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Running Title: Anti-inflammatory effects of LA-Dec hybrid

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ABSTRACT

The anti-inflammatory effects of α-lipoic acid (LA) and the decursinol (Dec) hybrid compound LA-Dec were evaluated and compared with its prodrugs, LA and Dec. LA-Dec dose-dependently inhibited lipopolysaccharide (LPS) and generated nitric oxide (NO) in BV2 mouse microglial cells, whereas no or mild inhibitory effect was shown by Dec and LA, respectively. LA-Dec demonstrated dose-dependent protection from activation-induced cell death in BV2 cells. LA-Dec, but not LA or Dec individually, inhibited LPS-induced increased expressions of induced NO synthase (iNOS) and cyclooxygenase-2 (COX-2) proteins in a dose-dependent manner in both BV2 and mouse macrophage, RAW264.7 cells. Furthermore, LA-Dec inhibited LPS-induced expressions of iNOS, COX-2, interleukin-6, tumor necrosis factor-α, and interleukin-1β mRNA in BV2 cells, whereas the same concentration of LA or Dec was ineffective. Signaling studies demonstrated that LA-Dec inhibited LPS-activated signal transducer and activator of transcription 3 and protein kinase B activation, but not nuclear factor-kappa B or mitogen-activated protein kinase signaling. The data implicate the LA-Dec hybrid compound as a potential therapeutic agent for inflammatory diseases of the peripheral and central nervous systems.

INTRODUCTION

Microglia are brain macrophages that function as primary inflammatory cells of the central nervous system (CNS). Over-activation or sustained activation of microglia are often associated with the pathogenesis of neurodegenerative diseases through the increased neuronal cell death [1]. Increased nitric oxide (NO) production is proposed as a key mediator of neuronal death induced by microglial activation. Of the three different isoforms of NO synthase (NOS), endothelial, neuronal, and inducible NOS (iNOS), the gene encoding iNOS is increased in response to lipopolysaccharide (LPS) or proinflammatory cytokines [2, 3].

Alpha-lipoic acid (LA) is a natural antioxidant found in plant and animals [4]. LA also displays anti-inflammatory and regulatory effects on metabolic diseases, such as diabetes [5, 6]. Although LA exerts health benefits, it is not readily bioavailable because of low solubility, low gastric absorption, and high metabolic rate in the liver [7]. Hybrid drugs possess improved efficacy and bioavailability compared to a two-drug cocktail. Hybridization can potentially synergize, amplify, or modify the effects of the individual drug components [8].

In the current study, we investigated the anti-inflammatory effects and toxicity of a hybrid drug composed of LA and decursinol (Dec), and compared these effects with those produced by LA and Dec individually. Dec is a naturally present coumarin derivative with diverse pharmacological activities in cognitive dysfunction and neurotoxicity [9-11]. The LA-Dec hybrid molecule protects neurons from ischemic damage in the hippocampus by inhibiting glial activation [12]. This study further investigated the anti-inflammatory effects of the LA-Dec hybrid in the LPS-induced expression of iNOS/NO at the cellular level and identified the relevant signaling pathways. The findings implicate LA-Dec as a potentially useful therapeutic compound for inflammation in the peripheral and central nervous systems.

RESULTS

Effects of LA, Dec, and LA-Dec on LPS-induced NO generation in BV2 cells

The LA-Dec hybrid compound can protect pyramidal neurons from ischemic injury and can reduce inflammation in the brain after ischemic injury [12]. To further examine the anti-inflammatory effect of LA-Dec in the cell system, we compared the effects of LA, Dec, and the LA-Dec hybrid compound on LPS-induced NO generation and LPS-induced cytotoxicity in BV2 cells. BV2 cells were treated with the indicated concentrations of LA, Dec, or LA-Dec for 2 h prior to the 24-h stimulation with LPS (100 ng/ml). LPS-induced nitrite production was suppressed by LA-Dec in dose-dependent manner (Fig. 1A). LA, but not Dec, significantly but much less effectively inhibited LPS-induced nitrite production. LA-Dec (30 μM), but not LA or Dec individually, suppressed LPS-induced NO production in RAW264.7 cells (data not shown).

