



HAL
open science

Lipopolysaccharide Induces GFAT2 Expression to Promote O -Linked β - N -Acetylglucosaminylation and Attenuate Inflammation in Macrophages

Hasanain Al-Mukh, Léa Baudoin, Abdelouhab Bouaboud, José-Luis Sanchez-Salgado, Nabih Maraqa, Mostafa Khair, Patrick Pagesy, Georges Bismuth, Florence Niedergang, Tarik Issad

► To cite this version:

Hasanain Al-Mukh, Léa Baudoin, Abdelouhab Bouaboud, José-Luis Sanchez-Salgado, Nabih Maraqa, et al.. Lipopolysaccharide Induces GFAT2 Expression to Promote O -Linked β - N -Acetylglucosaminylation and Attenuate Inflammation in Macrophages. *Journal of Immunology*, 2020, 205 (9), pp.2499-2510. 10.4049/jimmunol.2000345 . hal-03026534

HAL Id: hal-03026534

<https://hal.science/hal-03026534v1>

Submitted on 26 Nov 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **LPS induces GFAT2 expression to promote O-GlcNAcylation and**
2 **attenuate inflammation in macrophages**

3
4
5 Running title: **GFAT2 is a FoxO1-dependent LPS-inducible gene**

6
7 Hasanain AL-MUKH, Léa BAUDOIN, Abdelouhab BOUABOUD, José-Luis SANCHEZ-
8 SALGADO, Nabih MARAQA, Mostafa KHAIR, Patrick PAGESY, Georges BISMUTH,
9 Florence NIEDERGANG and Tarik ISSAD

10
11 *Université de Paris, Institut Cochin, CNRS, INSERM, F-75014 Paris, France*

12 Address correspondence to: Tarik Issad, Institut Cochin, Department of Endocrinology,
13 Metabolism and Diabetes, 24 rue du Faubourg Saint-Jacques, 75014 Paris FRANCE. Tel : + 33 1
14 44 41 25 67; E-mail: tarik.issad@inserm.fr

15
16

1 **Abstract**

2 O-GlcNAc glycosylation is a reversible post-translational modification that regulates the
3 activity of intracellular proteins according to glucose availability and its metabolism through
4 the hexosamine biosynthesis pathway (HBP). This modification has been involved in the
5 regulation of various immune cell types, including macrophages. However, little is known
6 concerning the mechanisms that regulate protein O-GlcNAcylation level in these cells. In the
7 present work, we demonstrate that LPS treatment induces a marked increase in protein O-
8 GlcNAcylation in RAW264.7 cells, bone-marrow-derived and peritoneal mouse
9 macrophages, as well as human monocyte-derived macrophages. Targeted deletion of OGT in
10 macrophages resulted in an increased effect of LPS on NOS2 expression and cytokine
11 production, suggesting that O-GlcNAcylation may restrain inflammatory processes induced
12 by LPS. The effect of LPS on protein O-GlcNAcylation in macrophages was associated with
13 an increased expression and activity of glutamine fructose 6-phosphate amido-transferase
14 (GFAT), the enzyme that catalyzes the rate-limiting step of the HBP. More specifically, we
15 observed that LPS potently stimulated GFAT2 isoform mRNA and protein expression.
16 Genetic or pharmacological inhibition of FoxO1 impaired LPS effect on GFAT2 expression,
17 suggesting a FoxO1-dependent mechanism. We conclude that *GFAT2* should be considered as
18 a new LPS-inducible gene involved in regulation of protein O-GlcNAcylation, which permits
19 to limit exacerbated inflammation upon macrophage activation.

20

21

22 Key points:

23 - LPS stimulates GFAT2 expression in macrophages via a FoxO1-dependent mechanism

24 - LPS-induced GFAT activity promotes a general increase in protein O-GlcNAcylation

25 - Protein O-GlcNAcylation limits excessive LPS-triggered inflammation in macrophages

26

27

1 **Introduction**

2 O-GlcNAcylation is a post-translational modification that regulates the activity of cytosolic,
3 nuclear and mitochondrial proteins. This modification is controlled by only two enzymes:
4 OGT, that adds N-Acetylglucosamine (GlcNAc) on serine or threonine residues, and OGA,
5 that removes it. O-GlcNAcylation, which regulates a wide array of biological processes (1),
6 depends on the availability of glucose and its metabolism through the hexosamine
7 biosynthesis pathway (**Fig. 1A**). This modification has been involved in the modulation of
8 various signalling pathways, and perturbations of O-GlcNAcylation participate in several
9 important human pathologies (2-4). Moreover, a number of studies indicated a link between
10 O-GlcNAcylation and inflammatory conditions, including diabetes, auto-immune diseases
11 and cancer (5-11). Moreover, several lines of evidence have suggested a role for O-
12 GlcNAcylation in immune cell signalling. Indeed, O-GlcNAcylation was first discovered at
13 the surface of lymphocytes (12) and dynamic changes upon lymphocyte activation were
14 described at the beginning of the nineties (13). More recently, several studies indicated that
15 protein O-GlcNAcylation plays major roles in the immune system. In T cells, TCR (T-cell
16 receptor) activation results in global elevation of protein O-GlcNAcylation (14, 15), increased
17 O-GlcNAcylation of several transcription factors (16-19) and accumulation of OGT at the
18 immunological synapse (14). Moreover, in B lymphocytes, activation of the B-cell receptor
19 (BCR) induces O-GlcNAcylation of several signalling molecules involved in BCR signalling
20 (20, 21). Overall, these studies strongly support a major role in O-GlcNAcylation in adaptive
21 immunity. However, the molecular mechanisms by which immune cell activation modulates
22 protein O-GlcNAcylation remain elusive.

23 In macrophages, contradictory results have been obtained concerning the effect of LPS on
24 protein O-GlcNAcylation and its role in inflammatory processes. Whereas some studies
25 indicated that LPS induced a general increase in protein O-GlcNAcylation (22, 23), others
26 found that LPS decreases protein O-GlcNAcylation in macrophages (24, 25). Moreover,
27 whereas several lines of evidence indicate that increased O-GlcNAcylation of signaling
28 proteins in the NF κ B pathway potentiates inflammatory processes (26-29), other studies
29 indicate that increased O-GlcNAcylation may inhibit pro-inflammatory signals (24, 30). More
30 recently, O-GlcNAcylation of the signalling adaptor MAVS in macrophages has been
31 involved in antiviral signalling response (31), whereas increased RIPK3 O-GlcNAcylation
32 was shown to regulate necroptosis signalling upon LPS stimulation (25). Thus, whereas
33 numerous evidences suggest that modulation of O-GlcNAcylation signalling constitutes an

1 important facet of innate immune response, the mechanisms by which macrophage activation
2 regulates O-GlcNAc, and its consequences on inflammatory processes, remain to be firmly
3 established.

4 In the present work, using different macrophage cell models, we clearly demonstrated that
5 LPS markedly stimulates protein O-GlcNAcylation in macrophages through increased
6 expression and activity of the rate-limiting enzyme of the hexosamine biosynthetic pathway,
7 glutamine fructose-6-phosphate amidotransferase (GFAT). More specifically, we showed that
8 whereas resting macrophages express mainly the GFAT1 isoform, upon LPS stimulation, a
9 marked increase in GFAT2 expression was observed, revealing GFAT2 as a new LPS-
10 inducible gene in macrophages that promotes a general increase in protein O-GlcNAcylation.
11 In macrophages with conditional OGT deletion, lack of LPS-induced O-GlcNAcylation was
12 associated with an increased in the production of pro-inflammatory molecules, suggesting that
13 GFAT2 induction may be part of a regulatory loop that may limit inflammation and/or permit
14 its resolution after TLR4 activation.

15

16

1 **Materiel and Methods**

2 **Chemicals and antibodies**

3 Thiamet G (3aR,5R,6S,7R,7aR)-2-(ethylamino)-3a,6,7,7a-tetrahydro-5-(hydroxymethyl)-5H-
4 Pyrano.thiazole-6,7-diol) and LPS (Lipopolysaccharides) from Salmonella enterica serotype
5 typhimurium were from Sigma-Aldrich (Saint Quentin Fallavier France). FoxO1 inhibitor
6 AS1842856 was from Calbiochem. PUGNAc (*O*-(2-acetamido-2-deoxy-d-
7 glucopyranosylidene)-amino-*N*-phenylcarbamate) was from Toronto Research Chemicals,
8 Inc. (North York, ON, Canada). Anti-GFAT2 antibody (EPR 19095) and Anti-FOXO1A antibody
9 (Chip Grade ab39670) were from Abcam; Anti-GFAT1 (H-49), Anti-NOS2 (N-20), Anti-GAPDH
10 (O411), Anti-Tubulin (TU-02) Anti-UBF (F9) and HRP-conjugated anti-rabbit antibodies were from
11 Santa-Cruz Biotechnology; Anti-FOXO1 antibody for western-blotting (L27) was from Cell
12 Signaling Technology; Anti-O-GlcNAc Transferase antibody (O 6264) was from Sigma; Anti-O-
13 GlcNAcase antibody (NBP2-32233) was from Novus Biologicals, Anti-O-GlcNAc antibody (RL2)
14 was from Thermo Fisher; Anti-Clathrin antibody (610500) was from BD Transduction Laboratories
15 and HRP-conjugated anti-mouse antibody was from Jackson ImmunoResearch, Laboratories.

16

17 **cDNA constructs**

18 The cDNA coding for nuclear, cytosolic and plasma membrane FRET O-GlcNAc biosensors
19 (32) were generously provided by Prof. L.K. Mahal (University of Texas, Austin, USA).
20 BRET biosensors were developed based on these FRET constructs by replacing the CFP by a
21 Rluc8 sequence (33).

22 Human (-801>>>0) and mouse GFAT2 (-501>>>0) putative promoter sequences were
23 amplified by PCR and cloned in a firefly luciferase plasmid (pGL4-20, Promega). FoxO1
24 binding sites on GFAT2 promoter were identified using Regulatory Sequence Analysis Tools
25 (RSAT) web server (<http://rsat.ulb.ac.be/rsat/>). Mutagenesis of Foxo1 binding sites on the
26 mouse GFAT2 reporter gene was performed using mutagenesis kit (QuikChangeII XL-Agilent
27 Technologies).

28 Constitutively active FOXO1-TM (mutated on the 3 Akt phoshorylation sites) has been
29 described previously (34).

30

31 **Cell culture and transfection**

32 RAW264.7 murine macrophage cells were maintained in media constituted of RPMI 1640-
33 glutamax medium supplemented with 10% fetal calf serum (FCS), 50µM β-mercaptoethanol,
34 1 mM sodium pyruvate, 10 mM HEPES and 2 mM L-Glutamine (GIBCO).

1 Plasmid transfections were performed by cell electroporation using the Electrobuffer kit (Cell
2 projects Ltd). For each transfection, cells grown to sub-confluence in a 100 mm plate were
3 transfected with 15 µg of plasmid DNA. Cells were electroporated at 250 V, 900 µF in 0.4 cm
4 cuvettes (Biorad) using the Gene Pulser X electroporation system (Bio-Rad Laboratories).
5 After electroporation, cells were immediately re-suspended in culture medium, transferred into
6 96-well White Optiplates previously coated with polylysine (Perkin Elmer) and then cultured
7 for 18 hours at 37°C and 5% CO₂ before treatments.

8 HEK 293-T cells were cultured in DMEM and transfected with Fugene as described
9 previously (34).

10

11 **Chromatin immunoprecipitation (ChIP):**

12 RAW264.7 cells (1x10⁷ cells) were prepared for ChIP assay using HighCell# ChIP kit protein
13 A (Diagenode). After cross-linking with formaldehyde, DNA was sonicated into 200-300bp
14 fragments, and protein-DNA complexes were immunoprecipitated using either FoxO1-ChIP
15 grade antibody (Abcam, ab39670) or control rabbit IgG. Protein-DNA crosslinks were
16 reversed by heating, and precipitated DNA was quantified by real-time PCR using primers
17 (Suppl. Table 1) that amplify either Foxo1 binding site 1 or 2 present in the 500bp upstream
18 of the transcription start site of the mouse GFAT2 gene.

19

20 **BRET experiments**

21 Transfected cells were treated with LPS (100ng/mL) and/or Thiamet G (10µM) for 24h.
22 BRET experiments were then performed exactly as described previously (35, 36) using the
23 Infinite F200 Pro microplate analyser (Tecan). Briefly, cells were pre-incubated for 5 min in
24 PBS in the presence of 5µM coelenterazine. Each measurement corresponded to the signal
25 emitted by the whole population of cells present in a well. BRET signal was expressed in
26 milliBRET Unit (mBU). The BRET unit has been defined previously as the ratio 530 nm/485
27 nm obtained in cells expressing both luciferase and YFP, corrected by the ratio 530 nm/485
28 nm obtained under the same experimental conditions in cells expressing only luciferase (37,
29 38).

30

31 **Animals**

32 8 to 12 weeks-old C57BL/6J male mice were used. To study the function of Foxo1 in
33 macrophages, we crossed mice carrying two floxed *Foxo1* alleles kindly provided by Prof.
34 Hedricks, Univ. of California, San Diego, USA) with LysM-Cre transgenic mice (kindly

1 provided by Carol Peyssonnaud, Institut Cochin, Paris) in which Cre is specifically expressed
2 in the myelomonocytic cell lineage (LysMCre-Foxo1/Foxo1 knock-out (KO) mice, thereafter
3 referred to as Foxo1-KO mice). To study the role of O-GlcNAcylation on pro-inflammatory
4 effects of LPS, mice with OGT deletion in the myelomonocytic cell lineage were generated by
5 crossing mice carrying two floxed *OGT* alleles (obtained from Jackson laboratories) with
6 LysM-Cre transgenic mice (LysMCre-OGT knock-out (KO) mice, thereafter referred to as
7 OGT-KO mice). All mice were housed in the Institut Cochin animal facility. All experiments
8 were performed in accordance with accepted standards of animal care, as established in the
9 Institut National de la Santé et de la Recherche Médicale (INSERM) and the Centre National
10 de la Recherche Scientifique (CNRS) guidelines and were approved by the national ethical
11 committee (APAFIS N°A751402).

12

13 **Preparation of bone-marrow-derived and peritoneal macrophages from mice.**

14 Mice were sacrificed by CO₂ asphyxiation. Bone marrow-derived macrophages (BMDM)
15 were prepared from bone marrow cells flushed from femurs and tibias (39). Cells were seeded
16 in sterile Petri dishes at the concentration of 10⁶/ml in RPMI medium supplemented with 10%
17 FCS, 100µg/ml gentamycin, 10mM HEPES, 1mM sodium pyruvate, 50µM β-mercaptoethanol
18 and 20ng/mL mouse MCSF (Miltenyi Biotec). Cells were differentiated during 6 days, then
19 washed to eliminate non-adherent cells, and macrophages were detached in cold PBS -/- and
20 seeded in 6 well-plates at 10⁶ cells/ml in complete media. Cells were treated the day after.

