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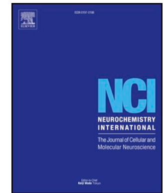

Dopaminergic neuroprotective effects of rotigotine via 5-HT1A receptors: Possibly involvement of metallothionein expression in astrocytes

Nami Isooka[a], Ikuko Miyazaki[a], Ryo Kikuoka[a,b], Kouichi Wada[a], Erika Nakayama[a], Kotaro Shin[a], Daichi Yamamoto[a], Yoshihisa Kitamura[b], Masato Asanuma[a,*]

[a] Department of Medical Neurobiology, Okayama University Graduate School of Medicine, Dentistry and Pharmaceutical Sciences, Okayama, 700-8558, Japan
[b] Department of Clinical Pharmacy, Okayama University Graduate School of Medicine, Dentistry and Pharmaceutical Sciences, Okayama, 700-8558, Japan

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ABSTRACT

Astrocytes exert neuroprotective effects through production of antioxidant molecules and neurotrophic factors. A recent study showed that stimulation of astrocyte serotonin 1A (5-HT1A) receptors promotes astrocyte proliferation and upregulation of the antioxidant molecules metallothionein (MT)-1,2, which protect dopaminergic neurons against oxidative stress. Rotigotine, an anti-parkinsonian drug, can bind to dopamine and 5-HT1A receptors. In this study, we examined neuroprotective effects of rotigotine in models of Parkinson's disease and involvement of astrocyte 5-HT1A receptors in neuroprotective effects of rotigotine against dopaminergic neurodegeneration. Rotigotine increased the number of astrocytes and MT-1,2 expression in cultured astrocytes. Pretreatment with conditioned media from rotigotine-treated astrocytes significantly inhibited 6-hydroxydopamine (6-OHDA)-induced dopaminergic neurotoxicity. These effects were completely blocked by a 5-HT1A antagonist or MT-1,2 specific antibody. Subcutaneous administration of rotigotine increased MT-1,2 expression in striatal astrocytes and prevented reduction of dopaminergic neurons in the substantia nigra of a 6-OHDA-lesioned mouse model of Parkinson's disease. These effects were blocked by co-administration with a 5-HT1A antagonist. These results suggest that rotigotine exerts neuroprotective effects through upregulation of MT expression in astrocytes by targeting 5-HT1A receptors. Our findings provide a possible therapeutic application of rotigotine to prevent dopaminergic neurodegeneration in Parkinson's disease.

1. Introduction

Parkinson's disease (PD) is a progressive neurodegenerative disease. Motor symptoms such as tremor, bradykinesia, and rigidity are induced by degeneration of dopaminergic neurons in the substantia nigra pars compacta (SNpc), which causes depletion of dopaminergic nerve terminals and dopamine (DA) content in the striatum (Chen et al., 2012; Dauer and Przedborski, 2003; Halliday et al., 1996). PD patients also develop non-motor symptoms including psychological manifestations such as depression, and autonomic disorders such as orthostatic hypotension and constipation (Berg et al., 2013; Grinberg et al., 2010; Singaram et al., 1995). Although pathogenesis in sporadic PD has not been characterized, oxidative stress is thought to be an important neurotoxic factor (Wang and Michaelis, 2010). Major medications used to treat PD patients provide dopaminergic therapy for managing motor disability. Therefore, it is essential to develop neuroprotectants that can prevent or delay progression of dopaminergic neurodegeneration.

Astrocytes are abundant neuron-supporting glial cells which comprise blood brain barrier, and regulate cerebral blood flow and synaptic function (Abbott et al., 2006; Araque et al., 1999; Attwell et al., 2010; Gordon et al., 2011; Koehler et al., 2009). In addition, astrocytes exert neuroprotective effects by producing antioxidants and neurotrophic factors, and by taking up excess extracellular glutamate (Banker, 1980; Dringen, 2000; Dringen and Hirrlinger, 2003). Recently, various studies have demonstrated neuroprotective actions of astrocytes (Drukarch et al., 1998; Jewett et al., 2017; Miyazaki and Asanuma, 2016; Nam et al., 2015). We previously reported that striatal astrocytes produced and secreted antioxidant molecules, metallothioneins (MTs), in response to oxidative stress, resulting in protection of dopaminergic neurons (Miyazaki et al., 2011). Stimulation of astrocyte serotonin 1A (5-HT1A) receptors enhances astrocyte proliferation and upregulates MT expression in striatal astrocytes, resulting in protection of dopaminergic neurons in a mouse model of PD (Miyazaki et al., 2013). These findings indicated that astrocyte 5-HT1A receptors may be a novel