Examination of the cytotoxic effects of LA, Dec, and LA-Dec in the presence and absence of LPS in BV2 cells revealed that LA and Dec did not significantly affect cell viability or proliferation, while LA-Dec dose-dependently increased proliferation of BV2 cells (Fig. 1B). LA-Dec, but not LA or Dec, strongly and dose-dependently inhibited activation-induced cell death of BV2 cells in response to LPS.

Effects of LA, Dec, and LA-Dec on LPS-induced iNOS and COX-2 protein expression in BV2 cells

The effect of LA-Dec, LA, and Dec on LPS-induced iNOS and COX-2 expression was assessed. BV2 (Fig. 2, left panels) or RAW264.7 (Fig. 2, right panels) cells were treated with the indicated concentrations of LA-Dec, LA, or Dec for 2 h prior to stimulation with LPS (100 ng/ml). Stimulation of BV2 or RAW264.7 cells with LPS induced the expression of iNOS and COX-2 proteins at 24 h. LA-Dec inhibited the expression of iNOS and COX-2 protein in a dose-dependent manner in BV2 and RAW264.7 cells, while the same doses of LA or Dec were ineffective.

LA-Dec inhibits cell death and mRNA upregulation of proinflammatory molecules in response to LPS in BV2 cells

We examined the effects of LA-Dec on cell morphology and LPS-induced expression of inflammatory genes that have been reported to be induced by the LPS in microglia. BV2 cells were treated with 30 μM LA, Dec, or LA-Dec for 2 h prior to stimulation with LPS (100 ng/ml) for 24 h. As previously reported [13], morphological examinations by microscopy indicated that LPS caused activation-induced cell death at 24 h in BV2 cells (Fig. 3A). LA-Dec significantly protected from activation-induced cell death and inhibited LPS-induced nitrite production (Fig. 3B). However, LA or Dec exerted no protective effects. Furthermore, stimulation of BV2 cells with LPS (100 ng/ml) induced the increased mRNA expressions of iNOS, COX-2, interleukin (IL)-6, IL-1β, and tumor necrosis factor-alpha (TNFα) at 24 h. Pretreatment with 30 μM LA-Dec inhibited LPS-induced expressions of iNOS, COX-2, IL-6, IL-1β, and TNFα as measured by RT-PCR and quantitative real time PCR (Fig. 3C). However, the same dose of LA or Dec did not inhibit the mRNA levels of these inflammatory molecules.

LA-Dec suppresses LPS-induced STAT3 and Akt phosphorylation

We next examined the effect of LA-Dec on the activation of mitogen-activated protein kinases (MAPKs), protein kinase B (Akt), nuclear factor-kappa B (NF-κB), and signal transducer and activator of transcription 3 (STAT3), the major signaling proteins involved in the regulation of the expression of the inflammatory mediators. LA-Dec, LA, and Dec did not influence LPS-induced phosphorylation of ERK1/2, p38, JNK, or IκBα at 30 min, 2 h, and 6 h in BV2 cells (Fig. 4A). However, LA-Dec significantly inhibited Akt phosphorylation (Ser473) at 2 and 6 h LPS treatment in BV2 (Fig. 4B, upper panels) and at 6 h in RAW264.7 cells (Fig. 4B, lower panels). Furthermore, LA-Dec inhibited LPS-induced phosphorylation of STAT3 (Ser727) at 2 h in BV2 cells and at 2 and 6 h in RAW264.7 cells. The same dose of LA or Dec did not inhibit the LPS-induced Akt or STAT3 phosphorylation in BV2 and RAW264.7 cells.