21 For peritoneal macrophages collection, after mice sacrifice, the peritoneum was infused with
22 10mL of cold RPMI. Cells were seeded in 6 well-plates at 10⁶cells/ml in complete media and
23 allowed to adhere overnight. Non-adherent cells were then washed away and macrophages
24 treated with LPS.

25 In some experiments, mice were injected intraperitoneally with LPS (0.6 mg/kg). 6h after
26 injection, mice were sacrificed and peritoneal cells were harvested as described above and
27 plated in a 6 well-plate at 37 °C with 5% CO₂. After 2h, non-adherent cells were washed
28 away, and adherent cells were lysed for analysis by western blot.

29 To evaluate the effect of LPS on cytokine production *in vivo* in OGT-KO mice, LPS was
30 injected intraperitoneally, mice were sacrificed 6h after injection and blood was collected by
31 cardiac puncture. Blood was centrifuged at 1500 rpm for 10 min at 4°C and the serum was
32 collected and frozen at -80°C for subsequent determination of cytokine concentrations using
33 MSD kit.

34

1 **Preparation of Human monocytes derived macrophages**

2 Human primary macrophages were isolated from blood of healthy donors (Etablissement
3 Français du Sang, Ile-de-France, Site Trinité, Agreement number INSERM-EFS:18/EFS/030)
4 by density gradient sedimentation on Ficoll (GE Healthcare), followed by negative selection
5 on magnetic beads (Stem cells, Cat n°19059) and adhesion on plastic at 37°C during 2 h. Cells
6 were then cultured in the presence of complete culture medium (RPMI 1640 supplemented
7 with 10 % FCS (Eurobio), 100 mg/ml streptomycin/penicillin and 2 mM L-glutamine (Gibco)
8 containing 10 ng/ml rhM-CSF (R&D systems) during 4-5 days (40).

9
10 **RNA extraction, reverse transcription and qPCR**

11 Macrophages cultured in 6-well plates were lysed in Trizol reagent (Life Technologies). RNA
12 was isolated and reverse transcribed (41). Levels of the cDNA of interest were measured by
13 qPCR (LightCycler FastStart DNA Master SYBR Green 1 kit; Roche Diagnostics). The
14 absence of genomic DNA contamination was verified by treating RNA samples in parallel
15 without reverse transcriptase and controlling for the absence of amplification by qPCR. Gene
16 expression was normalized over cyclophilin and HPRT (Hypoxanthine-guanine
17 phosphoribosyltransferase) RNA levels. The sequences of the primers used for qPCR are
18 given in Supplemental Table 1.

19
20 **OGA enzymatic assay.**

21 Control and LPS-treated RAW264.7 cells were lysed in extraction buffer containing 50mM
22 Tris, 137 mM NaCl, 1% triton, 10% glycerol, phosphatases (50 mM NaF, 10 mM di-sodium
23 β -glycerophosphate, 1 mM Na_3VO_4) and proteases (AEBSF, leupeptine, antipaine aprotinine
24 and pepstatine, 1 μ g/ml each) inhibitors. OGA activity was measured using 4-
25 methylumbellifery-N-acetyl β -D-glucosamine (MU-GlcNAc, Sigma), which is converted into
26 fluorescent 4-methylumbelliferon upon hydrolysis by OGA and other hexosaminidases (42).
27 4-methylumbelliferon fluorescence was measured at 448 nm after excitation at 362 nm.
28 Fluorescent measurements were performed after 30 min and 60 min of incubation at 37 °C, to
29 ensure that the determination was performed during the linear phase of the reaction. To
30 specifically determine OGA activity versus other hexosaminidase present in the lysate, all
31 reactions were performed both in absence and presence of 100 μ M Thiamet G (a specific
32 OGA inhibitor). The difference between the fluorescent signals obtained in absence (activity
33 of OGA plus other hexosaminidases) and presence of Thiamet G (activity of the other
34 hexosaminidases) reflected the amount of 4-methylumbelliferon produced by OGA (9).

1 **OGT enzymatic assay.**

2 Control and LPS-treated RAW264.7 cells were lysed in extraction buffer containing 50mM
3 Tris, 137 mM NaCl, 1% triton, 10% glycerol, phosphatases (50 mM NaF, 10 mM di-sodium
4 β -glycerophosphate, 1 mM Na_3VO_4) and proteases (AEBSF, leupeptine, antipaine aprotinine
5 and pepstatine, 1 μ g/ml each) inhibitors. Immunoprecipitation of OGT was performed as
6 described below. 400 μ g of proteins were incubated with 1.5 μ g of anti-OGT antibody
7 (Sigma-Aldrich) for 2h at 4°C. Precipitation was performed by incubating 25 μ L equilibrated
8 protein G-sepharose beads (GE Healthcare) for 30 min at 4°C. After 3 washes, the
9 precipitated proteins were submitted to an additional wash in OGT assay buffer containing 50
10 mM Tris-HCl and 12.5 mM MgCl_2 , pH7.5. OGT assay was then performed on protein-G
11 sepharose bound OGT (33) using the bioluminescent UDP-Glo™ glycosyltransferase assay
12 (Promega) exactly as described in the manufacturer instructions (43).

13

14 **GFAT enzymatic assay.**

15 Glutamine fructose-6-phosphate amidotransferase enzymatic activity was measured as
16 described previously (44). Control and LPS-treated RAW264.7 cells, human monocyte-
17 derived macrophages or mouse bone-marrow-derived macrophages were lysed in extraction
18 buffer containing 50mM Tris, 137 mM NaCl, 1% triton, 10% glycerol, phosphatases (50 mM
19 NaF, 10 mM di-sodium β -glycerophosphate, 1 mM Na_3VO_4) and proteases (AEBSF,
20 leupeptine, antipaine aprotinine and pepstatine, 1 μ g/ml each) inhibitors. 15-30 μ g of proteins
21 were incubated in a buffer containing 10 mM fructose 6-phosphate, 6 mM glutamine, 0.3 mM
22 3-acetylpyridine adenine dinucleotide (APAD), 50 mM KCl, 100 mM KH_2PO_4 (pH 7.5), 1
23 mM dithiothreitol and 30 unit/ml of glutamate dehydrogenase. After incubation for 30 min at
24 37°C, the change in absorbance due to reduction of APAD to APADH was monitored
25 spectrophotometrically at 365 nm using TECAN™ infinite M1000 Pro Microplate Reader.

26 **Western blotting**

27 Cells were lysed with buffer containing 50mM Tris-HCl (pH 8), 137mM NaCl, 10% (v/v)
28 glycerol, 1% (v/v) triton, 50mM NaF, 10mM di-sodium β -glycerophosphate, 1mM Na_3VO_4 ,
29 protease inhibitors (1 μ g/ml pepstatin, antipain, leupeptin, aprotinin and AEBSF),
30 supplemented with 10 μ M PUGNAc in order to preserve the GlcNAcylation state of proteins
31 during the extraction procedure. Proteins were then analysed by SDS-PAGE followed by
32 western-blotting as described previously (45). Clathrin was used as a loading control, because

1 its molecular weight (180 kDa) is far away from the 50-70 kDa region where many proteins
2 of interest are found (46, 47).

3 In some experiments, O-GlcNAcylated proteins were precipitated on wheat germ lectin as
4 described previously (48, 49). Briefly, cell lysates (400 µg of proteins) were incubated for 2
5 hours at 4° C on a rotating wheel with 20 µl of agarose beads coupled to wheat germ lectin
6 (which binds the N-Acetyl-Glucosamine pattern). At the end of the incubation, the beads were
7 pelleted by centrifugation at 3000 g for 2 min. The supernatant was removed and the pellet
8 was washed 3 times in extracting buffer. Twenty µL of Laemmli sample buffer were added to
9 the beads, and the samples were boiled at 95°C for 5 minutes and then submitted to western-
10 blotting as described previously (48, 49).

11 Western-blots were revealed by chemoluminescence (Thermo Scientific) and visualized using
12 a Fusion FX7-Vilber Lourmat camera. The signals obtained were then quantified using Image
13 J software.

14

15 **Statistical analysis**

16 Statistical analyses were performed using PRISM software. Comparison between groups were
17 performed using Student's t test, or ANOVA followed by Dunnett's or Tukey's post-test as
18 indicated in the figure legends.

19

1 **Results**

2 **LPS stimulation markedly increased protein O-GlcNAcylation in macrophages**

3 Sub-cellular localisation of OGT in different cell compartments has been observed upon
4 stimulation of membrane receptors (50, 51), resulting in compartment specific changes in O-
5 GlcNAcylation activity. In order to evaluate whether LPS stimulation affects protein O-
6 GlcNAcylation in different cellular compartments in macrophages, we used BRET-based O-
7 GlcNAc biosensors (33). These biosensors are composed of Rluc8 luciferase fused to a lectin
8 domain (GafD), a known OGT substrate peptide derived from casein kinase II, followed by
9 the Venus variant of the yellow fluorescent protein (**Fig. 1B**). Upon O-GlcNAcylation, the
10 casein kinase peptide binds to the lectin, resulting into a conformational change detected as an
11 increased BRET signal. These biosensors were fused to addressing sequences for targeting to
12 the internal face of the plasma membrane (using Lyn myristoylation/palmitoylation
13 sequence), the cytosol (using the HIV-1 Rev protein nuclear exclusion sequence) or the
14 nucleus (using the SV40 nuclear localisation sequence) (32).

15 RAW264.7 cells transfected with these biosensors were incubated for 24h in presence of
16 LPS, Thiamet G (an inhibitor of OGA) or both. We observed that LPS treatment increased
17 BRET signal with all three biosensors (**Fig. 1B**), indicating that LPS stimulation promotes a
18 general rather than compartment-specific increase in O-GlcNAcylation in RAW264.7
19 macrophages. Interestingly, the effects of LPS and Thiamet G were additive, suggesting that
20 the effect of LPS on O-GlcNAcylation is independent of OGA activity.

21 LPS-induced O-GlcNAcylation of proteins, both in absence and presence of Thiamet G, was
22 further demonstrated by western-blotting using anti-O-GlcNAc antibody in RAW264.7 cells,
23 but also in mouse bone marrow-derived and peritoneal primary macrophages, as well as in
24 human monocyte-derived macrophages (**Fig. 1C**). Therefore, increased O-GlcNAcylation
25 upon LPS stimulation also appears to occur in primary macrophages from different origins
26 and species, suggesting a general mechanism elicited by TLR4 activation.

27 **GFAT2 is a LPS-inducible gene in macrophages**

28 We further explored, using RAW264.7 macrophages, the mechanism involved in this LPS-
29 induced O-GlcNAcylation. As shown in **Figure 2**, LPS-induced increase in protein O-
30 GlcNAcylation (**Fig. 2A**) was not associated with any detectable change in OGT and OGA
31 mRNA or protein expression (**Fig. 2B and C**), suggesting that it was not mediated by
32 regulation of the expression level of O-GlcNAc cycling enzymes. GFAT, the enzyme that
33 catalyzes the rate-limiting step of the hexosamine biosynthesis pathway (**Fig.1A**), exists as
34 two isoforms (GFAT1 and GFAT2), encoded by two separate genes (also denominated *GFPT1*

1 and *GFPT2*, respectively) that are differentially expressed in a cell-type specific manner. We
2 observed that in the basal state, only GFAT1 protein was highly expressed in macrophages,
3 whereas GFAT2 protein expression was barely detectable (**Fig. 2B**). GFAT1 protein
4 expression was moderately increased (1.3 fold) by LPS treatment, whereas LPS induced a
5 major increase (7 fold) in GFAT2 protein expression (**Fig. 2B**). In agreement with these
6 results, **Figure 2C** shows that LPS increased the expression of GFAT1 mRNA by 2 to 3-fold,
7 and markedly induced (by 10 to 15-fold) the expression of GFAT2 mRNA, suggesting a
8 regulation of GFAT1 and 2 at the transcriptional level. Enzymatic assays indicated that
9 whereas LPS treatment had no detectable effect on OGT or OGA activities, it significantly
10 increased the activity of GFAT in macrophages (**Fig. 2D**). These results suggest that LPS-
11 induced increase in the expression of GFAT, and more specifically GFAT2, translates into an
12 increase in the activity of the rate-limiting step of the hexosamine biosynthesis pathway.
13 Time-course experiments indicated that maximal induction of GFAT2 mRNA was observed
14 3h after LPS stimulation, whereas GFAT1 mRNA expression was barely modified at early
15 time points (**Suppl. Fig. S1A**), revealing that *GFAT2* is an early TLR4-target gene. However,
16 despite marked stimulation of GFAT2 mRNA at early time-points, GFAT2 protein expression
17 was barely increased after 6h of LPS treatment, and robust stimulation was only detected after
18 24h of treatment with LPS (**Suppl. Fig. S1B**). Interestingly, GFAT activity was also barely
19 increased after 6h of treatment, and closely followed the increase in GFAT2 protein
20 expression at time 24h (**Suppl. Fig. S1C**). In agreement with this, LPS-induced increase in
21 protein O-GlcNAcylation could be detected at 6h, but became statistically significant only at
22 time 24h (**Suppl. Fig. S1D**).

23 Increased GFAT2 protein and mRNA expression was also observed in human monocyte-
24 derived macrophages (**Fig. 3A**), mouse bone marrow-derived macrophages (**Fig. 3B**), as well
25 as well as peritoneal macrophages (**Fig. 3C**). In agreement with these results, GFAT
26 enzymatic activity was also increased upon LPS stimulation in human and mouse primary
27 macrophages (**Suppl. Fig. S2A**). Moreover, intraperitoneal injection of LPS in mice also
28 induced a modest increase in GFAT1 and a marked increase in GFAT2 protein expression in
29 peritoneal cells, indicating that this response was also operative *in vivo* (**Suppl. Fig. S2B**).

30 Altogether, our results suggest that LPS induces an increase in protein O-GlcNAcylation
31 through stimulation of the expression of the rate-limiting enzyme of the hexosamine
32 biosynthesis pathway.