* Corresponding author. Department of Medical Neurobiology, Okayama University Graduate School of Medicine, Dentistry and Pharmaceutical Sciences, 2-5-1 Shikata-cho, Kita-ku, Okayama, 700-8558, Japan. Tel.: (+81) 86 235 7096; Fax: (+81) 86 235 7103
E-mail address: asachan@cc.okayama-u.ac.jp (M. Asanuma).

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Abbreviations

ACM	astrocyte conditioned media
ANOVA	analysis of variance
Ara-C	cytosine-β-D-arabinofuranoside
DMEM	Dulbecco's Modified Eagle's Medium
DMSO	Dimethyl sulfoxide
ELISA	enzyme-linked immunosorbent assay
FBS	fetal bovine serum
GFAP	glial fibrillary acidic protein
GSH	glutathione
MT	metallothionein
Nrf2	nuclear factor erythroid 2-related factor
PBS	Phosphate buffered saline
PFA	paraformaldehyde
PD	Parkinson's disease
PMSF	phenyl methylsulfonyl fluoride
RT	room temperature
SD	Sprague-Dawley
SNpc	substantia nigra pars compacta
TH	tyrosine hydroxylase
WAY100635	N-[2-[4-(2-methoxyphenyl)-1-piperazinyl]ethyl]-N-(2-pyridinyl) cyclohexanecarboxamide maleate salt
5-HT1A	serotonin 1A
6-OHDA	6-hydroxydopamine

target for neuroprotection.

Rotigotine, a DA agonist, is used to treat PD. Rotigotine binds to all DA receptor subtypes (D1-D5), but has particularly high affinity for D2, D1, and D3 receptors (Wood et al., 2015). In addition to acting as a DA agonist, rotigotine is also a 5-HT1A partial agonist (Scheller et al., 2009). In the present study, we examined neuroprotective effects of rotigotine in a 6-hydroxydopamine (6-OHDA)-lesioned mouse PD model, and explored involvement of astrocyte 5-HT1A receptors in neuroprotective actions of rotigotine.

2. Materials and methods

2.1. Animals and animal care

All experimental procedures were conducted following the Guideline for Animal Experiments of Okayama University Advanced Science Research Center, and were approved by the Animal Care and Use Committee of Okayama University Advanced Science Research Center (approval reference number OKU-2016167; OKU-2019542). Male Crl:CD1 (ICR) mice and pregnant Sprague-Dawley (SD) rats were purchased from Charles River Japan Inc. (Yokohama, Japan). Mice and rats were housed under temperature- and humidity-controlled condition, which was maintained on a 12 h light/dark cycle with free access to food and water in Okayama University Advanced Science Research Center.

2.2. Cell culture

Primary cultured neurons and astrocytes were prepared from the mesencephalon and striata of SD rat embryos at 15 days of gestation using a previously described method (Miyazaki et al., 2013). To collect astrocyte conditioned media (ACM) and examine effects of rotigotine on MT expression in astrocytes, astrocyte cultures were prepared using striata of rat embryos. Dissected striata were cut into small pieces with scissors, and then incubated in 0.125% trypsin-EDTA (Thermo Fisher Scientific, Waltham, MA, USA) at 37 °C for 15 min. After centrifugation (1500 g for 3 min), the cell pellet was treated with 0.004% DNase I (Sigma-Aldrich, St. Louis, MO, USA) containing 0.003% trypsin inhibitor (Thermo Fisher) at 37 °C for 7 min. Following centrifugation (1500 g for 3 min), cells were plated in Dulbecco's Modified Eagle's Medium (DMEM) (Invitrogen, San Diego, CA, USA) containing 10% fetal bovine serum (FBS) (Sigma-Aldrich) at a density of 2×10^5 cells/cm^2 on poly-D-lysine-coated 6-well plates (Falcon, Corning, NY, USA). Cells were cultured for 4–7 days in the same medium, then subcultured to obtain enriched astrocyte cultures. Subcultured cells were plated at a density of 3.6×10^4 cells/cm^2 onto 6-well culture plates (Falcon) for preparation of conditioned media or nuclear protein extraction, or at a density of 2×10^4 cells/cm^2 onto four-chambered glass culture slides coated with poly-D-lysine (Falcon) for immunohistochemical analysis. After 7 days of culture, greater than 95% cells expressed astrocyte marker proteins.