DISCUSSION

Previous studies in stroke mouse models have shown that LA-Dec protects against brain ischemic damages, potentially by inhibiting brain inflammation. However, the anti-inflammatory activity of LA-Dec at the cellular level is unknown. In the current study, we investigated the anti-inflammatory effects of the LA-Dec hybrid compound and compared with its lead compounds, LA and Dec, in BV2 microglia and RAW264.7 macrophage cells. We have previously reported that acetylated LA hybridized to dopamine exhibits a strong anti-inflammatory effect in response to LPS in both BV2 and RAW264.7 cells [14]. However, cytotoxic effects was observed when BV2 or RAW264.7 cells were incubated with concentrations of the LA-dopamine hybrid exceeding 40 μM, particularly with longer incubation (> 48 h). The findings indicated that an LA hybrid compound with minimum cytotoxicity could have better therapeutic benefit in terms of anti-inflammatory activity. Presently, the LA-Dec hybrid displayed no cytotoxic effect at 24 and 48 h up to a concentration of 100 μM. Instead, it promoted BV2 cell proliferation at 1, 10, 20, and 30 μM in the presence or absence of LPS. It has been previously shown that LA promotes neuroproliferation through its antioxidant activity [15]. Therefore, LA-Dec potentially increased BV2 cell proliferation through its antioxidant activity. Although the underlying mechanism by which LA-Dec increases microglia proliferation remains unclear, the LA-Dec hybrid may protect from ischemia-induced neuronal injury through the anti-inflammatory effect and the increased proliferation of glial cells.

MAPKs and NF-κB are important regulators of various genes involved in immune and inflammatory responses, including iNOS and COX-2 [16]. LPS stimulation induces the phosphorylation of p38 MAPKs, ERK-1/2, and JNK, leading to the activation of NF-κB in macrophages and microglia. LA-Dec did not inhibit MAPKs or IκB activation in response to

LPS. Rather, LA-Dec slightly increased LPS-induced NF-κB activity measured by reporter assay (data not shown), suggesting that the anti-inflammatory effect of LA-Dec is independent of MAPKs or NF-κB. LA-Dec, instead, inhibited LPS-mediated activation of the Akt and STAT3 phosphorylation. The JAK-STAT signal pathway plays myriad and pivotal roles in immune and inflammatory responses [17]. We have previously shown that inhibition of STAT signaling reduces iNOS expression and that the inhibition of NF-κB in turn, inhibits STAT3 activation and completely suppresses iNOS induction in response to LPS in BV2 cells [18], suggesting that STAT3 is one of the many downstream targets of NF-κB that regulates iNOS transcription. However, our results implied that LA-Dec regulated STAT3 in an NF-κB-independent manner. LA-Dec potentially suppressed STAT3 phosphorylation in the Akt-associated signaling pathway for iNOS induction. A previous study reported that activation of Akt and STAT3 signaling increases the survival and proliferation of microglia [19], implicating Akt and STAT3 activation in microglia proliferation. Furthermore, inhibition of Akt with LY294002 inhibits STAT3 phosphorylation, suggesting that the Akt pathway is responsible for STAT3 phosphorylation in rat hippocampal neurons [20]. In particular, based on previous observation that Akt and STAT3 signalings play critical roles in TLR-linked inflammation [21], we propose that LA-Dec regulates Akt-dependent STAT3 signaling and modulates LPS-induced neuroinflammatory responses. However, the detailed underlying mechanisms of Akt-STAT3 signaling regulations in response to LPS and/or LA-Dec remain to be elucidated.

In conclusion, LA-Dec can suppress the phosphorylation of STAT-3 and Akt in LPS-stimulated BV2 microglia or RAW264.7 macrophages, which may positively correlate with the downregulation of iNOS and other proinflammatory molecules. Accordingly, LA-Dec may serve as a promising therapeutic compound in the treatment of neurodegenerative or other inflammation-related diseases, either alone or as an adjunct to enhance the efficacy of immuno-regulating molecules.