33 **Impaired O-GlcNAcylation promotes pro-inflammatory response in macrophages**

34 To evaluate the role of LPS-induced O-GlcNAcylation in macrophages, we isolated

1 peritoneal macrophages from mice with conditional deletion of OGT in the myeloid lineage.
2 As expected, OGT expression and LPS-induced O-GlcNAcylation were markedly impaired in
3 OGT-KO cells (**Fig. 4A**), although residual protein O-GlcNAcylation was sometimes
4 observed, probably reflecting incomplete deletion of OGT by LysM-Cre in resident peritoneal
5 macrophages. We noticed that basal GFAT1 and both basal and LPS-induced GFAT2
6 expression were increased in OGT-KO macrophages, suggesting a compensatory response to
7 the low level of O-GlcNAcylation in these cells. Interestingly, OGT deletion resulted in an
8 increase in LPS-induced NOS2 expression. Moreover, we observed an increased production
9 of IFN γ and IL1 β in the culture medium of OGT-KO macrophages. These results suggest that
10 increased O-GlcNAcylation upon LPS stimulation may have a counter-regulatory effect that
11 restrains excessive cytokines production by macrophages (**Fig. 4B**). In agreement with this
12 notion, increases in pro-inflammatory cytokines IFN γ , IL1 β and TNF α were also observed *in*
13 *vivo* in the serum of OGT-KO mice intraperitoneally injected with LPS (**Fig. 4C**). We also
14 evaluated time-dependency of cytokine production by measuring IL1 β and IFN γ in the culture
15 medium of control and OGT-KO macrophages 6h and 24h after LPS stimulation (**Suppl. Fig.**
16 **S2C**). These experiments indicated that after 6 hours of treatment, LPS-induced increase in
17 IL1 β secretion was higher in culture medium of OGT-KO macrophages than wild-type
18 macrophages. IFN γ secretion also appeared to be higher at 6 hours, although the difference
19 was not statistically significant at this time point (**Suppl. Fig. S2C**).

20 These results suggest that increased O-GlcNAcylation upon LPS stimulation participates in
21 the counter-regulation of proinflammatory signalling in macrophages. Induction of GFAT2
22 expression may therefore constitute a new mechanism to limit excessive inflammation upon
23 LPS stimulation. However, it cannot be excluded that the lack of basal O-GlcNAcylation in
24 OGT-KO macrophages, independently of LPS-induced O-GlcNAcylation, may also
25 participate in the observed alterations on gene expression and cytokine production, for
26 instance by perturbing the expression or activity of signaling intermediates or transcription
27 factors that are involved in the regulation LPS pro-inflammatory effects.

28 **GFAT2 expression is dependent on FoxO1 transcription factor in macrophages**

29 The transcription factor FoxO1 has been shown previously to display dual regulatory
30 effects on inflammatory signals in myeloid cells, with either pro- (52-55) or anti-
31 inflammatory (56-59) effects, depending on the pathophysiological context. Analysis of
32 mouse and human GFAT2 putative promoters revealed canonical FoxO1 recognition sites
33 within the 500bp and 800bp regions upstream of the transcription start site of the mouse and

1 human genes, respectively (**Suppl. Fig. S3A**). We inserted these upstream sequences in a
2 luciferase reporter gene plasmid. Transfection in HEK293 cells with this plasmid revealed that
3 the activities of both human and mouse reporter genes were markedly increased by co-
4 transfection with a constitutively active form of FOXO1, FOXO1-TM (**Fig. 5A**).

5 The mouse 500bp promoter contains two FoxO1 recognition sites (referred to as Site 1 and
6 Site 2 on **Fig. 5B** and **Suppl Fig. S3A**). To further demonstrate the contribution of these sites,
7 we mutated either one or both FoxO1 binding sites and measured the activity of the mutated
8 promoters in the luciferase assay.

9 As shown in **Fig. 5B**, FOXO1-TM effect was markedly reduced by mutation of Site 1 and
10 totally abolished when both Site 1 and Site 2 were mutated. This suggests that both sites
11 might be important for regulation of GFAT2 expression by FoxO1. Binding of Foxo1 to Site 1
12 and Site 2 was further demonstrated on the endogenous GFAT2 promoter in RAW264.7 cells,
13 in chromatin immunoprecipitation experiments using a FoxO1-specific antibody (**Fig. 5C**).

14 These results suggested that FoxO1 may be involved in the regulation of GFAT2
15 expression in macrophages. To evaluate the potential involvement of FoxO1 in the regulation
16 of GFAT2 expression, we used a small molecule specific inhibitor of FoxO1 activity, the
17 AS1842856 drug (60). We observed, both in RAW264.7 cells (**Fig. 6A**) and human monocyte-
18 derived macrophages (**Fig. 6B**), that inhibition of FoxO1 by this compound markedly
19 impaired the effect of LPS on induction of GFAT2 mRNA and protein expression. The effect
20 of AS1842856 on GFAT1 mRNA and protein expression was quite variable. In HMDM,
21 AS1842856 had no significant effect on GFAT1 mRNA or protein expression. In RAW264.7
22 cells, whereas AS1842856 appeared to reduce LPS effect on GFAT1 mRNA expression, it had
23 no significant effect on GFAT1 protein expression. In agreement with a major role of GFAT2
24 in LPS-induced GFAT activity, we observed that basal GFAT activity was not affected by
25 AS1842856 treatment, whereas inhibition of LPS-induced GFAT2 expression by this
26 compound was associated with a marked inhibition of LPS-induced GFAT activity (**Suppl.**
27 **Fig. S3B**).

28 To further demonstrate the role of Foxo1 in LPS-induced GFAT2 expression, we also
29 evaluated the effect of LPS on peritoneal macrophages from mice with conditional Foxo1
30 deletion in the myeloid lineage. We observed that LPS-induced GFAT2 protein and mRNA
31 expression was markedly impaired in Foxo1 KO macrophages (**Fig. 6C**). Again, higher
32 variability was observed concerning GFAT1 expression, but Foxo1 invalidation appeared to
33 have no significant effect on GFAT1 mRNA or protein expression. Inhibition of GFAT2
34 expression was associated with inhibition of LPS effect on protein O-GlcNAcylation. These

1 results demonstrate that Foxo1 is necessary for induction of GFAT2 by LPS and support the
2 notion that increased GFAT2 mediates LPS-induced increase in protein O-GlcNAcylation in
3 macrophages.

1 **Discussion**

2 Several lines of evidence have suggested a role for O-GlcNAcylation in the regulation of
3 inflammatory processes in macrophages (61). However, contradictory results have been
4 obtained concerning the effect of TLR4 activation on protein O-GlcNAcylation. Indeed,
5 depending on the experimental setting, both increases (22, 23) and decreases (24, 25) in the
6 general O-GlcNAcylation profile were observed upon LPS stimulation.

7 In the present work, we showed, using two different methodological approaches (BRET-
8 based assay (**Fig. 1B**) and western-blotting on crude cell lysate as well as WGL-bound
9 fraction (**Fig. 1C and 2A**)) that LPS induced a major increase in global protein O-
10 GlcNAcylation in RAW264.7 macrophages. The use of plasma membrane-, cytosol- or
11 nucleus- targeted BRET O-GlcNAc biosensors indicated that the LPS-induced increase in O-
12 GlcNAcylation was not restricted to a specific cell compartment. Increased protein O-
13 GlcNAcylation upon LPS treatment was also confirmed in primary mice and human
14 macrophages, indicating that our observation was not a cell line specific effect. The reason
15 underlying the discrepancies between different laboratories are unknown at the present time.
16 However, it is possible technical differences in the extraction procedure may affect the
17 detection of O-GlcNAc by western-blotting. For instance, whereas investigators generally add
18 proteases and phosphatases inhibitors in their cell lysis buffer, they do not mention the use of
19 any hexosaminidase inhibitor to prevent loss of O-GlcNAc during the extraction procedure.
20 Given that O-GlcNAc is a very dynamic and labile modification, that can be rapidly
21 hydrolyzed upon cellular damage or during protein isolation (62), it is quite possible that loss
22 of O-GlcNAc might occur during the sample preparation. In contrast, we always included
23 PUGNAc at a concentration of 10 μ M in our extraction buffer, in order to preserve O-
24 GlcNAcylation state of proteins obtained in cells after LPS treatment. In addition, the
25 confirmation of our western-blotting results by an independent technique based on the use of
26 a BRET biosensor, which monitors O-GlcNAcylation changes in intact living cells without
27 any processing of cellular proteins, strongly argues in favour of an LPS-induced general
28 increase in O-GlcNAcylation in macrophages.

29 Interestingly, the effect of LPS on protein O-GlcNAcylation were additive to those of a
30 maximally inhibitory concentration of the OGA inhibitor, Thiamet G. This suggested that
31 LPS-induced O-GlcNAcylation was not mediated by regulation of OGA activity. In
32 agreement with this notion, using a fluorogenic substrate, we observed that OGA activity was
33 similar in cell extracts from control and LPS stimulated RAW264.7 macrophages (**Fig.2 D**).
34 Moreover, using a luminescent assay (33, 43), we found that LPS treatment had no detectable

1 effect on OGT activity in cell extracts from RAW264.7 cells (**Fig. 2D**). Therefore, LPS-
2 induced O-GlcNAcylation does not appear to be mediated by regulation of O-GlcNAc cycling
3 enzymes.

4 One of the most important finding of our study is that LPS treatment resulted in an
5 increased expression and activity of GFAT (**Fig. 2**). GFAT is the enzyme that catalyses the
6 rate limiting step of the hexosamine biosynthesis pathway, which eventually leads to the
7 production of UDP-GlcNAc, the substrate used by OGT for protein O-GlcNAcylation. GFAT
8 exists in two isoforms, GFAT1 and GFAT2, encoded by two different genes (63, 64). Although
9 little data are available concerning differential roles of these enzymes, these two isoforms
10 present different tissue distribution, with GFAT1 mRNA being predominantly expressed in
11 pancreas, placenta and testis, whereas GFAT2 mRNA were found throughout the central
12 nervous system (64). Whereas some differences in the regulation of their catalytic activities
13 by cAMP-induced phosphorylation has been described (65), very little is known about
14 differential regulation of GFAT1 versus GFAT2 expression in different cell types. Most
15 surprisingly, to our knowledge, only one study evaluated in macrophages the expression of
16 GFAT in a mouse macrophage cell line (ANA-1) (66). These authors reported that GFAT1
17 was constitutively expressed in these cells and they indicated (as data not shown) that no
18 effect of LPS or IFN γ on its expression was observed. However, GFAT2 expression was not
19 evaluated in this study. Interestingly, we found that GFAT1 mRNA and protein were indeed
20 expressed at significant levels in resting macrophages, whereas GFAT2 expression was barely
21 detectable. LPS stimulated both GFAT1 and GFAT2 expression, although the stimulatory
22 effect was much higher for GFAT2, whereas the effect of LPS on GFAT1 expression was
23 comparatively much lower and quite variable, depending on the experimental conditions.
24 LPS-induced increase in O-GlcNAcylation is likely to be at least in part mediated by the
25 induction of the expression of the GFAT2 isoform in macrophages. Indeed, several
26 observations argue in favor of a predominant role of GFAT2 in LPS effect on protein O-
27 GlcNAcylation. First, measurement of GFAT activity 6 and 24 h after LPS stimulation
28 indicated that LPS-induced GFAT activity tightly correlated with LPS-induced GFAT2
29 protein expression level (**Suppl. Fig. S1B and C**). Second, the inhibition of FoxO1 in
30 RAW264.7 cells markedly impaired GFAT2 expression, whereas it had no significant effect
31 on GFAT1 expression. Accordingly, basal GFAT activity was not affected by AS1842856,
32 whereas LPS-induced activity was markedly impaired upon inhibition of LPS-induced
33 GFAT2 expression by this compound (**Fig. 6A and Suppl. Fig. S3B**). Third, in Foxo1 KO
34 macrophages, GFAT1 protein expression was not significantly affected, whereas LPS-

1 induced GFAT2 expression was markedly impaired. This was accompanied by blunted LPS-
2 induced protein O-GlcNAcylation, while basal protein O-GlcNAcylation remained essentially
3 unaffected (**Fig. 6C**). Together, these observations strongly suggest that that while GFAT1 is
4 the enzyme that control HBP under basal condition and thereby permit protein O-
5 GlcNAcylation in the basal state, GFAT2 induction permit to increase the activity of the
6 pathway and mediate LPS-induced protein O-GlcNAcylation.

7 In addition to GFAT, it cannot be excluded that other enzymatic steps involved in glucose
8 metabolism in the HBP pathway may be affected by LPS treatment, contributing to increased
9 in protein O-GlcNAcylation. However, even if LPS stimulated the expression or activity of
10 other enzymes, the resulting increase in the flux through the HBP pathway will eventually be
11 conditioned by the activity of the rate-limiting enzyme GFAT, and therefore, by LPS effect on
12 GFAT2 expression.

13 It is also possible that part of the increase in protein O-GlcNAcylation is mediated by
14 subtle changes in OGT expression that were not detected in our studies. Indeed, we noticed on
15 several occasions a small increase in OGT mRNA or protein level. Although these changes
16 generally did not reach significance, we cannot exclude that modification of OGT expression
17 may also participate in LPS-induced protein O-GlcNAcylation.

18 Our work clearly demonstrates that GFAT2 is an early LPS-inducible gene in
19 macrophages. Although the mechanism by which LPS stimulates GFAT2 expression remains
20 elusive, we provide strong evidence for a role of FoxO1 in this process. Indeed, using gene
21 reporter as well as chromatin immunoprecipitation assays, we demonstrated the presence of
22 FoxO1 binding sites on GFAT2 putative promoter. Moreover, pharmacological inhibition or
23 genetic deletion of FoxO1 in macrophages markedly impaired LPS-induced GFAT2
24 expression, confirming the involvement of FoxO1 in this regulation. However, the exact
25 mechanism by which LPS stimulates FoxO1 activity in these cells remains to be explored.
26 FoxO1 activity is known to be controlled by regulation of its nucleo-cytoplasmic localization
27 (67). In cell fractionation experiments, we did not detect any significant change in FoxO1
28 subcellular localization (**Suppl Fig. S3C**), suggesting that other mechanisms must be
29 involved. FoxO1 activity can also be controlled independently of any change in its nuclear
30 localization through various post-translational modifications (68) as well as interaction with
31 numerous binding partners (69). Clearly, elucidation of the mechanism by which LPS induces
32 FoxO1 activity to stimulate GFAT2 expression deserves further investigations.

33 Previous studies have shown that O-GlcNAcylation can either promote inflammation or
34 reduces it, according to the cellular context and type of insult. Thus, whereas O-

1 GlcNAcylation has pro-inflammatory effects in situations of chronic hyperglycaemia, it
2 appears to be protective in acute stress conditions, such as ischemia-reperfusion injury in the
3 heart (61). We observed that impaired O-GlcNAcylation in OGT-KO macrophages resulted in
4 marked increase in NOS2 expression and pro-inflammatory cytokines production, suggesting
5 that the O-GlcNAc tone may exert a break on inflammatory processes. Therefore, the rapid
6 induction of GFAT2 expression may constitute a protective mechanism to limit exacerbated
7 inflammation upon LPS stimulation.