To prepare enriched neuronal cultures, the mesencephalon was treated with 0.125% trypsin-EDTA and 0.004% DNase I containing 0.003% trypsin inhibitor as described above. Cells were plated in DMEM containing 10% FBS at a density of 2×10^5 cells/cm^2 on poly-D-lysine-coated four-chambered culture slides (Falcon). The medium was replaced within 24 h with fresh medium supplemented with 2 μM cytosine-β-D-arabinofuranoside (Ara-C) (Sigma-Aldrich) to inhibit replication of glial cells, and incubated for 6 days. Ninety-five percent of cells were microtubule-associated protein 2-positive neurons, and 1% of the cells were tyrosine hydroxylase (TH)-positive dopaminergic cells.

Mesencephalic neuronal and striatal astrocyte cocultures were prepared by culturing striatal astrocytes for 4 days, then seeding astrocytes at a density of 4×10^4 cells/cm^2 directly onto mesencephalic neurons that had been cultured on four-chambered culture slides for 4 days. All cultures were maintained at 37 °C in a 5% CO_2 atmosphere.

2.3. Preparation of astrocyte conditioned medium (ACM)

Striatal astrocytes were plated onto 6-well plates and grown in DMEM containing 10% FBS for 7 days. Astrocyte conditioned media (ACM) were prepared by treating astrocytes with 1 μM rotigotine (Sigma-Aldrich) (rotigotine-ACM), 10 nM N-[2-[4-(2-methoxyphenyl)-1-piperazinyl]ethyl]-N-(2-pyridinyl) cyclohexanecarboxamide maleate salt (WAY100635, a 5-HT1A receptor antagonist, Sigma-Aldrich) (WAY100635-ACM), WAY100635 and rotigotine (WAY100635 + rotigotine-ACM), or vehicle (control-ACM) for 24 h. Conditioned media were collected, centrifuged at 3000 g for 3 min to remove cellular debris, and supernatants were stored at −80 °C until use.

2.4. Cell treatments

Rotigotine was prepared fresh in dimethylsulfoxide (DMSO) (Sigma-Aldrich) for each experiment, then diluted to final concentration in medium (final concentration of DMSO: 0.1% v/v). To investigate the effects of rotigotine on astrocyte proliferation, striatal astrocytes were treated with rotigotine (0.01, 0.1, or 1 μM) one day after subculture for 24 h, and then counterstained with Hoechst 33342 nuclear stain. To examine effects of rotigotine on MT-1,2 expression in astrocytes, astrocytes cultured for 7 days were treated with rotigotine (0.01, 0.1, or 1 μM) for 24 h. To study the involvement of the 5-HT1A receptor in rotigotine-induced MT-1,2 up-regulation and Nrf2 nuclear translocation, astrocytes were treated with rotigotine (1 μM) dissolved in phosphate buffered saline (PBS) with or without WAY100635 (10 nM) for 24 h or 6 h respectively. Enriched neuronal cultures and neuron-astrocyte cocultures were treated with rotigotine (1 μM) for 24 h. After culture media were changed to fresh media, these cells were exposed to 10–150 μM 6-OHDA (Sigma-Aldrich) for 24 h. To examine whether neuroprotection by rotigotine against 6-OHDA-induced neurotoxicity was mediated by astrocytes, enriched neuronal cultures were treated with control- or

rotigotine-ACM for 24 h followed by 6-OHDA exposure. Involvement of astrocyte 5-HT1A receptors in neuroprotection by rotigotine was confirmed by treatment with WAY100635 + rotigotine-ACM. For neutralization assay, an anti-MT-1,2 antibody (DAKO Cytomation, Glostrup, Denmark) was preincubated with rotigotine-ACM (1:250; 200 μg/ml) for 1 h at room temperature (RT), then applied to the neuronal cultures. After 24 h treatment with ACM, or rotigotine-ACM with or without the antibody, culture media were exchanged for fresh media, and neurons were exposed to 6-OHDA (25 μM) for 24 h. All ACM contained 2 μM Ara-C throughout the neuronal culture treatment period.