MATERIALS AND METHODS

Reagents

Except where otherwise noted, all reagents were purchased from Sigma-Aldrich (St. Louis, MO).

Synthesis of LA-Dec

Decursin and decursinol angelate were isolated from Dang Gui. Both were hydrolyzed under a NaOH basic condition to obtain Dec. Dec-LA was synthesized as previously described [12]. In brief, Dec (500 mg, 2.03 mmol) and LA (Xi'an Union Pharmpro Co., Xi'an, China; 0.86 g, 4.47 mmol) were hybridized in the presence of 4-dimethylaminopyridine (DMAP; 120 mg, 1.02 mmol) and 1-ethyl-3-(3-dimethylaminopropyl)carbodiimide (EDC; 86 mg, 4.47 mmol) in 20 ml CH_2Cl_2 (450 mg, 51% yield).

Cell Cultures

The BV2 murine microglial cell line is a suitable model for *in vitro* studies of activated microglia [13]. BV2 microglia and RAW264.7 macrophage cells were maintained at 37°C in an atmosphere of 5% CO_2 in Dulbecco's modified Eagle's medium supplemented with 10% fetal bovine serum (Hyclone, Logan, UT), streptomycin, and penicillin.

Cell Viability

Cell viability was measured by the 3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyltetrasolium bromide (MTT) assays as described previously [14]. In brief, BV2 cells were seeded in each well of 24-well plates at a density of 5×10^4 cells/well. After 24 h, cells were stimulated with LPS (100 ng/ml) and/or LA, Dec, or LA-Dec. MTT solution (50 µl) was added to each well and the plates were incubated in the dark for 4 h at 37ºC. Formazan crystals that formed in viable cells were dissolved in a solution containing equal volumes of dimethylsulfoxide and ethanol. Absorbance at 595 nm was read on a microplate reader. The results are expressed as a percentage (%) of the untreated control.

Nitrite Measurement

The level of nitrite, as an index of NO production, was measured in the supernatant of BV2 cells by the Griess method [14]. Cells were seeded in each well of 24-well plates at a density of 5×10^4 cells/well. After 24 h, cells were stimulated with LPS (100 ng/ml) and/or LA, Dec, or LA-Dec. Nitrite accumulation in the culture medium was measured at various time points by adding equal volumes of Griess reagent (1% sulphanilamide, 0.1% naphthylenediamine 5% phosphoric acid) and samples of medium. The optical density at 550 nm (OD 550) was measured with a microplate reader. Sodium nitrite diluted in culture medium (10–100 µM) was used to generate a standard curve.

RT-PCR and Quantitative Real-time PCR

Total RNA from BV2 cells was extracted with TRIzol™ (Invitrogen, Carlsbad, CA). RNA samples were reverse-transcribed into cDNA using SuperScript II. PCR was performed using specific mouse primers described below (Table 1). Gene expression values were compared with the housekeeping gene glyceraldehyde 3-phosphate dehydrogenase (GAPDH). The PCR reaction mixture (15 µl) contained 1.5 mM magnesium chloride ($MgCl_2$), 250 µM deoxy-nucleoside triphosphate, 1.25 units Taq DNA polymerase, 10 picomoles of primer, and 25 ng DNA templates. The PCR products were electrophoresed in 1% agarose gel in

Tris/Borate/EDTA (TBE) buffer. The gels were observed and taken pictures using an ultraviolet imaging apparatus.

The expressions of mRNAs were quantitatively determined by measuring incorporation of fluorescent SYBR green into double-stranded DNA (iCycleriQ; Bio-Rad, Hercules, CA). Relative mRNA levels were calculated from the PCR profiles of each sample using the threshold cycle (Ct), corresponding to the cycle at which a statistically significant increase in fluorescence occurred. Ct is considered the amount of template present in the starting reaction. To correct for differences in the amount of total cDNA in the initial reaction, Ct values for an endogenous control (input DNA) were subtracted from those of the corresponding sample. All real-time PCR data presented are the results of two independent DNA preparations and amplifications.