8 In summary, we have shown that LPS stimulation promotes a general increase in protein O-
9 GlcNAcylation in macrophages. This effect is at least in part mediated by increased
10 expression and activity of the rate-limiting enzyme of the hexosamine biosynthesis pathway,
11 GFAT, with the GFAT2 isoform being the most responsive to LPS activation. Indeed, while
12 GFAT1 may control the activity of the HBP in the basal state, our work revealed that *GFAT2*
13 is a new TLR4-inducible gene in macrophages, permitting a rapid adaptive response to
14 environmental changes.

15

1 **Acknowledgments**

2 We are very grateful to Prof. L.K. Mahal for the cDNA coding for the FRET O-GlcNAc
3 biosensors. We also thank Laura Francese for her help in some of the BMDM experiments.

4 This work was performed within the Département Hospitalo-Universitaire AUToimmune and
5 HORmonal diseases.

6

7

1 References

- 2 1. Hart, G. W., M. P. Housley, and C. Slawson. 2007. Cycling of O-linked beta-N-
3 acetylglucosamine on nucleocytoplasmic proteins. *Nature* 446:1017-1022.
- 4 2. Issad, T., E. Masson, and P. Pagesy. 2010. O-GlcNAc modification, insulin signaling and
5 diabetic complications. *Diabetes Metab* 36:423-435.
- 6 3. Fardini, Y., V. Dehennaut, T. Lefebvre, and T. Issad. 2013. O-GlcNAcylation: A New Cancer
7 Hallmark? *Front Endocrinol (Lausanne)* 4:99.
- 8 4. Hart, G. W. 2019. Nutrient regulation of signaling and transcription. *J Biol Chem* 294:2211-
9 2231.
- 10 5. Ma, Z., D. J. Vocadlo, and K. Vosseller. 2013. Hyper-O-GlcNAcylation Is Anti-apoptotic and
11 Maintains Constitutive NF-kappaB Activity in Pancreatic Cancer Cells. *J Biol Chem* 288:15121-
12 15130.
- 13 6. Yang, Y. R., D. H. Kim, Y. K. Seo, D. Park, H. J. Jang, S. Y. Choi, Y. H. Lee, G. H. Lee, K. Nakajima,
14 N. Taniguchi, J. M. Kim, E. J. Choi, H. Y. Moon, I. S. Kim, J. H. Choi, H. Lee, S. H. Ryu, L. Cocco,
15 and P. G. Suh. 2015. Elevated O-GlcNAcylation promotes colonic inflammation and
16 tumorigenesis by modulating NF-kappaB signaling. *Oncotarget* 6:12529-12542.
- 17 7. Liu, R., X. Ma, L. Chen, Y. Yang, Y. Zeng, J. Gao, W. Jiang, F. Zhang, D. Li, B. Han, R. Han, R. Qiu,
18 W. Huang, Y. Wang, and J. Hao. 2017. MicroRNA-15b Suppresses Th17 Differentiation and Is
19 Associated with Pathogenesis of Multiple Sclerosis by Targeting O-GlcNAc Transferase. *J*
20 *Immunol* 198:2626-2639.
- 21 8. Machacek, M., H. Saunders, Z. Zhang, E. P. Tan, J. Li, T. Li, M. T. Villar, A. Artigues, T. Lydic, G.
22 Cork, C. Slawson, and P. E. Fields. 2019. Elevated O-GlcNAcylation enhances pro-
23 inflammatory Th17 function by altering the intracellular lipid microenvironment. *J Biol Chem*.
- 24 9. Pagesy, P., C. Tachet, A. Mostefa-Kara, E. Larger, and T. Issad. 2018. Increased OGA
25 expression and activity in leukocytes from patients with diabetes: correlation with
26 inflammation markers *Exp Clin Endocrinol Diabetes* doi: 10.1055/a-0596-7337.
- 27 10. Filhoulaud, G., F. Benhamed, P. Pagesy, C. Bonner, Y. Fardini, A. Ilias, J. Movassat, A. F.
28 Burnol, S. Guilmeau, J. Kerr-Conte, F. Pattou, T. Issad, and C. Postic. 2019. O-GlcNAcylation
29 Links TxNIP to Inflammasome Activation in Pancreatic beta Cells. *Front Endocrinol (Lausanne)*
30 10:291.
- 31 11. Szymura, S. J., J. P. Zaemes, D. F. Allison, S. H. Clift, J. M. D'Innocenzi, L. G. Gray, B. D.
32 McKenna, B. B. Morris, S. Bekiranov, R. D. LeGallo, D. R. Jones, and M. W. Mayo. 2019. NF-
33 kappaB upregulates glutamine-fructose-6-phosphate transaminase 2 to promote migration
34 in non-small cell lung cancer. *Cell Commun Signal* 17:24.
- 35 12. Torres, C. R., and G. W. Hart. 1984. Topography and polypeptide distribution of terminal N-
36 acetylglucosamine residues on the surfaces of intact lymphocytes. Evidence for O-linked
37 GlcNAc. *J Biol Chem* 259:3308-3317.
- 38 13. Kearse, K. P., and G. W. Hart. 1991. Topology of O-linked N-acetylglucosamine in murine
39 lymphocytes. *Arch Biochem Biophys* 290:543-548.
- 40 14. Lund, P. J., J. E. Elias, and M. M. Davis. 2016. Global Analysis of O-GlcNAc Glycoproteins in
41 Activated Human T Cells. *J Immunol* 197:3086-3098.
- 42 15. Swamy, M., S. Pathak, K. M. Grzes, S. Damerow, L. V. Sinclair, D. M. van Aalten, and D. A.
43 Cantrell. 2016. Glucose and glutamine fuel protein O-GlcNAcylation to control T cell self-
44 renewal and malignancy. *Nat Immunol* 17:712-720.
- 45 16. Ramakrishnan, P., P. M. Clark, D. E. Mason, E. C. Peters, L. C. Hsieh-Wilson, and D. Baltimore.
46 2013. Activation of the transcriptional function of the NF-kappaB protein c-Rel by O-GlcNAc
47 glycosylation. *Sci Signal* 6:ra75.
- 48 17. Juang, Y. T., E. E. Solomou, B. Rellahan, and G. C. Tsokos. 2002. Phosphorylation and O-linked
49 glycosylation of Elf-1 leads to its translocation to the nucleus and binding to the promoter of
50 the TCR zeta-chain. *J Immunol* 168:2865-2871.

- 1 18. Liu, B., O. C. Salgado, S. Singh, K. L. Hippen, J. C. Maynard, A. L. Burlingame, L. E. Ball, B. R.
2 Blazar, M. A. Farrar, K. A. Hogquist, and H. B. Ruan. 2019. The lineage stability and
3 suppressive program of regulatory T cells require protein O-GlcNAcylation. *Nat Commun*
4 10:354.
- 5 19. Golks, A., T. T. Tran, J. F. Goetschy, and D. Guerini. 2007. Requirement for O-linked N-
6 acetylglucosaminyltransferase in lymphocytes activation. *Embo J* 26:4368-4379.
- 7 20. Wu, J. L., H. Y. Wu, D. Y. Tsai, M. F. Chiang, Y. J. Chen, S. Gao, C. C. Lin, C. H. Lin, K. H. Khoo, Y.
8 J. Chen, and K. I. Lin. 2015. Temporal regulation of Lsp1 O-GlcNAcylation and
9 phosphorylation during apoptosis of activated B cells. *Nat Commun* 7:12526.
- 10 21. Wu, J. L., M. F. Chiang, P. H. Hsu, D. Y. Tsai, K. H. Hung, Y. H. Wang, T. Angata, and K. I. Lin.
11 2017. O-GlcNAcylation is required for B cell homeostasis and antibody responses. *Nat*
12 *Commun* 8:1854.
- 13 22. Ryu, I. H., and S. I. Do. 2011. Denitrosylation of S-nitrosylated OGT is triggered in LPS-
14 stimulated innate immune response. *Biochem Biophys Res Commun* 408:52-57.
- 15 23. Hwang, J. S., M. Y. Kwon, K. H. Kim, Y. Lee, I. K. Lyoo, J. E. Kim, E. S. Oh, and I. O. Han. 2017.
16 Lipopolysaccharide (LPS)-stimulated iNOS Induction Is Increased by Glucosamine under
17 Normal Glucose Conditions but Is Inhibited by Glucosamine under High Glucose Conditions in
18 Macrophage Cells. *J Biol Chem* 292:1724-1736.
- 19 24. Hwang, S. Y., J. S. Hwang, S. Y. Kim, and I. O. Han. 2013. O-GlcNAc transferase inhibits LPS-
20 mediated expression of inducible nitric oxide synthase through an increased interaction with
21 mSin3A in RAW264.7 cells. *Am J Physiol Cell Physiol* 305:C601-608.
- 22 25. Li, X., W. Gong, H. Wang, T. Li, K. S. Attri, R. E. Lewis, A. C. Kalil, F. Bhinderwala, R. Powers, G.
23 Yin, L. E. Herring, J. M. Asara, Y. L. Lei, X. Yang, D. A. Rodriguez, M. Yang, D. R. Green, P. K.
24 Singh, and H. Wen. 2019. O-GlcNAc Transferase Suppresses Inflammation and Necroptosis by
25 Targeting Receptor-Interacting Serine/Threonine-Protein Kinase 3. *Immunity* 50:576-590
26 e576.
- 27 26. Yang, W. H., S. Y. Park, H. W. Nam, H. Kim do, J. G. Kang, E. S. Kang, Y. S. Kim, H. C. Lee, K. S.
28 Kim, and J. W. Cho. 2008. NFkappaB activation is associated with its O-GlcNAcylation state
29 under hyperglycemic conditions. *Proc Natl Acad Sci U S A* 105:17345-17350.
- 30 27. Allison, D. F., J. J. Wamsley, M. Kumar, D. Li, L. G. Gray, G. W. Hart, D. R. Jones, and M. W.
31 Mayo. 2012. Modification of RelA by O-linked N-acetylglucosamine links glucose metabolism
32 to NF-kappaB acetylation and transcription. *Proc Natl Acad Sci U S A* 109:16888-16893.
- 33 28. Pathak, S., V. S. Borodkin, O. Albarbarawi, D. G. Campbell, A. Ibrahim, and D. M. van Aalten.
34 2012. O-GlcNAcylation of TAB1 modulates TAK1-mediated cytokine release. *Embo J* 31:1394-
35 1404.
- 36 29. Kawauchi, K., K. Araki, K. Tobiume, and N. Tanaka. 2009. Loss of p53 enhances catalytic
37 activity of IKKbeta through O-linked beta-N-acetyl glucosamine modification. *Proc Natl Acad*
38 *Sci U S A* 106:3431-3436.
- 39 30. Xing, D., K. Gong, W. Feng, S. E. Nozell, Y. F. Chen, J. C. Chatham, and S. Oparil. 2011. O-
40 GlcNAc modification of NFkappaB p65 inhibits TNF-alpha-induced inflammatory mediator
41 expression in rat aortic smooth muscle cells. *PLoS One* 6:e24021.
- 42 31. Li, T., X. Li, K. S. Attri, C. Liu, L. Li, L. E. Herring, J. M. Asara, Y. L. Lei, P. K. Singh, C. Gao, and H.
43 Wen. 2018. O-GlcNAc Transferase Links Glucose Metabolism to MAVS-Mediated Antiviral
44 Innate Immunity. *Cell Host Microbe* 24:791-803 e796.
- 45 32. Carrillo, L. D., J. A. Froemming, and L. K. Mahal. 2011. Targeted in vivo O-GlcNAc sensors
46 reveal discrete compartment-specific dynamics during signal transduction. *J Biol Chem*
47 286:6650-6658.
- 48 33. Groussaud, D., M. Khair, A. I. Tollenaere, L. Waast, M. S. Kuo, M. Mangeney, C. Martella, Y.
49 Fardini, S. Coste, M. Souidi, L. Benit, C. Pique, and T. Issad. 2017. Hijacking of the O-
50 GlcNAcZYME complex by the HTLV-1 Tax oncoprotein facilitates viral transcription. *PLoS*
51 *Pathog* 13:e1006518.