2.5. Treatment of mice with rotigotine

Healthy male ICR mice weighing 38–42 g (8-week-old) were injected subcutaneously with rotigotine (0.125, 0.25, or 0.5 mg/kg) dissolved in vehicle 2% DMSO in corn oil (NACALAI TESQUE, INC., Kyoto, Japan) once per day for 7 days. All animals were arbitrarily allocated to groups by the experimenter. One day after the final injection of rotigotine, mice were perfused transcardially with 4% paraformaldehyde (PFA) (NACALAI TESQUE) for immunohistochemical analysis under deep pentobarbital anesthesia (80 mg/kg, i.p.).

2.6. 6-OHDA-lesioned parkinsonian mice and drug treatment

Male ICR mice weighing 38–42 g (8-week-old) were anesthetized by inhalation of isoflurane (Pfizer, Tokyo, Japan) and placed in a stereotaxic apparatus (Narishige, Tokyo, Japan). All mice received unilateral intrastriatal injections of 6-OHDA (7 μg/site, dissolved in 1 μl of 0.9% saline containing 0.1% ascorbic acid; Sigma-Aldrich) into three sites in the right striatum at the following coordinates: A +1.2 mm, L +2.0 mm, V +3.0 mm; A +0.9 mm, L +1.4 mm, V +3.0 mm; A +0.5 mm, L +2.0 mm, V +3.0 mm from the bregma, according to a mouse brain atlas (Franklin and Paxinos, 1997). The injection rate was 1 μl/2 min. After injection, the syringe was left in the striatum for an additional 3 min before being retracted slowly. Two weeks after 6-OHDA injections, mice that exhibited asymmetric rotation behavior towards the contralateral side (> 30 turns/min) after 0.5 mg/kg apomorphine injection (Sigma-Aldrich) were determined to have developed hemi-parkinsonism. One week after the apomorphine test (3 weeks after 6-OHDA injection), all parkinsonian animals were arbitrarily allocated to groups by the experimenter. Parkinsonian mice were subcutaneously injected with rotigotine (0.125, 0.25 or 0.5 mg/kg/day) or vehicle 2% DMSO in corn oil for 7 days. To examine whether agonism of 5-HT1A by rotigotine was involved in neuroprotective effects, parkinsonian mice were intraperitoneally injected with the 5-HT1A antagonist WAY100635 (0.25, 0.5 mg/kg/day, Sigma-Aldrich) dissolved in saline 1 h prior to rotigotine treatment. The following exclusion criteria were applied: more than 10% severe weight loss, severe behavioral deficits (paralysis, convulsions), or infections. No animal met the exclusion criteria during the study. One day after final injections, mice were perfused transcardially with 4% PFA for immunohistochemical analysis under deep pentobarbital anesthesia (80 mg/kg, i.p.). For Western blot analysis and ELISA, mice were perfused with ice-cold saline under deep anesthesia, and ventral midbrain and striatum tissues were dissected out immediately.

2.7. Immunohistochemistry

Cells on chamber slides were fixed with 4% PFA for 20 min at RT, blocked with 2.5% normal goat serum for 20 min, and reacted with the following primary antibodies for 18 h at 4 °C: mouse anti-TH (1:1000; Millipore, Temecula, CA, USA), rabbit anti-glial fibrillary acidic protein (GFAP) (1:500; Novus Biologicals, Littleton, CO, USA), or mouse anti-MT-1/-2 antibodies (1:50; Dako Cytomation) diluted in 10 mM PBS containing 0.1% Triton X-100 (Wako Pure Chemical Corporation, Osaka, Japan) (0.1% PBST). The secondary antibodies used were goat anti-mouse IgG conjugated to Alexa Fluor 594 (Invitrogen) or goat anti-rabbit IgG conjugated to Alexa Fluor 488 (Invitrogen). Cells were then counterstained with Hoechst 33342 nuclear stain.