Mouse PCR primers used in this study

	Forward Primer	Reverse Primer
iNOS	ACTTCCGAGTGTGGAACTCG	TGGCTACTTCCTCCAGGATG
COX-2	GCTGTACAAGCAGTGGCAAA	GTCTGGAGTGGGAGGCACT
IL-1β	GGAGAAGCTGT GGCAGCTA	GCTGATGTACCAGTTGGGGA
IL-6	CCGGAGAGGAGACTTCACAG	TGGTCTTGGTCCTTAGCCAC
TNF-α	GACCCTCACACTCAGATCAT	TTGAAGAGAACCTGGGAGTA
GAPDH	TCATTGACCTCAACTACATGGT	CTAAG CAGTTGGTGGTGCAG

Immunoblotting

Total cell protein was prepared by lysing the cells in buffer (10 mM Tris, 140 mM NaCl, 1% Triton, 0.5% sodium dodecyl sulfate (SDS), and protease inhibitors; pH 8.0).

Prepared protein samples (20-40 μg protein each) were separated by SDS-PAGE and transferred to Hybond^{TM}-ECL^{TM} nitrocellulose membranes (Amersham Biosciences, Piscataway, NJ). All of the antibodies used were from Santa Cruz Biotechnology (Santa Cruz, CA), except antibodies against iNOS (BD Biosciences, San Jose, CA), COX-2 (Cayman Chemicals, Ann Arbor, MI), GAPDH (Cell Signaling Technology, Danvers, MA), extracellular signal-regulated kinase (ERK)1/2 (Cell Signaling Technology), phospho- c-Jun NH_2-terminal kinase (p-JNK) (Invitrogen), JNK (Cell Signaling Technology), p-P38 (Cell Signaling Technology), and α-tubulin (Calbiochem, Darmstadt, Germany). The membrane was incubated with antibodies for overnight at 4°C. After washing with TBST (50 mM Tris, 150 mM NaCl, and 0.05% Tween 20; pH 7.6), the membrane was incubated in a buffer containing horseradish peroxidase-conjugated secondary antibody (1:10,000 dilution in TBST) for 1 h at room temperature. The protein bands were detected using an ECL detection reagent (Amersham Biosciences).

Statistical Analysis

Data are expressed as the mean ± standard deviation (S.D., error bars) of three independent experiments and analyzed for statistical significance using an unpaired Student's *t* test. A *p*-value <0.05 was considered significant.

ACKNOWLEDGMENTS

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CONFLICTS OF INTEREST

The authors declare no competing interests.

FIGURE LEGENDS

Figure 1. Examination of LPS-induced nitrite production and cytotoxicity by decursinol (Dec), lipoic acid (LA) and LA-Dec hybrid in BV2 cells

BV2 cells were pre-treated with the indicated concentrations of LA, Dec, or LA-Dec for 2 h and stimulated with 0.1 μg/ml LPS. Nitrite levels in the culture medium were measured at 24 h (A). Cell viability was determined using the MTT assay, and the results are expressed as percentages compared to the untreated control (B). * represents significant differences from untreated control; ** represents significant differences from the LPS-treated samples

Figure 2. Inhibition of expression of LPS-induced iNOS and COX-2 proteins by LA-Dec

(A) BV2 (left panel) or RAW264.7 (right panel) cells were pre-treated with the indicated concentrations of Dec, LA, or LA-Dec for 2 h and then treated with 0.1 μg/mL LPS for 24 h. iNOS, COX-2, and GAPDH protein levels were measured by Western blotting. The blots are representative of three independent experiments.