- 1 34. Kuo, M., V. Zilberfarb, N. Gangneux, N. Christeff, and T. Issad. 2008. O-glycosylation of FoxO1
2 increases its transcriptional activity towards the glucose 6-phosphatase gene. *FEBS Lett*
3 582:829-834.
- 4 35. Lacasa, D., N. Boute, and T. Issad. 2005. Interaction of the insulin receptor with the receptor-
5 like protein tyrosine phosphatases PTPalpha and PTPepsilon in living cells. *Mol Pharmacol*
6 67:1206-1213.
- 7 36. Blanquart, C., J. Achi, and T. Issad. 2008. Characterization of IRA/IRB hybrid insulin receptors
8 using bioluminescence resonance energy transfer. *Biochem Pharmacol* 76:873-883.
- 9 37. Issad, T., N. Boute, and K. Pernet. 2002. A homogenous assay to monitor the activity of the
10 insulin receptor using Bioluminescence Resonance Energy Transfer. *Biochem Pharmacol*
11 64:813-817.
- 12 38. Nouaille, S., C. Blanquart, V. Zilberfarb, N. Boute, D. Perdereau, J. Roix, A. F. Burnol, and T.
13 Issad. 2006. Interaction with Grb14 results in site-specific regulation of tyrosine
14 phosphorylation of the insulin receptor. *EMBO Rep* 7:512-518.
- 15 39. Niedergang, F., J. C. Sirard, C. T. Blanc, and J. P. Kraehenbuhl. 2000. Entry and survival of
16 *Salmonella typhimurium* in dendritic cells and presentation of recombinant antigens do not
17 require macrophage-specific virulence factors. *Proc Natl Acad Sci U S A* 97:14650-14655.
- 18 40. Mazzolini, J., F. Herit, J. Bouchet, A. Benmerah, S. Benichou, and F. Niedergang. 2010.
19 Inhibition of phagocytosis in HIV-1-infected macrophages relies on Nef-dependent alteration
20 of focal delivery of recycling compartments. *Blood* 115:4226-4236.
- 21 41. Strobel, A., K. Siquier, V. Zilberfarb, A. D. Strosberg, and T. Issad. 1999. Effect of
22 thiazolidinediones on expression of UCP2 and adipocyte markers in human PAZ6 adipocytes.
23 *Diabetologia* 42:527-533.
- 24 42. Kim, E. J., D. O. Kang, D. C. Love, and J. A. Hanover. 2006. Enzymatic characterization of O-
25 GlcNAcase isoforms using a fluorogenic GlcNAc substrate. *Carbohydr Res* 341:971-982.
- 26 43. Rodriguez, A. C., S. H. Yu, B. Li, H. Zegzouti, and J. J. Kohler. 2015. Enhanced transfer of a
27 photocross-linking N-acetylglucosamine (GlcNAc) analog by an O-GlcNAc transferase mutant
28 with converted substrate specificity. *J Biol Chem* 290:22638-22648.
- 29 44. Marshall, S., V. Bacote, and R. R. Traxinger. 1991. Discovery of a metabolic pathway
30 mediating glucose-induced desensitization of the glucose transport system. Role of
31 hexosamine biosynthesis in the induction of insulin resistance. *J Biol Chem* 266:4706-4712.
- 32 45. Liu, J. F., T. Issad, E. Chevet, D. Ledoux, J. Courty, J. P. Caruelle, D. Barritault, M. Crepin, and
33 B. Bertin. 1998. Fibroblast growth factor-2 has opposite effects on human breast cancer
34 MCF-7 cell growth depending on the activation level of the mitogen-activated protein kinase
35 pathway. *Eur J Biochem* 258:271-276.
- 36 46. Braun, V., V. Fraissier, G. Raposo, I. Hurbain, J. B. Sibarita, P. Chavrier, T. Galli, and F.
37 Niedergang. 2004. TI-VAMP/VAMP7 is required for optimal phagocytosis of opsonised
38 particles in macrophages. *Embo J* 23:4166-4176.
- 39 47. Dumas, A., G. Le-Bury, F. Marie-Anais, F. Herit, J. Mazzolini, T. Guilbert, P. Bourdoncle, D. G.
40 Russell, S. Benichou, A. Zahraoui, and F. Niedergang. 2015. The HIV-1 protein Vpr impairs
41 phagosome maturation by controlling microtubule-dependent trafficking. *J Cell Biol* 211:359-
42 372.
- 43 48. Issad, T., M. Combettes, and P. Ferre. 1995. Isoproterenol inhibits insulin-stimulated tyrosine
44 phosphorylation of the insulin receptor without increasing its serine/threonine
45 phosphorylation. *Eur J Biochem* 234:108-115.
- 46 49. Fardini, Y., E. Masson, O. Boudah, R. Ben Jouira, C. Cosson, C. Pierre-Eugene, M. S. Kuo, and
47 T. Issad. 2014. O-GlcNAcylation of FoxO1 in pancreatic beta cells promotes Akt inhibition
48 through an IGF1P1-mediated autocrine mechanism. *Faseb J* 28:1010-1021.
- 49 50. Yang, X., P. P. Ongusaha, P. D. Miles, J. C. Havstad, F. Zhang, W. V. So, J. E. Kudlow, R. H.
50 Michell, J. M. Olefsky, S. J. Field, and R. M. Evans. 2008. Phosphoinositide signalling links O-
51 GlcNAc transferase to insulin resistance. *Nature* 451:964-969.

- 1 51. Perez-Cervera, Y., V. Dehennaut, M. Aquino Gil, K. Guedri, C. J. Solorzano Mata, S. Olivier-Van
2 Stichelen, J. C. Michalski, F. Foulquier, and T. Lefebvre. 2013. Insulin signaling controls the
3 expression of O-GlcNAc transferase and its interaction with lipid microdomains. *Faseb J*
4 27:3478-3486.
- 5 52. Su, D., G. M. Coudriet, D. Hyun Kim, Y. Lu, G. Perdomo, S. Qu, S. Slusher, H. M. Tse, J.
6 Piganelli, N. Giannoukakis, J. Zhang, and H. H. Dong. 2009. FoxO1 links insulin resistance to
7 proinflammatory cytokine IL-1beta production in macrophages. *Diabetes* 58:2624-2633.
- 8 53. Fan, W., H. Morinaga, J. J. Kim, E. Bae, N. J. Spann, S. Heinz, C. K. Glass, and J. M. Olefsky.
9 2010. FoxO1 regulates Tlr4 inflammatory pathway signalling in macrophages. *Embo J*
10 29:4223-4236.
- 11 54. Becker, T., G. Loch, M. Beyer, I. Zinke, A. C. Aschenbrenner, P. Carrera, T. Inhester, J. L.
12 Schultze, and M. Hoch. 2010. FOXO-dependent regulation of innate immune homeostasis.
13 *Nature* 463:369-373.
- 14 55. Seiler, F., J. Hellberg, P. M. Lepper, A. Kamyschnikow, C. Herr, M. Bischoff, F. Langer, H. J.
15 Schafers, F. Lammert, M. D. Menger, R. Bals, and C. Beisswenger. 2013. FOXO transcription
16 factors regulate innate immune mechanisms in respiratory epithelial cells. *J Immunol*
17 190:1603-1613.
- 18 56. Baumgartl, J., S. Baudler, M. Scherner, V. Babaev, L. Makowski, J. Suttles, M. McDuffie, K.
19 Tobe, T. Kadowaki, S. Fazio, C. R. Kahn, G. S. Hotamisligil, W. Krone, M. Linton, and J. C.
20 Bruning. 2006. Myeloid lineage cell-restricted insulin resistance protects apolipoproteinE-
21 deficient mice against atherosclerosis. *Cell Metab* 3:247-256.
- 22 57. Senokuchi, T., C. P. Liang, T. A. Seimon, S. Han, M. Matsumoto, A. S. Banks, J. H. Paik, R. A.
23 DePinho, D. Accili, I. Tabas, and A. R. Tall. 2008. Forkhead transcription factors (FoxOs)
24 promote apoptosis of insulin-resistant macrophages during cholesterol-induced endoplasmic
25 reticulum stress. *Diabetes* 57:2967-2976.
- 26 58. Hwang, J. W., S. Rajendrasozhan, H. Yao, S. Chung, I. K. Sundar, H. L. Huyck, G. S. Pryhuber, V.
27 L. Kinnula, and I. Rahman. 2011. FOXO3 deficiency leads to increased susceptibility to
28 cigarette smoke-induced inflammation, airspace enlargement, and chronic obstructive
29 pulmonary disease. *J Immunol* 187:987-998.
- 30 59. Tsuchiya, K., M. Westerterp, A. J. Murphy, V. Subramanian, A. W. Ferrante, Jr., A. R. Tall, and
31 D. Accili. 2013. Expanded granulocyte/monocyte compartment in myeloid-specific triple
32 FoxO knockout increases oxidative stress and accelerates atherosclerosis in mice. *Circ Res*
33 112:992-1003.
- 34 60. Roux, A., H. Leroy, B. De Muylder, L. Bracq, S. Oussous, I. Dusanter-Fourt, G. Chougui, R.
35 Tacine, C. Randriamampita, D. Desjardins, R. Le Grand, F. Bouillaud, S. Benichou, F.
36 Margottin-Goguet, R. Cheynier, G. Bismuth, and M. Mangeney. 2019. FOXO1 transcription
37 factor plays a key role in T cell-HIV-1 interaction. *PLoS Pathog* 15:e1007669.
- 38 61. Baudoin, L., and T. Issad. 2015. O-GlcNAcylation and Inflammation: A Vast Territory to
39 Explore. *Front Endocrinol (Lausanne)* 5:235.
- 40 62. Hart, G. W., C. Slawson, G. Ramirez-Correa, and O. Lagerlof. 2011. Cross talk between O-
41 GlcNAcylation and phosphorylation: roles in signaling, transcription, and chronic disease.
42 *Annu Rev Biochem* 80:825-858.
- 43 63. Sayeski, P. P., A. J. Paterson, and J. E. Kudlow. 1994. The murine glutamine:fructose-6-
44 phosphate amidotransferase-encoding cDNA sequence. *Gene* 140:289-290.
- 45 64. Oki, T., K. Yamazaki, J. Kuromitsu, M. Okada, and I. Tanaka. 1999. cDNA cloning and mapping
46 of a novel subtype of glutamine:fructose-6-phosphate amidotransferase (GFAT2) in human
47 and mouse. *Genomics* 57:227-234.
- 48 65. Hu, Y., L. Riesland, A. J. Paterson, and J. E. Kudlow. 2004. Phosphorylation of mouse
49 glutamine-fructose-6-phosphate amidotransferase 2 (GFAT2) by cAMP-dependent protein
50 kinase increases the enzyme activity. *J Biol Chem* 279:29988-29993.

- 1 66. Manzari, B., J. E. Kudlow, P. Fardin, E. Merello, C. Ottaviano, M. Puppo, A. Eva, and L. Varesio.
2 2007. Induction of macrophage glutamine: fructose-6-phosphate amidotransferase
3 expression by hypoxia and by picolinic acid. *Int J Immunopathol Pharmacol* 20:47-58.
- 4 67. Barthel, A., D. Schmoll, and T. G. Unterman. 2005. FoxO proteins in insulin action and
5 metabolism. *Trends Endocrinol Metab* 16:183-189.
- 6 68. Wang, Z., T. Yu, and P. Huang. 2016. Post-translational modifications of FOXO family proteins
7 (Review). *Molecular medicine reports* 14:4931-4941.
- 8 69. van der Vos, K. E., and P. J. Coffey. 2008. FOXO-binding partners: it takes two to tango.
9 *Oncogene* 27:2289-2299.
- 10
11
12
13

1 **Figure legends**

2 **Figure 1: LPS induces O-GlcNAcylation in macrophages**

3 (A) The hexosamine biosynthetic pathway (HBP) flux controls O-GlcNAcylation of
4 intracellular proteins. This dynamic and reversible post-translational modification regulates
5 the activity, the localization and/or the stability of proteins, according to the rate of glucose
6 entering the HBP. Fructose-6-phosphate is converted to glucosamine-6-phosphate by the
7 glutamine:fructose-6-phosphate amidotransferase (GFAT), the rate limiting enzyme of the
8 pathway. After a subset of reactions, UDP-N-acetylglucosamine (UDP-GlcNAc) is generated
9 and used by the O-GlcNAc transferase (OGT) as a substrate to add GlcNAc on serine or
10 threonine residues of target proteins. O-GlcNAc moiety is removed from O-GlcNAc-modified
11 proteins by the O-GlcNAcase (OGA). Thiamet G is a highly selective inhibitor of OGA.

12 (B) RAW264.7 cells were transfected with plasma membrane, cytosol or nucleus-targeted
13 BRET biosensors. 18h after transfection, medium was changed and cells were cultured for an
14 additional 24h in presence of LPS (100ng/mL), Thiamet G (TG, 10 μ M) or both. BRET signal
15 was then measured every 45 seconds during 15 min. In each experiment, the mean of 20
16 repeated BRET measurements in a given experimental condition was taken as the BRET
17 value obtained in this experimental condition. Left panels show the signals obtained during
18 typical BRET experiments with each biosensor (white circles, control; grey squares, LPS;
19 grey circle, Thiamet G; black squares, LPS+ Thiamet G). Right panels correspond to the
20 increase BRET above basal induced by LPS, Thiamet G or LPS+Thiamet G (delta BRET
21 expressed in milliBRET Units) and are the means \pm SEM of 8 independent BRET
22 experiments. Statistical analysis was performed using ANOVA followed by Dunnett's post-
23 test (*, **: $p < 0.05$, $p < 0.01$, respectively, when compared to the control condition).

24 (C) RAW264.7 cells, bone marrow-derived and peritoneal primary mouse macrophages, and
25 human monocyte-derived macrophages were cultured during 24h in absence or presence of
26 LPS (100ng/mL), Thiamet G (10 μ M) or both. Proteins were extracted and analysed by
27 western-blotting using an anti-O-GlcNAc antibody (RL2). Membranes were then re-probed
28 with anti-clathrin antibody to control for protein loading in each well. Each blot is
29 representative of 4 independent experiments.

30

31 **Figure 2: Effect of LPS on OGT, OGA and GFAT expression and activity in RAW264.7**
32 **cells.**

33 RAW264.7 cells were cultured during 24h in absence or presence of LPS (100ng/mL) and
34 lysed for protein and RNA extraction. (A) O-GlcNAcylated proteins were precipitated on

1 wheat-germ lectin (WGL) agarose beads and submitted to western-blotting using anti-O-
2 GlcNAc antibody. Left panel, a typical western blot is shown. Right panel, the effect of LPS
3 on global protein O-GlcNAcylation was quantified by densitometric analysis of the blots.
4 Results are the means of 10 independent experiments (B) Protein expression level of OGA,
5 OGT, GFAT1, GFAT2, and NOS2 in total cell lysates. Left panel, a typical western blot is
6 shown. Right panel, densitometric analysis of the blots. Results are the means of 5 to 6
7 independent experiments. (C) mRNA expression levels of OGA, OGT, GFAT1, GFAT2 and
8 NOS2 were evaluated by RT-qPCR, each determination being performed in duplicate. Results
9 are the means of 5 to 7 independent experiments. (D) OGT, OGA, and GFAT enzymatic
10 activities in cell lysates from control and LPS-treated cells. Results are expressed as LPS-
11 induced fold-effect and are the mean \pm SEM of 5 to 6 independent experiments. Statistical
12 analysis was performed using Student's t test (*, **, ***: $p < 0.05$, $p < 0.01$, $p < 0.001$,
13 respectively; NS: non-significant).

14

15 **Figure 3: Effect of LPS on GFAT2 expression in human and mouse primary**
16 **macrophages**

17 Human monocyte-derived macrophages (A), mouse bone marrow-derived (B) and peritoneal
18 (C) macrophages were cultured during 24h in absence or presence of LPS (100ng/mL) and
19 lysed for protein and RNA extraction. The effect of LPS on global protein O-GlcNAcylation
20 level and on the expression of OGT, OGA, GFAT1 and GFAT2 was evaluated by
21 densitometric analysis of the western-blot. Results are expressed as LPS-induced fold-effect
22 and are the means \pm SEM of 4 to 12 independent experiments. mRNA expression levels of
23 GFAT2, GFAT1 and OGT were evaluated by RT-qPCR, each determination being performed
24 in duplicate. Results are expressed as LPS-induced fold-effect and are the mean \pm SEM of 3
25 to 12 independent experiments. Statistical analysis was performed using Student's t test (*,
26 **, *** $p < 0.05$, $p < 0.01$, $p < 0.001$, respectively; NS: non-significant).

