transcriptional activity, as shown by the κB-luc reporter gene assay (Fig. 3B). Next, we examined the effect of compound K on CREB, which is known to be involved in anti-inflammatory mechanisms of activated microglia (Jung et al., 2010; Woo et al., 2003). As shown in Fig. 3D, compound K significantly enhanced nuclear protein binding to CRE. The data collectively suggest that compound K may inhibit the expression of various...
inflammatory molecules by modulating NF-κB, AP-1, and CREB.

**Compound K inhibits LPS-induced ROS production, phosphorylation of p47phox of NADPH oxidase, and three types of MAP kinases**

Excessive ROS generation by microglia contributes to the aggravation of neuronal damage after a stroke (Sorce and Krause, 2009). In addition, ROS are known as second messengers in inflammatory reactions (Sayre et al., 2008). In the present study, compound K significantly attenuated LPS-induced ROS production in BV2 cells and primary microglia (Figs. 4A-B). Moreover, compound K suppressed the phosphorylation of p47phox, a major component of NADPH oxidase (Nox2) responsible for microglial ROS release (Fig. 4C) (Sorce and Krause, 2009). Thus, the antioxidant effect of compound K may partly attribute to reduced NADPH oxidase activity. Furthermore, compound K inhibited the LPS-induced phosphorylation of three types of MAPKs, which are also important upstream signaling molecules in inflammatory reactions (Fig. 4D).

**Compound K up-regulated HO-1 expression via ARE**

Next, we examined the effect of compound K on the expression of HO-1, which is known as a key molecule in the resolution of oxidative stress and inflammation (Min et al., 2006). RT-PCR and Western blot analyses showed that compound K increased HO-1 expression at the mRNA and protein levels (Figs. 5A & B). Because the AREs on the HO-1 promoter are critical for HO-1 transcription, we examined the effect of compound K on nuclear protein binding to ARE. As shown in Fig. 5C, compound K significantly
increased the ARE-nuclear protein complex. Moreover, compound K increased ARE-driven luciferase activity (Fig. 5D).

**Compound K repressed inflammatory responses in the septic brain of mice**

To determine whether compound K also reduced microglial activation in *in vivo*, we measured the immunoreactivity of Iba1, which is a marker for activation of microglia (Ito et al., 2001), in the mouse cortex and striatum 3 h after systemic administration of LPS. In the brain of LPS-injected mice, the number of Iba1-positive cells with a densely-stained round shape, indicative of activated cells, was increased compared to controls. However, pre-treatment with compound K (30 mg/kg) reduced the number of activated microglia, as seen following the quantification of activated microglia both in the cortex and the striatum (*p* < 0.01 compared to vehicle; Fig. 6A). In addition, compound K significantly reduced the expression of LPS-induced IL-1β and TNF-α protein in the cortex 6 h after LPS injection (Figs. 6B).

**Neuroprotective and anti-inflammatory effects of compound K on ischemic brain injury in mice**

Inflammation plays important roles in ischemic brain damage (Wang et al., 2007). Based on above results, we further examined the therapeutic potential of compound K on ischemic stroke induced by transient MCAO in mice. As shown in Fig. 7A, pretreatment of compound K (30 mg/kg) significantly decreased the total infarct volume compared to vehicle treatment (46% reduction, *p* = 0.012). The reduction in infarct volume was prominent in the cortex (-56% compared to vehicle, *p* = 0.049), the area of ischemic penumbra, but not in the striatum, which is the ischemic core. These findings
are consistent with the previous reports that the penumbra is salvageable area by neuroprotective therapeutics (Ginsberg, 2003; Shin et al., 2009 and 2010b). Next, we examined the effects of compound K on microglial activation in the ischemic brain by using Iba1 antibody. Iba1 expression was assessed by immunofluorescence labeling in the ipsilateral brain 24 h after MCAO. As shown in Fig. 7B, MCAO led to the appearance of numerous densely-stained, activated microglial cells in the cortex and striatum in vehicle-treated mice. Pre-treatment of compound K significantly reduced the number of activated microglia in the cortex, but not in the striatum (Fig. 7B). The results are correlated with the data in Fig. 7A, which show a reduction in infarct volume in the cortex, but not in the striatum. The data suggest that microglial inactivation is at least partly responsible for the neuroprotective effects of compound K against an ischemic insult.
Discussion

In the present study, we demonstrate the anti-inflammatory effects of compound K in activated microglia *in vitro* and *in vivo*. Compound K suppressed the expression of various inflammatory molecules in LPS-stimulated BV2 cells and primary microglia. The anti-inflammatory effects of compound K were supported by two animal models: systemic inflammation and cerebral ischemia. Compound K suppressed microglial activation induced by systemic LPS administration *in vivo*. In addition, compound K showed neuroprotective effects with reduction of microglial activation in the ischemic brains of mice. Detail mechanistic studies by using *in vitro* cell culture systems revealed that compound K suppresses inflammatory molecules via modulating ROS, MAPKs, NF-κB/AP-1 as well as HO-1/ARE signaling pathways.