Figure 3. Inhibition of mRNA levels of proinflammatory molecules in response to LPS by LA-Dec

BV2 cells were pre-treated with 30 μM of LA-Dec, LA, or Dec for 2 h and stimulated with 0.1 μg/ml LPS. The phenotypes of control, LA-Dec, LA, or Dec treated cells, with or without LPS, were observed using phase-contrast microscopy at 24 h (A). Nitrite levels in the culture medium were measured at 24 h (B). Total RNA was prepared at 24 h and the mRNA levels of iNOS, COX-2, IL-6, TNF-α, and IL-1β were determined using RT-PCR and quantitative real-time PCR. GAPDH mRNA served as a control (C). * represents significantly decreased from the LPS-treated samples. Cell images and RT-PCR results are representative of three independent experiments.

Figure 4. Inhibition of LPS-induced activation of Akt and STAT3 phosphorylation by LA-Dec

(A) BV2 cells were pre-treated with 30 μM of LA-Dec, LA, or Dec for 2 h and stimulated with 0.1 μg/ml LPS. Total cell lysates were prepared at 30 min, 2 h, or 6 h, and the levels of unphosphorylated- and phosphorylated-ERK1/2, -p38, -JNK, -Akt, and -STAT3 were measured by Western blotting. (B) BV2 (upper panels) or RAW264.7 cells (lower panels) were pre-treated with 30 μM of LA-Dec, LA, or Dec for 2 h and stimulated with 0.1 μg/ml LPS. Total cell lysates were prepared at 30 min, 2 h, or 6 h. The levels of unphosphorylated- and phosphorylated-IκBα, Akt and STAT3 were examined by Western blotting using specific antibodies. The blots are representative of three independent experiments.

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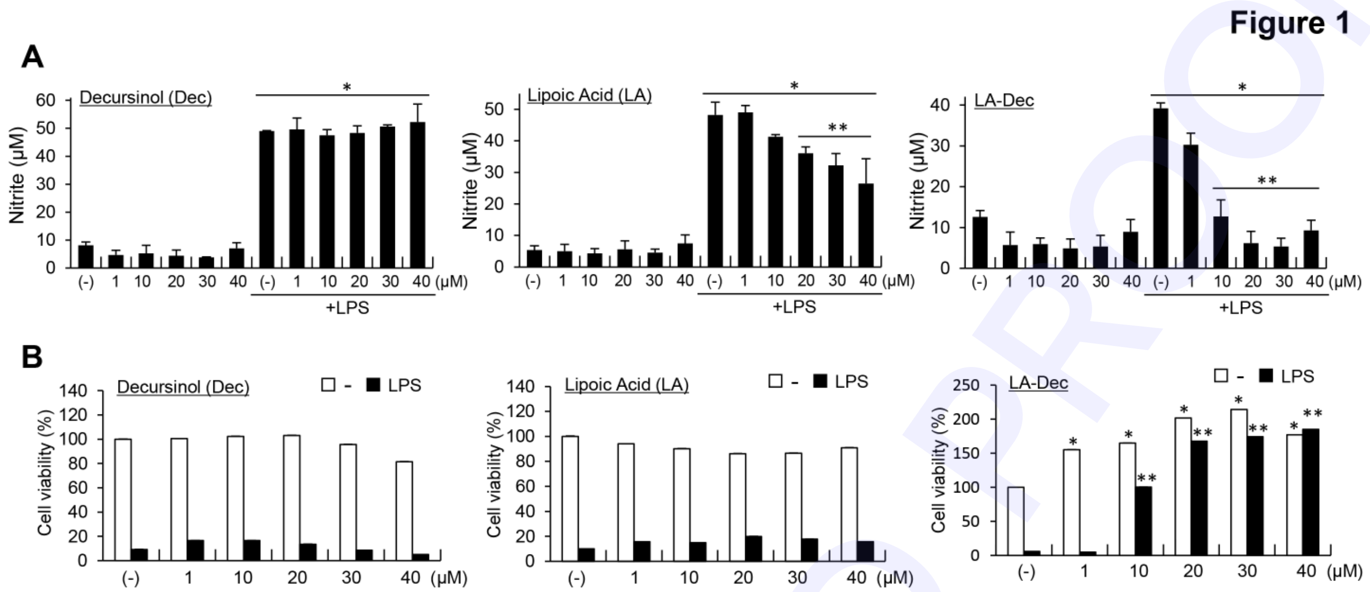
Figure 1
A
Decursinol (Dec)
Nitrite (μM)
(-) 1 10 20 30 40 (-) 1 10 20 30 40 (μM)
+LPS
Lipoic Acid (LA)
LA-Dec
B
Cell viability (%)
- LPS
(-) 1 10 20 30 40 (μM)