27

28 **Figure 4: Targeted deletion of OGT in macrophages increases the pro-inflammatory**
29 **effect of LPS**

30 (A, B) Peritoneal macrophages from control or OGT-KO mice were cultured during 24h in
31 absence or presence of LPS (100ng/mL). The culture medium was collected for measurement
32 of cytokine production in the medium, and cell were lysed for protein analysis. (A) Left panel,
33 typical western blot showing protein O-GlcNAcylation and expression of OGT, GFAT1,
34 GFAT2 and NOS2 in control and OGT-KO macrophages. Right panel, densitometric analysis

1 of the blots. Results are expressed as the mean \pm SEM of 4 independent experiments.
2 Statistical analysis was performed using ANOVA followed by Tukey's post-test (*, **, ***:
3 $p < 0.05$, $p < 0.01$, $p < 0.001$, respectively). (B) The concentration of IL1 β , TNF α and IFN γ
4 secreted in the culture medium by control and OGT-KO macrophages were determined using
5 MSD kit. Results are the means \pm SEM of 6 to 10 independent experiments. Statistical
6 analysis was performed using Student's t test (*, **, ***: $p < 0.05$, $p < 0.01$, $p < 0.001$,
7 respectively).

8 (C) Control and OGT-KO mice (n=9 in each group) were intraperitoneally injected with 0.6
9 mg/kg of LPS. 6h after injection, mice were sacrificed and blood was collected. The
10 concentration of IL1 β , TNF α and IFN γ in the serum were determined using MSD kit.

11 Results are expressed as the means \pm SEM of 8 to 9 independent experiments. Statistical
12 analysis was performed using Student's t test (*, **, ***: $p < 0.05$, $p < 0.01$, $p < 0.001$,
13 respectively).

14

15 **Figure 5: FoxO1 stimulates the activity of a GFAT2 promoter reporter gene.**

16 (A) HEK 293-T cells were co-transfected with a firefly luciferase reporter gene comprising
17 the 500bp or 800bp regions upstream of the transcription start site of the mouse and human
18 genes, respectively, a *Renilla* luciferase expression plasmid, and either pcDNA3 or the cDNA
19 coding for the constitutively active FOXO1-TM. Results are expressed as fold-activation of
20 the promoter by FOXO1 and are the means \pm SEM of 5 independent experiments, each
21 performed in biological triplicate. Statistical analysis was performed using Student's t test
22 (***: $p < 0.001$). (B) Mutation of FoxO1 binding sites on the mouse GFAT2 promoter inhibits
23 FoxO1 induced activation of the GFAT2 promoter reporter gene. Results are expressed as
24 fold-effect of the basal activity of the wild-type promoter and are the mean \pm SEM of at least
25 5 independent experiments, each performed in biological triplicate. Statistical analysis was
26 performed using ANOVA followed by Tukey's test (**, ***: $p < 0.01$, $p < 0.001$, respectively;
27 NS: non-significant). (C) Binding of Foxo1 on Site 1 and Site 2 of the endogenous mouse
28 promoter was shown by chromatin immunoprecipitation of Foxo1 in RAW264.7 cells.
29 Chromatin was immunoprecipitated with either control IgG or anti-FoxO1 antibody and
30 recovered DNA was amplified by qPCR. Results are the means \pm SEM of 5 independent
31 experiments, each performed in biological duplicate. Statistical analysis was performed using
32 Student's t test (**, $p < 0.01$).

33

1 **Figure 6: Pharmacological or genetic inhibition of FoxO1 impairs LPS effect on GFAT2**
2 **mRNA and protein expression.**

3 RAW264.7 cells (A) and human monocyte-derived macrophages (B) were cultured for 3 days
4 in the presence of the FoxO1 inhibitor AS1842856 (500nM) or vehicle only and then
5 incubated for an additional 24h in absence or presence of LPS (100ng/mL) and lysed for
6 protein and RNA extraction. Left panels: typical western blots showing the effect of LPS on
7 GFAT1 and GFAT2 protein expression. Right panels, quantification of the western-blot and
8 expression of GFAT1 and GFAT2 mRNA evaluated by RT-qPCR, each determination being
9 performed in duplicate. Results are expressed as fold-effect of control condition and are the
10 means \pm SEM of 3 to 6 independent experiments. Statistical analysis was performed using
11 ANOVA followed by Tukey's test (***, $p < 0.001$, NS: non-significant). (C) Effect of LPS on
12 protein O-GlcNAcylation and GFAT1 and GFAT2 protein and mRNA expression in bone-
13 marrow derived macrophages from wild-type and Foxo1-KO mice. Results are expressed as
14 fold-effect of wild-type control condition and are the means \pm SEM of 4 to 5 independent
15 experiments. Statistical analysis was performed using ANOVA followed by Tukey's test (*,
16 **: $p < 0.05$ and $p < 0.01$, respectively; NS: non-significant)

Fig. 1

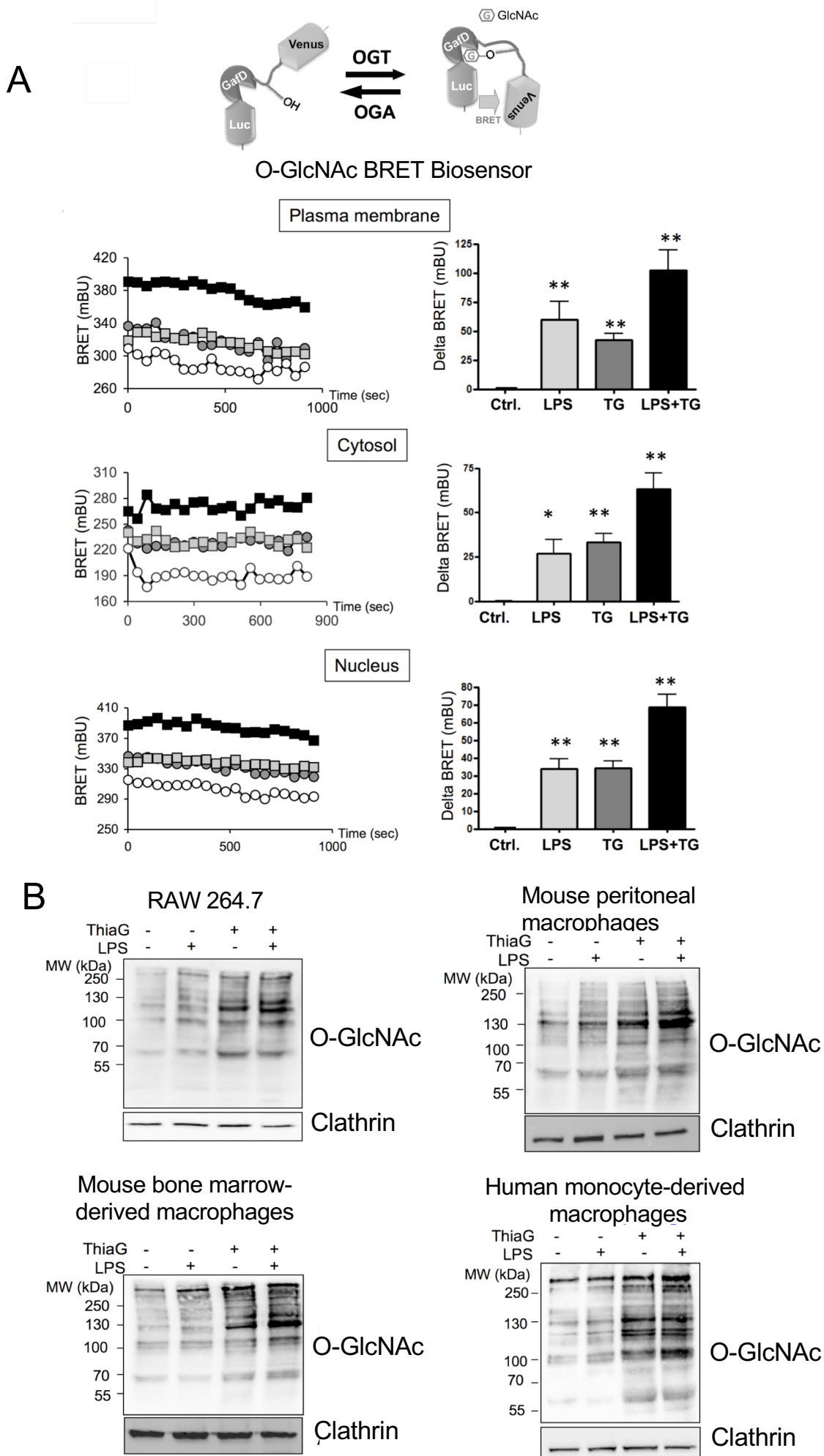


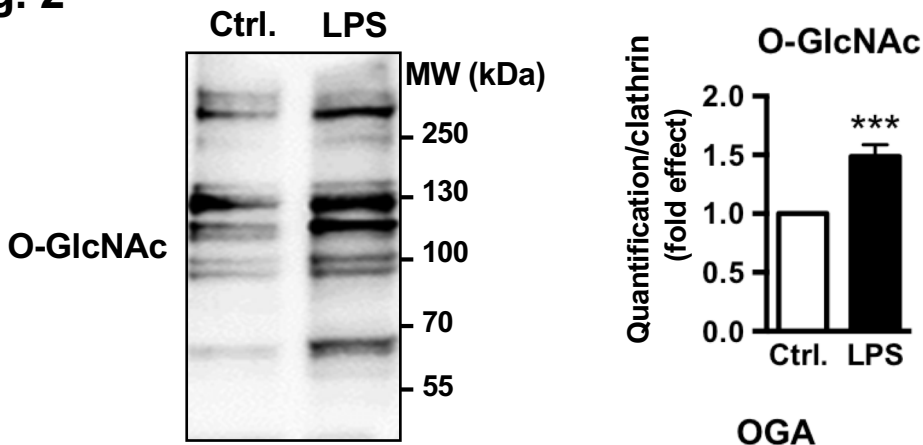
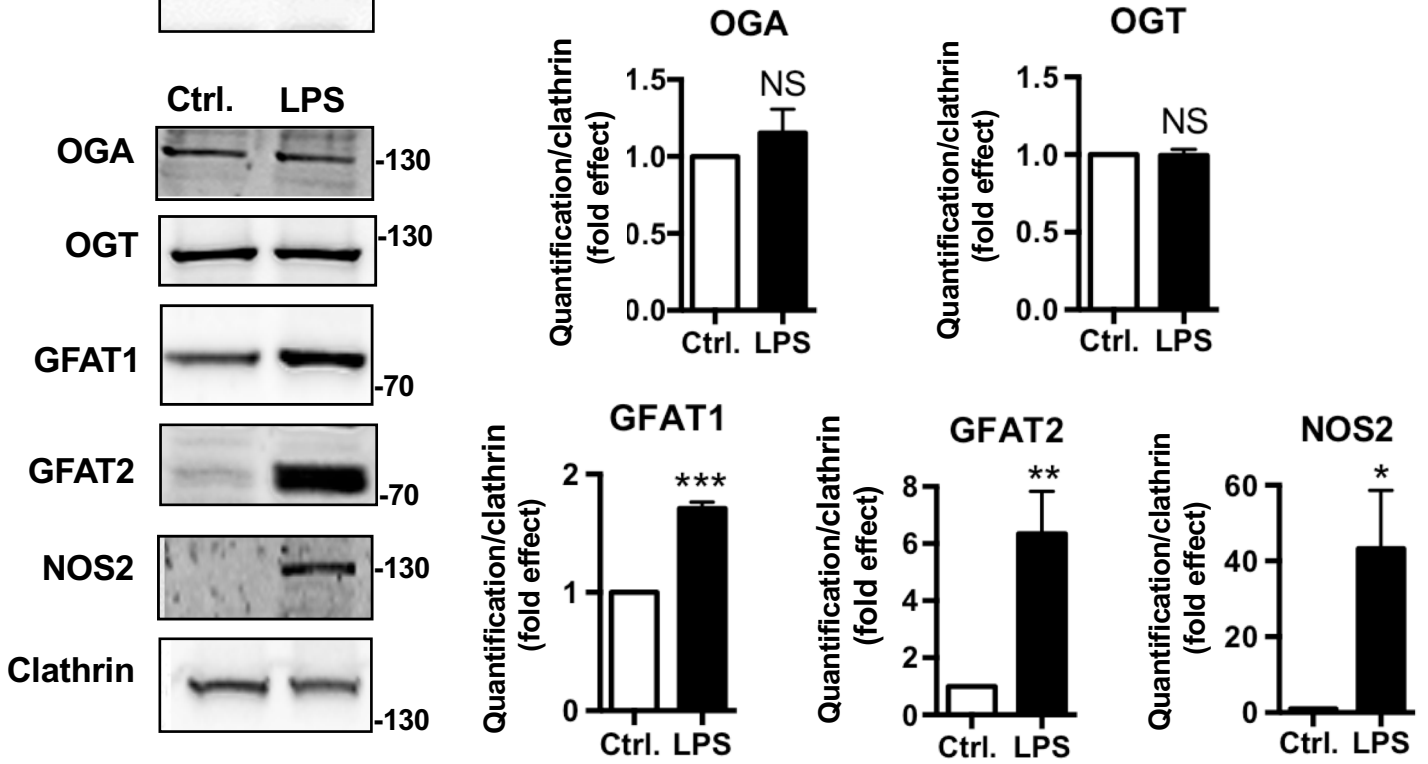
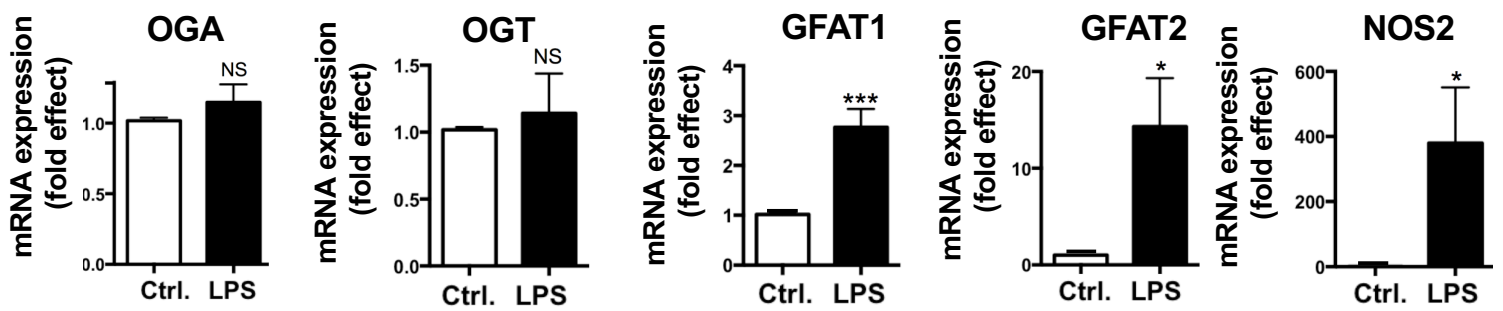
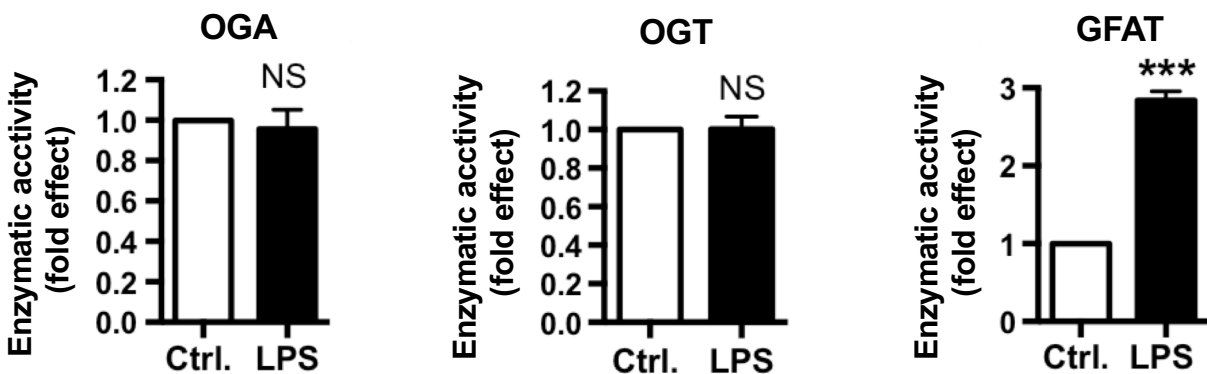
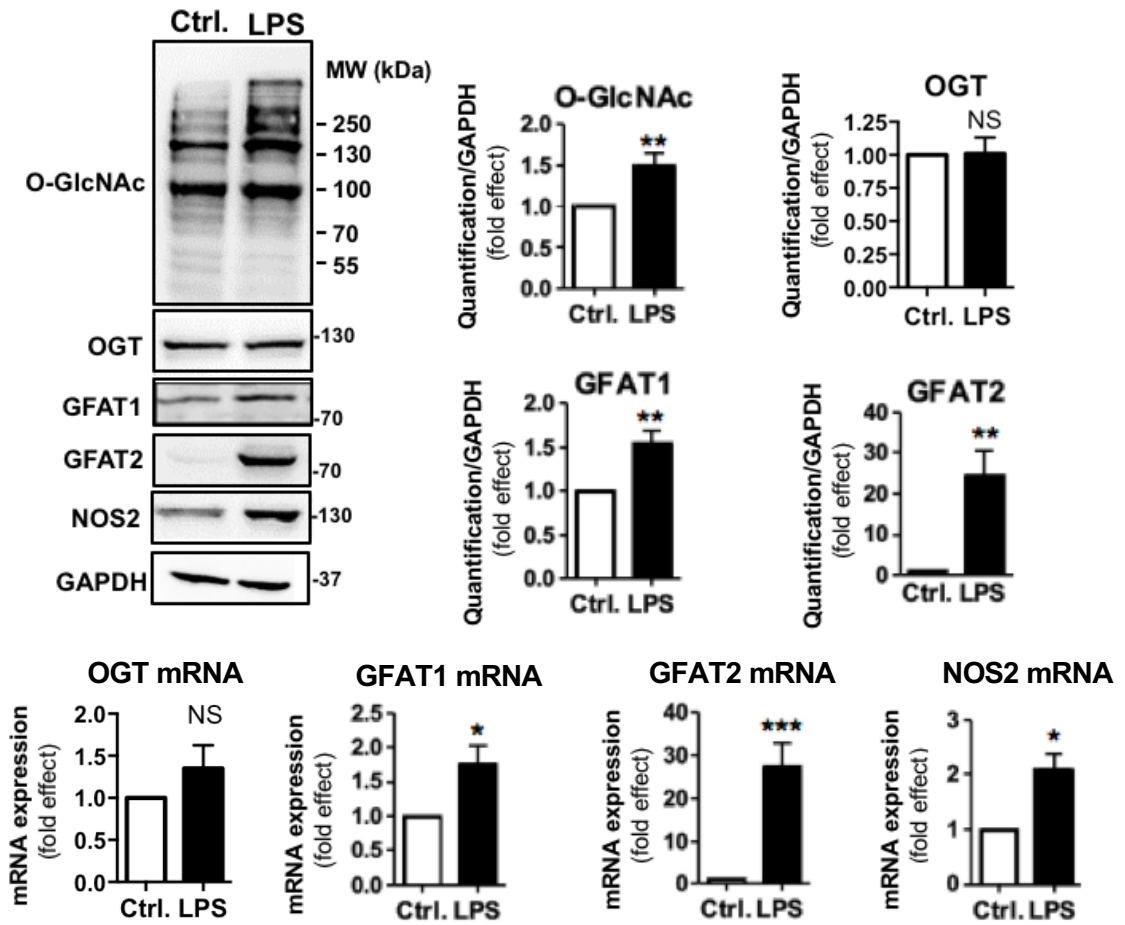
Fig. 2**A****B****C****D**