For preparation of brain slices, mice were perfused with ice-cold saline followed by a fixative containing 4% PFA under deep pentobarbital anesthesia (80 mg/kg, i.p.). Perfused brains were removed and post-fixed for 24 h in 4% PFA. Following cryoprotection in 15% sucrose in PB for 48 h, brains were snap-frozen with powdered dry ice and 20-μm-thick coronal sections were cut on a cryostat at levels containing the mid-striatum (+0.6 to +1.0 mm from the bregma) and the SNpc (−2.8 to −3.0 mm from the bregma). Striatal and SNpc sections were incubated in 1% normal goat serum for 30 min at RT, then reacted with mouse anti-MT-1,2 (1:100, DAKO), rabbit anti-MT-1,2 (1:500; Frontier Institute, Hokkaido, Japan) rabbit anti-GFAP (1:20,000, Novus Biologicals), mouse anti-GFAP (1:10,000; Millipore), rabbit anti-S100β (1:5000; Dako Cytomation) or mouse anti-S100β (1:10,000; Sigma Aldrich) antibodies diluted in 0.2% PBST for 18 h at 4 °C. After washing in 0.2% PBST, slices were reacted with Alexa Fluor 594- or Alexa Fluor 488-conjugated secondary antibodies, as appropriate. All slides were analyzed using a fluorescence microscope (Olympus, Tokyo, Japan) and a cellSens software imaging system (Olympus) using a mercury lamp through a 470–495 nm, 530–550 nm, or 360–370 nm band-pass filter to excite Alexa Fluor 488, Alexa Fluor 594, or Hoechst dye, respectively. Light emitted from Alexa Fluor 488, Alexa Fluor 594, or Hoechst was collected through a 510–550 nm band-pass filter, a 590 nm long-pass filter, or a 420 nm long-pass filter, respectively. Confocal laser microscope (ZEISS, Oberkochen, Germany) and ZEN software imaging system (ZEISS) were used to confirm the colocalization of MT-1,2 and GFAP- or S100β-positive astrocytes.

For immunostaining of TH in the SNpc, brain slices were treated with 0.5% H_2O_2 (Wako Pure Chemical Corporation) for 30 min at RT, blocked with 1% normal goat serum for 30 min, and incubated with anti-TH rabbit polyclonal antibody (1:1,000, Millipore) diluted in 0.2% PBST for 18 h at 4 °C. Slices were incubated with biotinylated goat anti-rabbit IgG (1:1000; Vector Laboratories, Burlingame, CA, USA) for 2 h followed by avidin-biotin peroxidase complex (1:2000; Vector Laboratories) for 1 h at RT. TH-immunopositive signals were visualized by 3,3′-diaminobenzidine tetrahydrochloride (Sigma-Aldrich), nickel (Wako Pure Chemical Corporation), and H_2O_2.

For analysis of proliferative activity induced by rotigotine, striatal astrocyte cultures were counterstained with Hoechst 33342 nuclear stain and counted cell number in 8 fields/well chosen arbitrarily under × 400 magnification. Numbers of MT- and GFAP-immunopositive cells in cell cultures were counted in 8–18 fields/well chosen arbitrarily under × 200 magnification, and expressed as the percentages of MT-immunopositive astrocytes to total cell number. The integrated density of MT was calculated as follows: integrated density (signal density – background density) × area of positive signal. TH-immunopositive cells in cultured cells were counted under a microscope in all areas of each chamber slide.

Cells immunopositive for MT-1,2, GFAP, or S100β in the dorsal striatum of normal ICR mice or parkinsonian mice were counted manually using a microscope at a magnification of × 200. The number of MT-1,2-, GFAP-, or S100β-positive cells and the ratio of MT-1,2-positive cells to GFAP- or S100β-positive cells were evaluated in each section. The number of TH-immunopositive neurons in the SNpc was counted manually under a microscope at × 100 magnification. The boundary between the SNpc and ventral tegmental area was defined by a line extending dorsally from the most medial boundary of the cerebral peduncle. The ratio of lesion area to the intact side was evaluated. No blinding was performed in the counting of immunopositive cell number and measurement of the immunoreactivity. Broken immunostained slices were excluded from the quantitative analyses.