Fig. 1. Fig.1

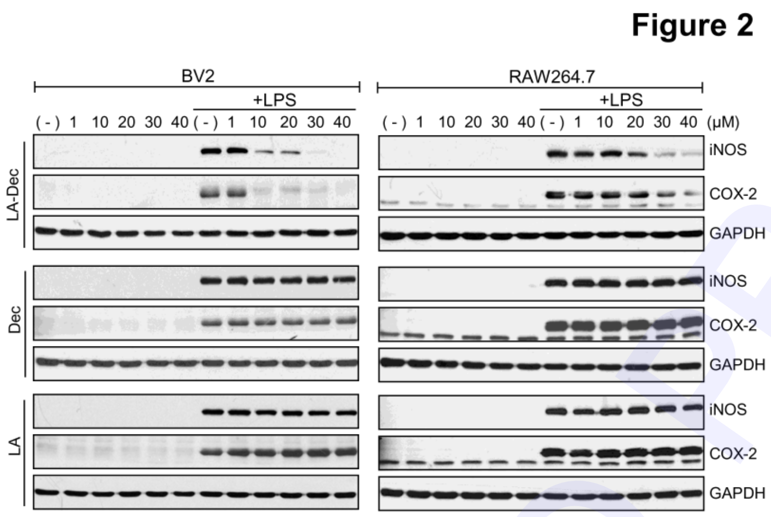
Figure 2
BV2
RAW264.7
+LPS
+LPS
(-) 1 10 20 30 40 (-) 1 10 20 30 40
(-) 1 10 20 30 40 (-) 1 10 20 30 40 (μM)
LA-Dec
Dec
LA
iNOS
COX-2
GAPDH
iNOS
COX-2
GAPDH
iNOS
COX-2
GAPDH

Fig. 2.