Fig.3
A



B

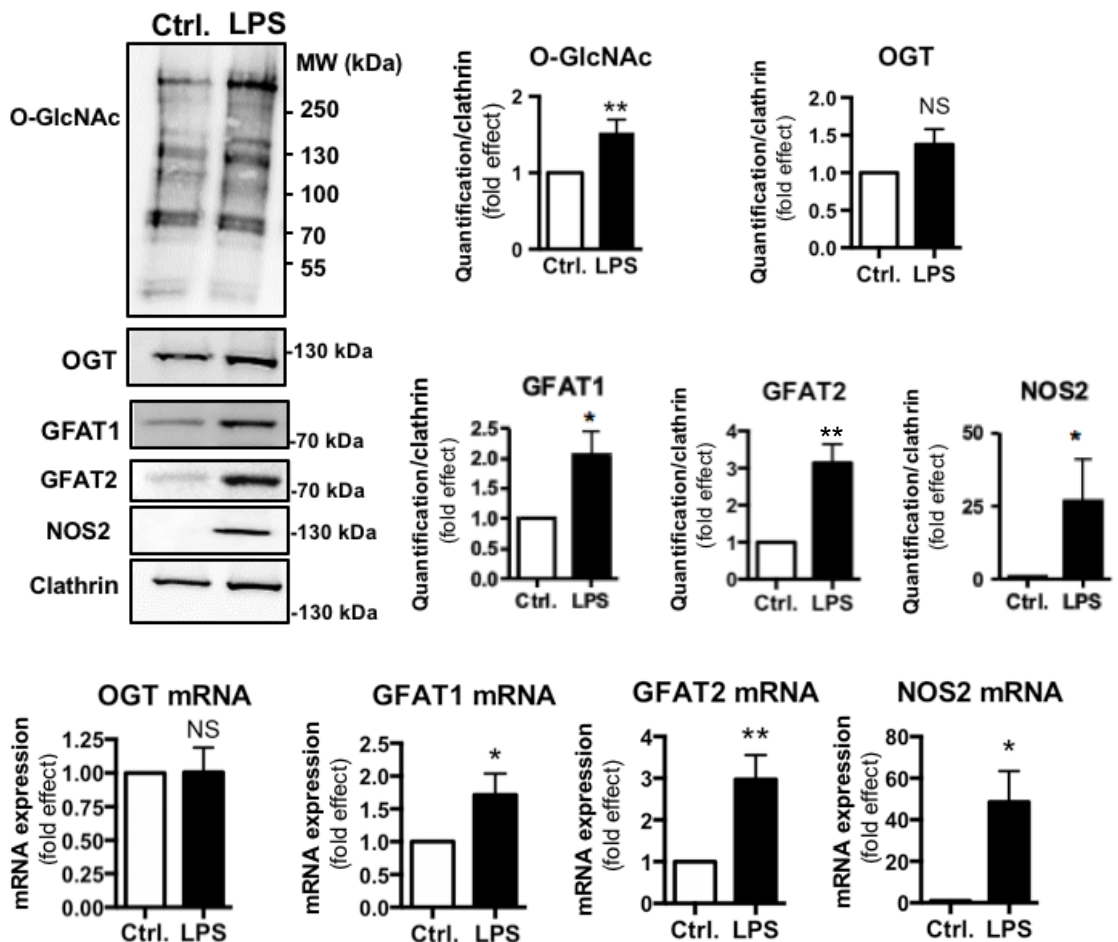


Fig.3

C

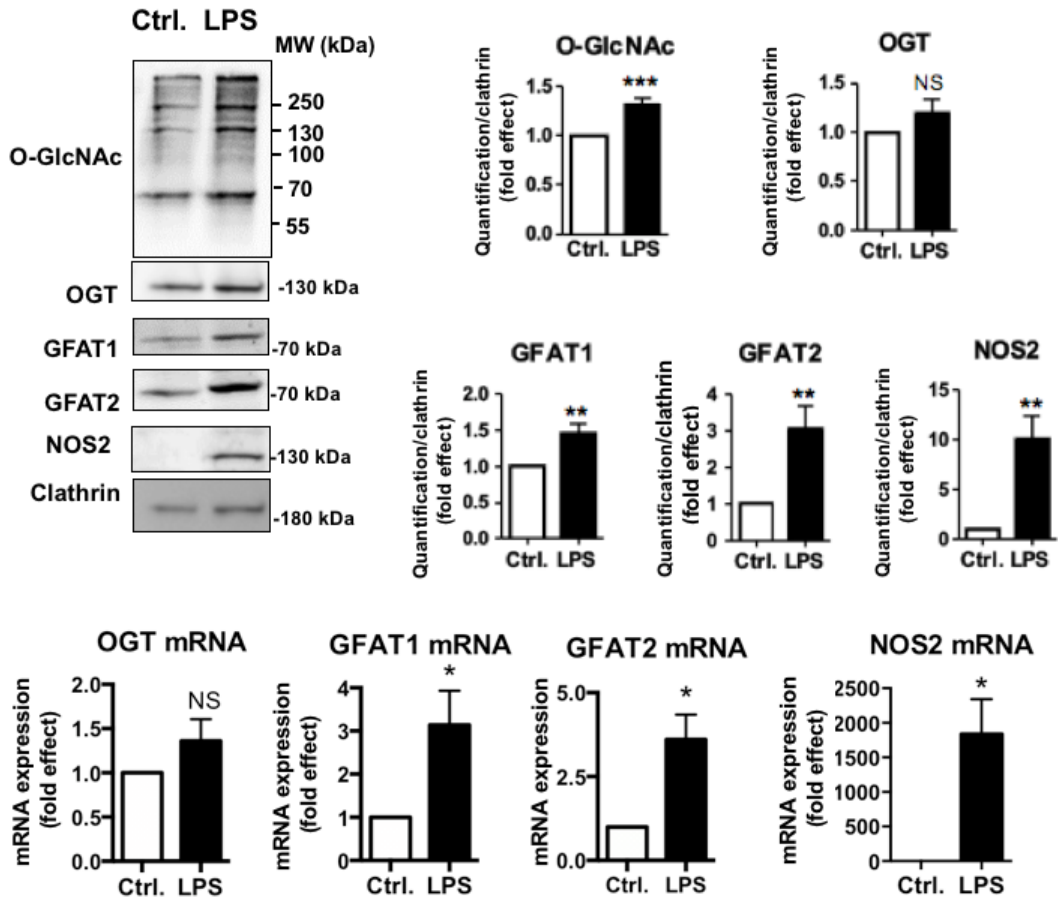


Fig.4

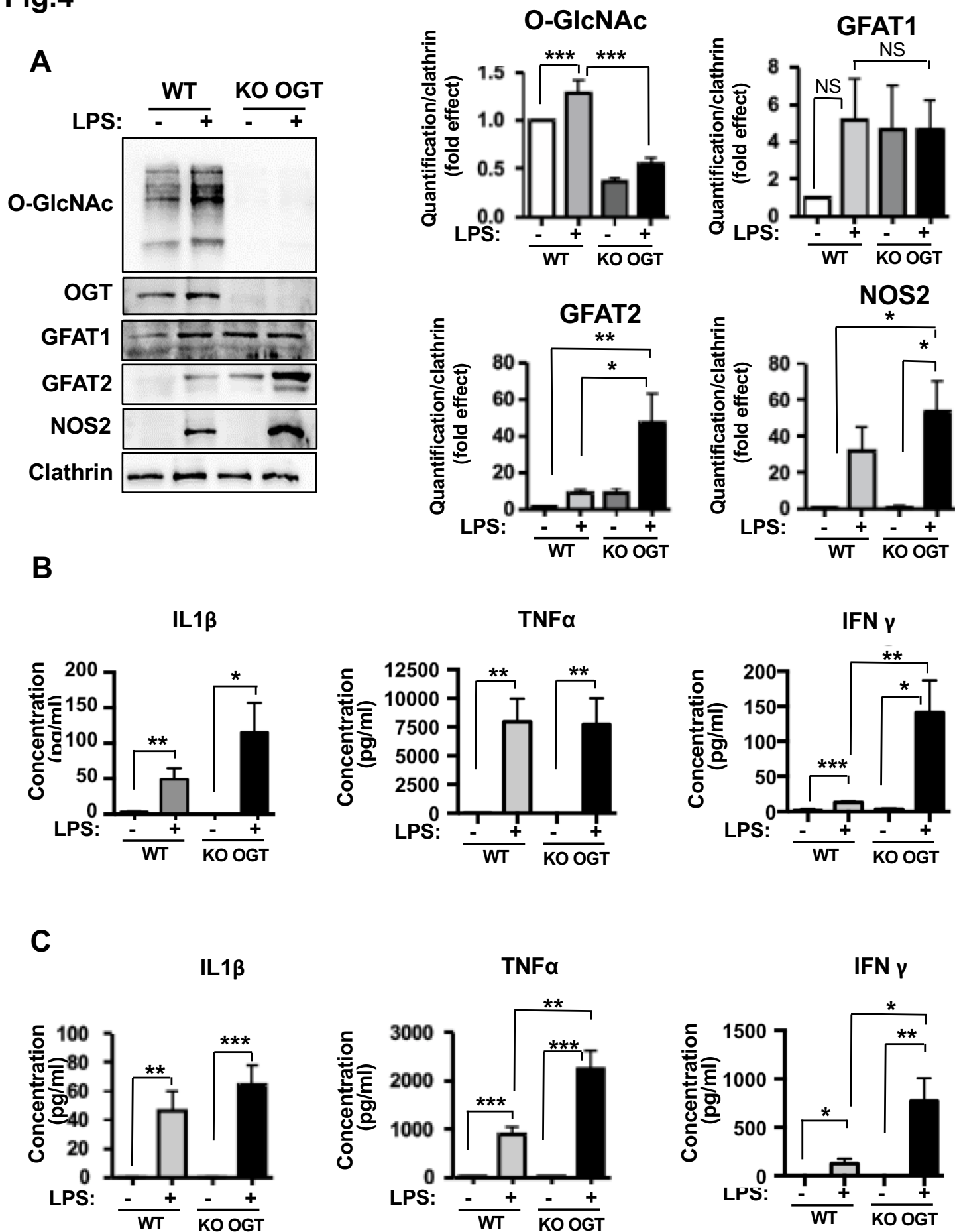


Fig.5

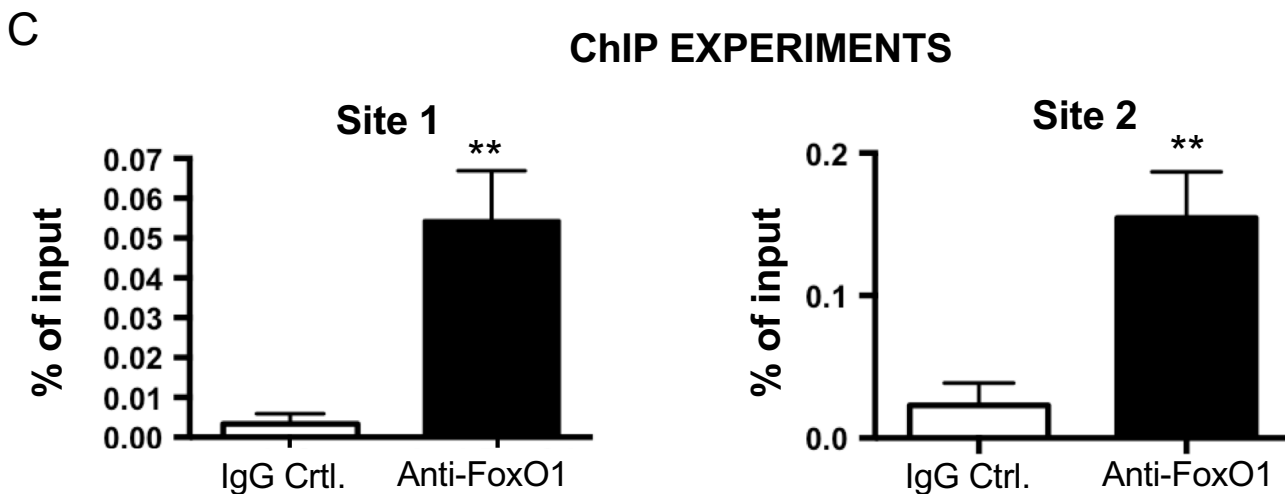
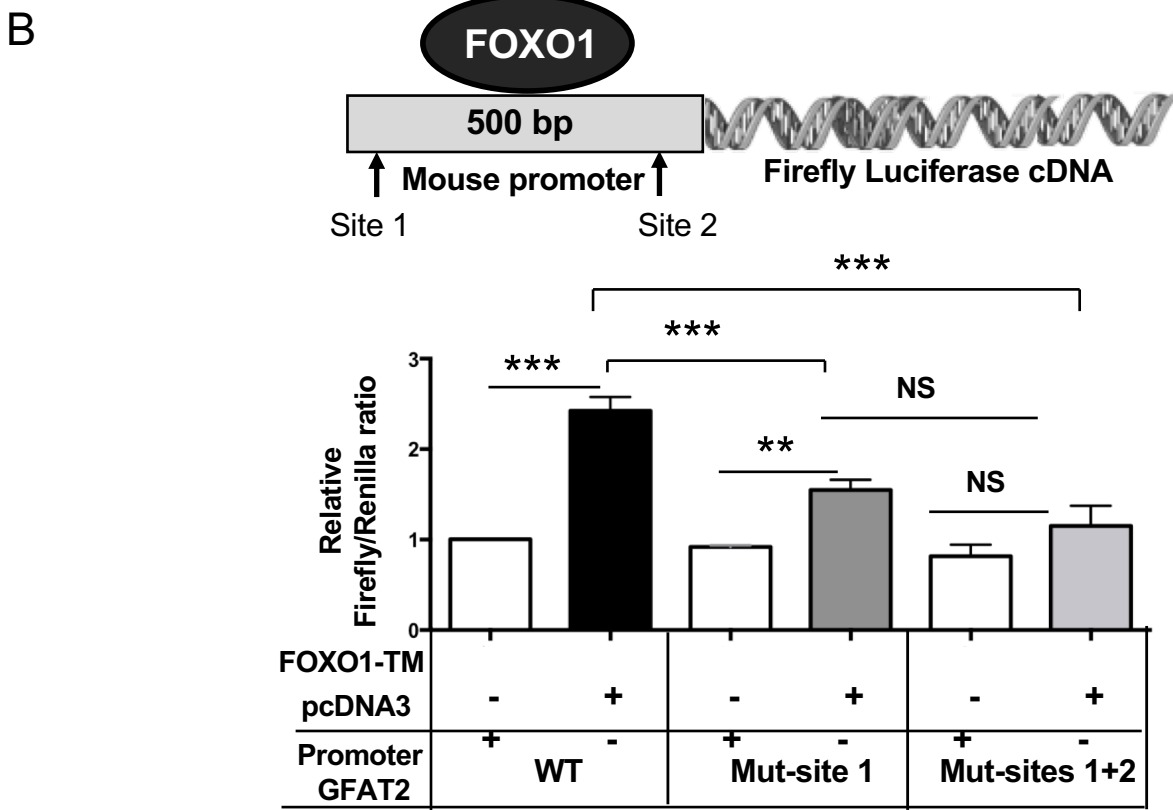
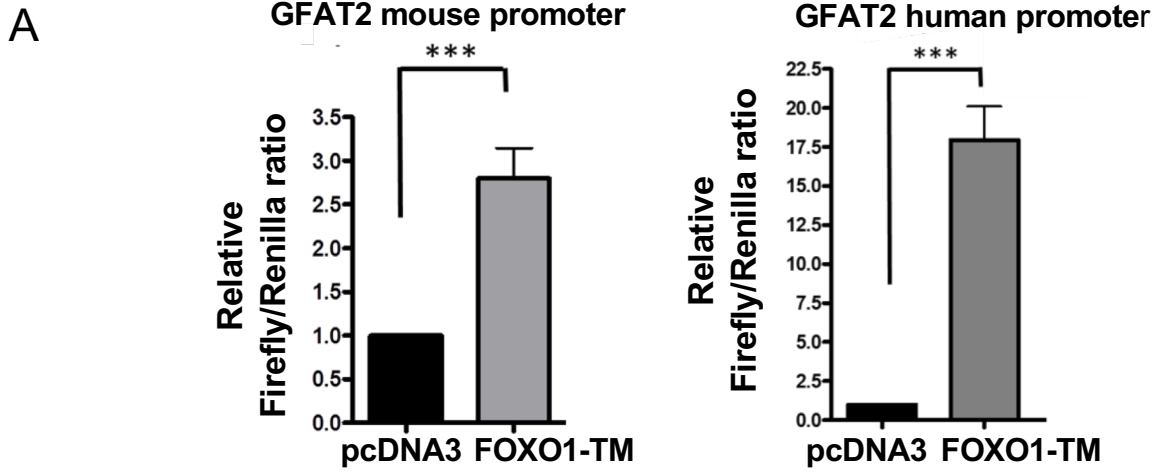
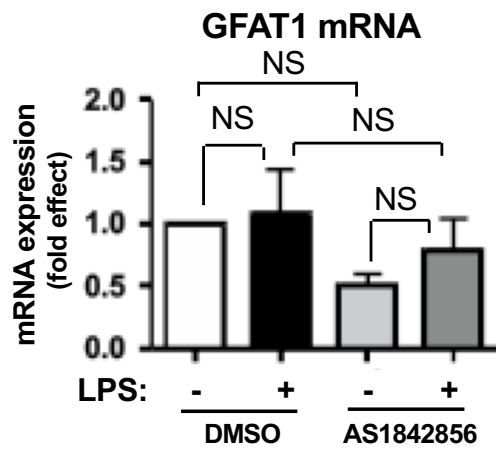
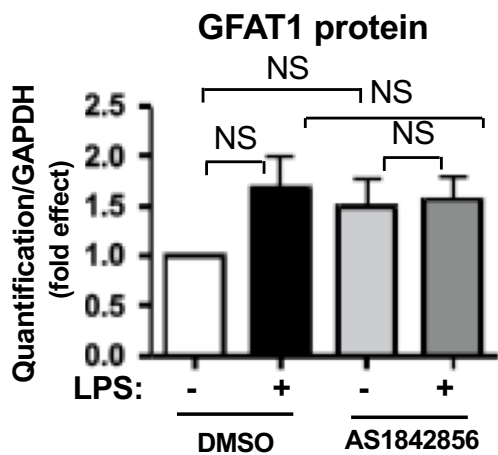