2.8. Western blot analysis

Nuclear lysates from cultured striatal astrocytes were extracted and

prepared using NE-PER Nuclear and Cytoplasmic Extraction Reagents (Thermo Fisher Scientific Inc., Rockford, IL) according to the protocol provided with the kit. Total cell lysates from ventral midbrain of mice extracted with RIPA buffer (1 mM PBS, pH 7.4, 1% Nonident P-40, 0.5% sodium deoxycholate, 0.1% sodium dodecyl sulfate (SDS)) containing phenyl methy lsulfonyl fluoride (PMSF). Western blot analysis was performed as described previously (Miyazaki et al., 2013). In brief, proteins were separated on 10% SDS polyacrylamide gels (Bio-Rad, Hercules, CA, USA) and electrophoretically transferred to polyvinylidene difluoride membranes (Hybond P, GE Healthcare, UK, Buckinghamshire, UK) at 20 mA/membrane for 60 min. The membranes were pre-incubated with blocking buffer (Block-Ace; DS Bio Pharma Medical, Tokyo, Japan), and incubated with rabbit polyclonal anti-nuclear factor erythroid 2-related factor (Nrf2) (1:100; Santa Cruz Biotechnology, Santa Cruz, CA, USA), goat polyclonal anti-Lamin B (1:200; Santa Cruz), rabbit polyclonal anti-TH (1:1000; Millipore) or mouse monoclonal anti α-tubulin (1:2000; Sigma-Aldrich) antibodies. After washing with 20 mM Tris-buffered saline containing 0.1% tween 20 (Wako Pure Chemical Corporation), the blots were incubated with the corresponding horseradish peroxidase-conjugated secondary antibodies. Signals were visualized via chemiluminescence using an ELC Western blotting detection system (GE Healthcare). Images were obtained and quantified using a FUJIFILM Luminescent Image Analyzer LAS-3000 (FUJIFILM, Tokyo, Japan) and Multi Gauge (v 3.0) software. For quantitative analysis, the signal ratio of Nrf2 (relative chemiluminescence unit) to that of constitutively expressed Lamin B or TH to α-tubulin protein was calculated to normalize for loading and transfer artifacts. The nuclear fraction for Western blot analysis with low concentration was excluded prior to electrophoresis.

2.9. Enzyme-linked immunosorbent assay (ELISA)

Levels of MT-1 in cultured astrocytes and striatal tissue of parkinsonian mice were measured by enzyme-linked immunosorbent assay (ELISA) with mouse MT-1 ELISA kit (SEB199Mu; Cloud-Clone Corp., Katy, TX, USA) according to the manufacturer's protocol. To extract total cell lysate from cultured astrocytes or striata of parkinsonian mice for ELISA, cells or tissues were homogenized using RIPA buffer containing PMSF. After centrifugation to remove cellular debris, the supernatants were stored at −80 °C until analyses. Protein concentration were determined using the Lowry-based Bio-Rad DC protein assay kit (Bio-Rad) with bovine serum albumin as a standard.

2.10. Statistical analysis

Values were expressed as means ± SEM. Differences between groups were examined for statistical significance using one-way analysis of variance (ANOVA) followed by *post-hoc* Fisher's PLSD test. A *p* value less than 0.05 was considered statistically significant. The sample size in our study was determined based on our previous reports (Miyazaki et al., 2013).