A number of studies have reported on the beneficial effects of ginsenosides (ginseng saponins) in the CNS. Ginsenosides potentiate brain functions by promoting neurogenesis and affecting neurotransmission (Liu et al., 2007; Shen and Zhang, 2007). Ginsenosides, such as Rh1, Rh2, Rb1, and Rg1, support memory and learning (Wang et al., 2009; Zhao et al., 2009). Among the ginsenosides, Rb1 is most thoroughly studied for its neuroprotective effects in cerebral ischemia. Several groups have reported that Rb1 prevents ischemic neuronal death by up-regulating the expression of anti-apoptotic Bcl-2, Bcl-XL proteins, and glial-derived neurotrophic factor (GDNF) in rats subjected to MCAO (Yuan et al., 2007; Zhang et al., 2006). Because Rb1 is metabolized into compound K by intestinal microflora before absorption in the body (Akao et al., 1998; Bae et al., 2004), the *in vivo* anti-ischemic effect of ginsenoside Rb1 might be due to the metabolites. In support of this notion, the present study demonstrates that compound K exerts protective effects against ischemic stroke. We found that compound K reduced
ischemic brain injury in the cortex, but not in the striatum, which is destined to be the necrotic core (Fig. 7A), indicating that compound K can be an effective therapeutic to rescue the salvageable penumbra from ischemic insults. In addition, we found that compound K repressed microglial activation, which contributes to ischemic brain damage by releasing proinflammatory cytokines and free radicals (Wang et al., 2007). The number of morphologically activated microglia that were detected prominently at 24 h after MCAO (Shin et al., 2010b) was decreased in the ischemic cortex of mice pretreated with compound K (Fig. 7B). The repression of microglia is not likely a result of reduced infarct volume because cortical infarction was not definitely visible at 24 h after MCAO, the time point that Iba-1 expression was examined. The reason that compound K repressed microglial activation only in the cortex might be explained by the different pathophysiology between the core and the penumbra. It has been shown that molecules released from damaged neurons, such as ATP and glutamate, activate microglia (Volonte et al, 2003), and the activated microglia can again increase neuronal death by releasing cytotoxic agents such as cytokines, ROS, proteases and glutamate (Kato and Kogure, 1999). Therefore, more prominent activation of microglia in the striatum may indicate more severe cytotoxic responses in the core of infarction, and the dose or treatment timing of compound K may not be enough to repress microglial activation in the core area. Although a direct link between microglial activation and neuroprotection by compound K remains to be further investigated in ischemic stroke models, we suggest that the reduction of infarct volume by compound K is associated with repression of microglial activation, and the data support the concept that the penumbra is salvageable area by suitable protective drugs.
Effects of compound K on microglial activation was further supported by studies using mice exposed to systemic administration of LPS, an acute model of infection causing inflammation in global area of the brain (Qin et al., 2007; Shin et al., 2010a). Compound K reduced microglial activation not only in the cortex but also in the striatum because there was no regional difference of injury severity between the cortex and the striatum in this model. Furthermore, compound K also reduced the expression of proinflammatory cytokines IL-1β and TNF-α (Fig. 6). Collectively, the data support the view that anti-inflammatory action may be one of the factors contributing to the neuroprotective effects afforded by compound K.

In BV2 microglial cells and primary cultured microglia, compound K inhibited not only the expression of pro-inflammatory molecules (iNOS, TNF-α, IL-1β, IL-6, MCP-1, and MMP-3/-9) but also ROS production. A recent paper reported on in vitro antioxidant properties of compound K (Lee et al., 2011). Compound K exhibits strong radical scavenging activities against DPPH (1,1-diphenyl-2-picrylhydrazyl), hydroxyl, superoxide and ABTS (2,2’-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid). Compound K also inhibited lipid peroxidation. Another paper reported that compound K regulates zymosan-induced inflammatory signaling through inhibition of ROS (Cuong et al., 2009). Therefore, the results suggest that compound K may be a useful antioxidant agent against reactive oxygen species.

In the present study, we found that compound K increased HO-1, which is known to have antioxidant, anti-apoptotic, and anti-inflammatory functions (Naidu et al., 2009). Previous studies have shown a link between HO-1 activity and reduction in iNOS expression (Min et al., 2006). In addition, HO-1 inhibits LPS-induced TNF-α and IL-1β expression through suppression of NF-κB (Rushworth et al., 2008). Furthermore,
carbon monoxide (CO), one of the products of HO-1, inhibits NADPH oxidase and TLR4, which are involved in LPS signaling (Nakahira et al., 2006). Thus, the induction of HO-1 may provide the basis not only for the anti-inflammatory activity of compound K, but also the antioxidant activity.