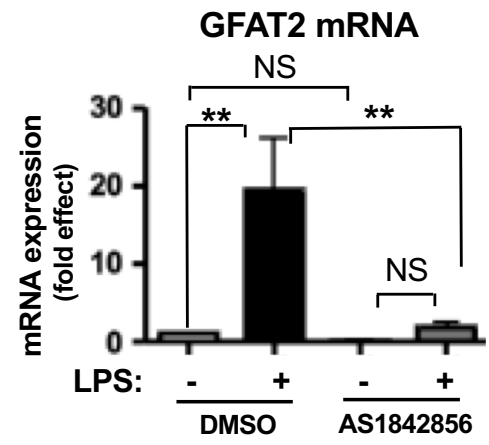
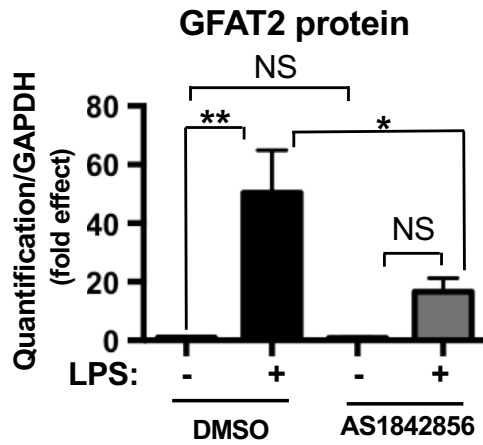
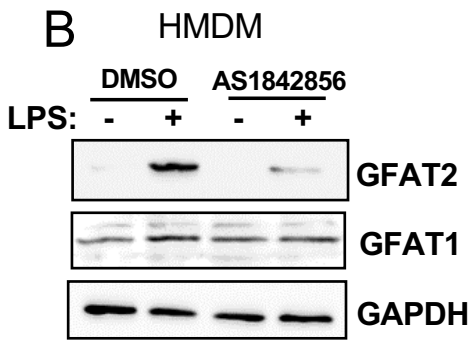
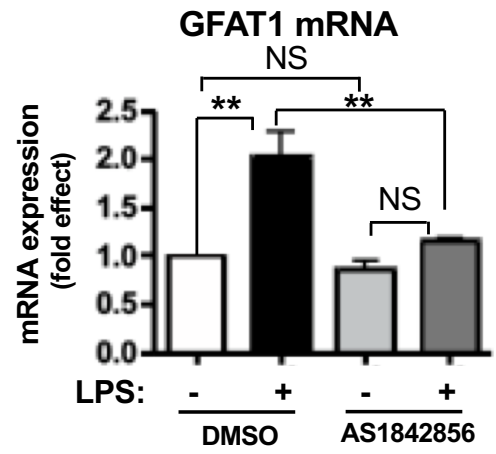
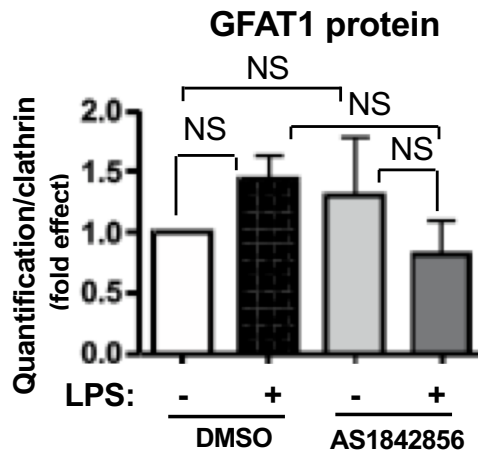
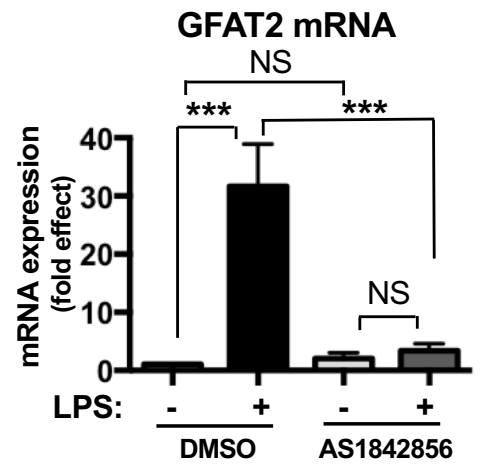
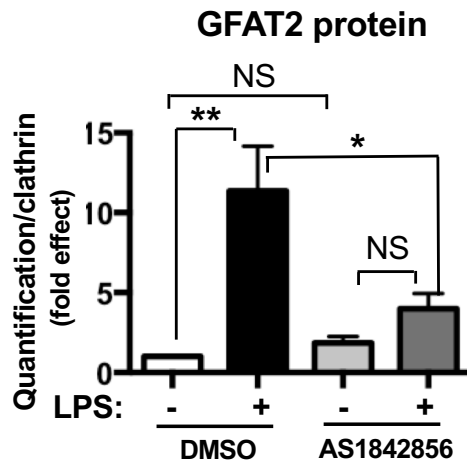
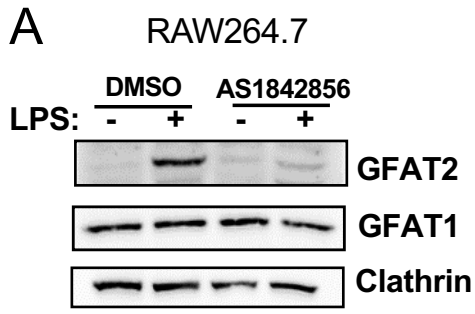


Fig.6



C