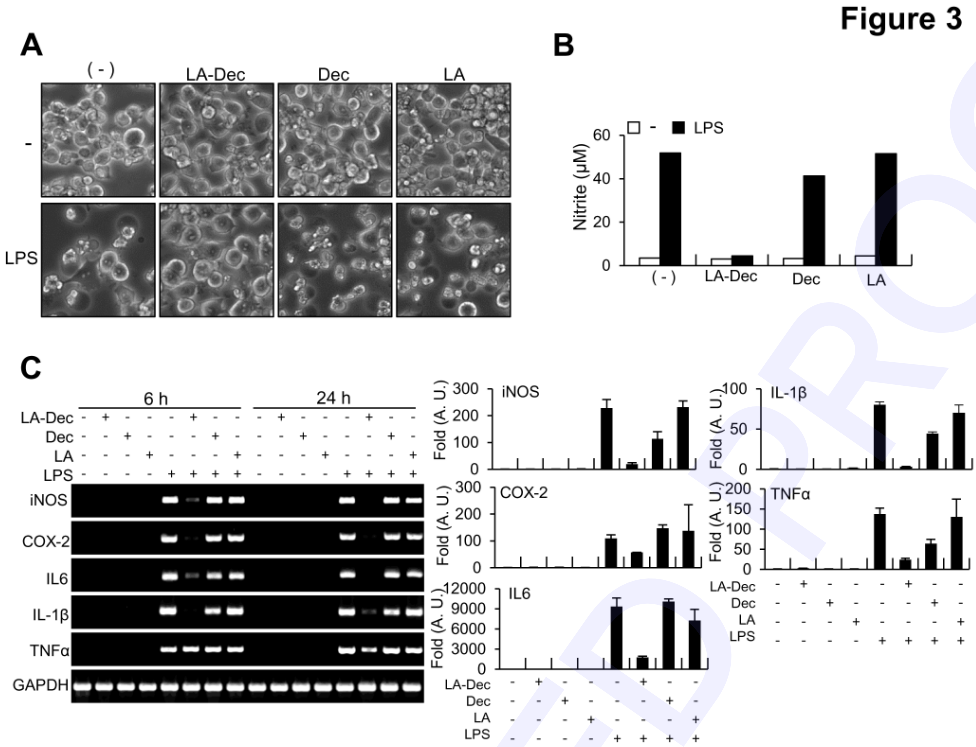
Figure 3
A
(-)
LA-Dec
Dec
LA
-
LPS
B
- LPS
Nitrite (μM)
60
40
20
0
(-)
LA-Dec
Dec
LA
C
6 h
24 h
LA-Dec
Dec
LA
LPS
iNOS
COX-2
IL6
IL-1β
TNFα
GAPDH
Fold (A. U.)
iNOS
IL-1β
COX-2
TNFα
IL6
300
200
100
0
12000
9000
6000
3000
150
50

Fig. 3.

Figure 4

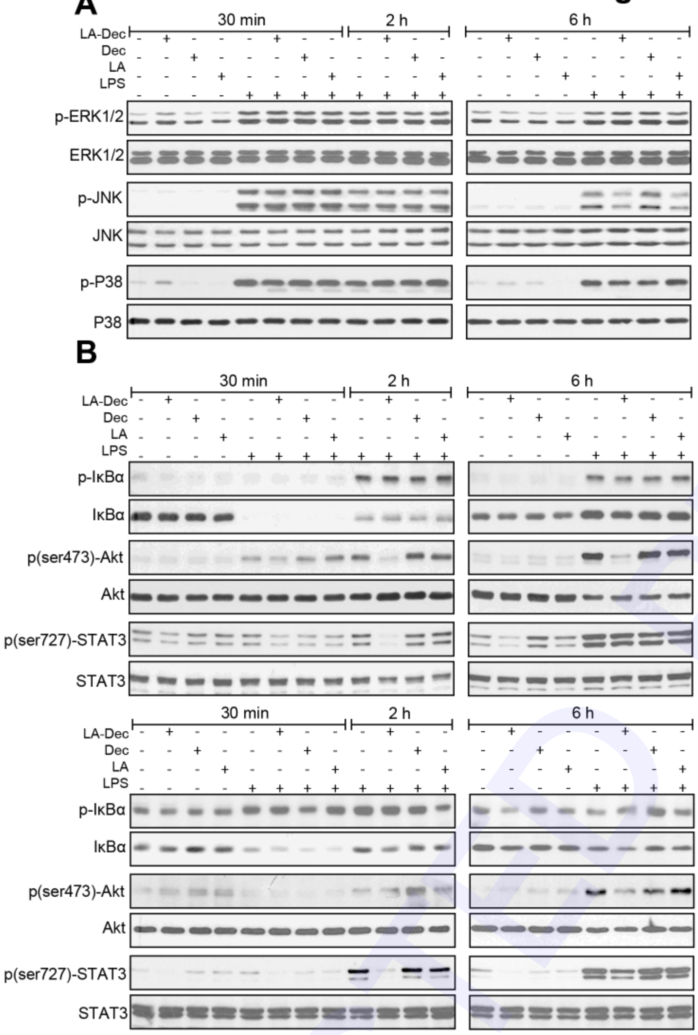

Fig. 4.