When we examined the effects of compound K on various transcription factors involved in the regulation of inflammatory molecules, compound K was shown to inhibit NF-κB and AP-1 activities, while increasing nuclear protein binding to CRE and ARE in LPS-stimulated microglia. Recent studies indicate that CREB, as well as Nrf2 (ARE binding protein), play a role in the regulation of ROS detoxification (Lee et al., 2009). In addition, the anti-oxidant enzyme, HO-1, has been shown to be under the influence of the CREB/CRE transcriptional pathway (Lee et al., 2009; Min et al., 2006). Therefore, CREB, in concert with HO-1, appears to play an important role in compound K-mediated anti-inflammation/anti-oxidant effects in microglia.

A recent study reported that compound K acts as an agonist of glucocorticoid receptor (GR) and induces tolerance to endotoxin-induced lethal shock (Yang et al., 2008). They suggested that the therapeutic effect of compound K on lethal sepsis is mediated through the modulation of TLR4-associated signaling via GR. Thus, the GR agonist function might be also related with the anti-inflammatory effects of compound K in our neuroinflammatory model systems. Further studies will be necessary to clarify this issue.

In conclusion, we report for the first time the anti-inflammatory effects of compound K in microglial cell culture systems and two in vivo models of brain disease in which inflammation plays important roles. Furthermore, the neuroprotective effect of compound K was demonstrated in a mouse model of ischemic brain injury. Detailed
mechanistic studies indicate that the inhibition of ROS, MAPKs, and NF-κB/AP-1, and the enhancement of the CREB and Nrf2/HO-1 signaling axis are responsible for strong anti-inflammatory/antioxidant effects of compound K in activated microglia.

Therefore, compound K is a promising therapeutic agent for prevention and/or treatment of ischemic brain injuries and other neurodegenerative diseases, which are accompanied by microglial activation.
Authorship Contributions

Participated in research design: E.M. Park, and H.S. Kim

Conducted experiments: J.S. Park, Shin, Jung, and E.M. Park

Contributed new reagents or analytical tools: Hyun, Le, and D.H. Kim

Performed data analysis: E.M. Park, and H.S. Kim

Wrote or contributed to the writing of the manuscript: J.S. Park, E.M. Park, and H.S. Kim
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Footnotes

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H.S.K. and E.M.P. contributed equally to this work.
Legends for Figures

Fig. 1. The chemical structure of compound K.

Fig. 2. Compound K inhibits the expressions of proinflammatory molecules in LPS-stimulated BV2 and primary microglial cells. (A) Cells were pre-treated with compound K for 1 h, followed by treatment with LPS (0.1 μg/ml) for 24 h. The amounts of nitrite in the supernatants were measured using Griess reagent, and TNF-α and IL-1β were measured by ELISA. The data are expressed as the mean ± S.E.M. of four independent experiments. *P < 0.05, compared to the value in cells treated with LPS alone. (B) Total RNA was isolated from microglial cells treated with LPS in the absence or presence of compound K for 6 h, and RT-PCR was performed to determine the mRNA levels of iNOS, TNF-α, IL-1β, IL-6, MCP-1, MMP-3 and MMP-9. The data are representative of three independent experiments.

Fig. 3. Compound K inhibits DNA binding activities of NF-κB and AP-1 with increasing nuclear protein binding to CRE. (A) Electrophoretic mobility shift assay (EMSA) for NF-κB DNA binding activity. The arrow indicates a DNA-protein complex of NF-κB. ‘F’ indicates free probe. Antibody supershift assay data is shown in the right panel. Coincubation with p65 or p50 antibody but not with Sp1 antibody diminished formation of NF-κB complex and/or generated supershift bands as indicated by arrows. (B) NF-κB reporter gene assay. BV2 cells were transfected with (κB)3-luc plasmid and pre-treated with compound K for 1 h before addition of LPS. After 6 h of LPS treatment, cells were harvested and the luciferase assay was performed. Values correspond to the mean ± S.E.M. of three independent experiments performed in duplicate. *P < 0.05,
significantly different from the value in cells treated with LPS alone. (C, D) EMSA for AP-1 and CRE binding activity. The autoradiograms are representative of three independent experiments.

**Fig. 4. Compound K inhibits LPS-induced ROS production and phosphorylation of NADPH oxidase p47\(^{phox}\) and MAP kinases.** (A) BV2 and primary microglial cells were pre-treated with compound K for 1 h, followed by treatment with LPS (0.1 μg/ml) for 16 h. Then, the intracellular ROS levels were measured by the DCF-DA method as described in the Materials and Methods section. The data are expressed as the mean ± S.E.M. of three independent experiments. *P < 0.05, significantly different from LPS-treated sample. (B) The representative picture of DCF-derived fluorescence in BV2 cells (n = 3). (C) Western blot analysis for phosphorylation of p47\(^{phox}\) in BV2 cells and densitography. Values correspond to the mean ± S.E.M. of three independent experiments. *P < 0.05, significantly different from LPS-treated samples. (D) Western blot detection of MAP kinases phosphorylation in BV2 cells. The blots are representative of four independent experiments.

**Fig. 5. Compound K increased HO-1 expression and ARE-mediated transcriptional activities in LPS-stimulated microglia.** (A) Western blot analysis shows the effect of compound K on HO-1 protein expression. BV2 cells were treated with compound K with or without LPS for 24 h and cell lysates were obtained. (B) RT-PCR was performed to determine the HO-1 mRNA expression. Quantification data are shown in the graph (n = 3). (C) EMSA for nuclear protein binding to ARE element (n = 3). The arrow indicates a DNA-protein complex of ARE. (D) BV2 cells were
transfected with ARE-luc plasmid and pre-treated with compound K for 1 h before addition of LPS. After 6 h of LPS treatment, cells were harvested and the luciferase assay was performed. Data are the mean ± S.E.M. of three independent experiments. *P < 0.05, significantly different from the control sample. #P < 0.05, significantly different from the LPS-treated sample.

**Fig. 6. Compound K reduced inflammatory responses in the septic brain of mice.**
(A) Immunofluorescence labeling of Iba1 and quantification of the number of activated Iba1-positive cells in the cortex and striatum 3 h after systemic LPS treatment (5 mg/kg). Representative images were obtained from one set of experiments and three experiments were done independently. Veh, vehicle; Comp K, compound K. The data are the mean ± S.E.M. (B) Western blots for IL-1β, TNF-α, and actin in the cortex 6 h after LPS treatment, and quantification of IL-1β and TNF-α protein levels with normalization by actin (n = 3 in each group). Values (mean ± S.E.M.) are the ratio vs. controls (assigned a nominal value of 1). *P < 0.05, significantly different from the value in control mice. #P < 0.05, significantly different from the value in vehicle-treated mice.

**Fig. 7. Compound K reduced ischemic brain injury of mice and suppressed microglial activation in the post-ischemic brain.** (A) Representative brain sections of cresyl violet staining and infarct volumes in total brain, cortex, and striatum from mice pre-treated with vehicle (n = 7) or compound K (n = 8). Dotted lines in brain sections indicate infarcted areas. *P < 0.05, significantly different from vehicle treated mice. The data are the mean ± S.E.M. (B) Immunofluorescence labeling and quantification of
Iba1-positive cells (green) in the cortex and striatum 24 h after MCAO. Representative images from one of three independent experiments are shown. Comp K, compound K. The data are the mean ± S.E.M. *P < 0.05, significantly different from the value in control mice. #P < 0.05, significantly different from the value in vehicle-treated mice.
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Fig. 3

A

+ LPS

Comp K (−) 0 25 50 (μM)

NF-κB

NF-κB

B

 Reporter plasmid: (κB)₃-Luc

Relative luciferase activity

Comp K (−) 0 25 50 (μM)

+ LPS

C

+ LPS

Comp K (−) 0 25 50 (μM)

AP-1

D

+ LPS

Comp K (−) 0 25 50 (μM)

CREB

Ab : (−) α p50 α p65 α Sp1

* supershift α p50 α p65 α Sp1

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Fig. 4

A

[**Fig. 4**

- Diagram of ROS production (fold induction) for BV2 cells and primary microglia with Comp K at different concentrations (+/- LPS).
- Graphs showing the effect of LPS on ROS production with and without Comp K.

B

- Images showing ROS production in BV2 cells and primary microglia with LPS and Comp K.

C

- Graph showing the effect of LPS on p-p47phox and β-actin expression with Comp K at different concentrations.
- Fold Induction of p-p47phox/β-actin with asterisks indicating statistical significance.

D

- Diagram showing the effect of LPS on various signaling molecules with Comp K at different concentrations.
- Bar graphs for p-ERK, ERK, p-JNK, JNK, p-p38, and p38.

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**Fig. 5**

A. Comp K 0 25 50 (μM)

B. Comp K 0 25 50 (μM)

C. Comp K 0 0 25 50 (μM)

D. Reporter plasmid: ARE-Luc

Relative luciferase activity

Comp K (-) 25 50 0 25 50 (μM)

+ LPS
Fig. 6
Fig. 7