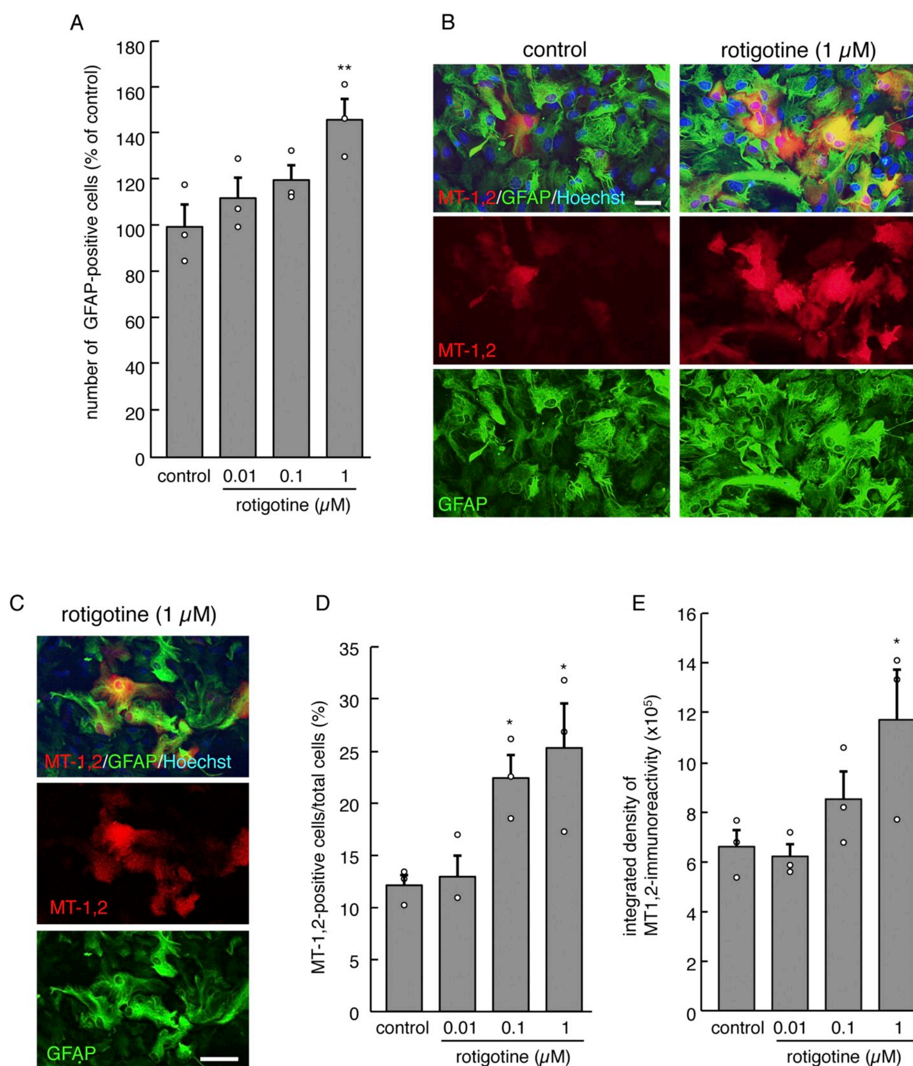

Fig. 1. Effects of rotigotine treatment on astrocyte proliferation and MT-1,2 expression.
Cultured striatal astrocytes were treated with rotigotine (0.01, 0.1, 1 μM) for 24 h. (A) Number of GFAP-positive astrocytes after rotigotine treatment. Each value is represented as the mean ± SEM (n = 3), expressed as a percentage of the control. (B) Representative photomicrographs of MT-1,2 and GFAP double immunostaining. Scale bar: 50 μm. (C) Photomicrographs of confocal laser microscope. Scale bar: 100 μm. (D, E) Rotigotine upregulated MT-1,2 expression in astrocytes. (D) Ratio of MT-1,2-immunopositive astrocytes to total cells. (E) Integrated density of MT-1,2 immunoreactivity. Data are expressed as means ± SEM (n = 3). *$p < 0.05$, **$p < 0.01$ vs. control group.

3. Results

3.1. Rotigotine promoted astrocyte proliferation and upregulated MT-1,2 expression

Treatment with rotigotine (0.1 or 1 μM) significantly increased the number of striatal astrocytes in cultured cells (Fig. 1A). Rotigotine also upregulated MT-1,2 in striatal astrocytes (Fig. 1B-E). We confirmed colocalization of GFAP and MT-1,2 signals using confocal laser microscope (Fig. 1C). The number of MT-1,2-positive astrocytes is shown in Fig. 1D and MT-1,2-immunoreactivity is shown in Fig. 1E. These results suggested that rotigotine promoted astrocyte proliferation and upregulated astrocytic antioxidative property in astrocyte cultures.

3.2. Rotigotine induced MT-1,2 expression and Nrf2 nuclear translocation via astrocyte 5-HT1A receptors

To examine whether rotigotine upregulated MT-1,2 in astrocytes via 5-HT1A receptors, striatal astrocyte cultures were treated with rotigotine (1 μM) and/or the 5-HT1A antagonist WAY100635 (10 nM) for 24 h. WAY100635 can bind to the 5-HT1A receptor with high affinity and selectivity. It is reported that the binding activity of WAY100635 is greater than 100-fold selectivity relative to binding at other 5-HT receptor subtypes and major neurotransmitter receptor, reuptake and ion

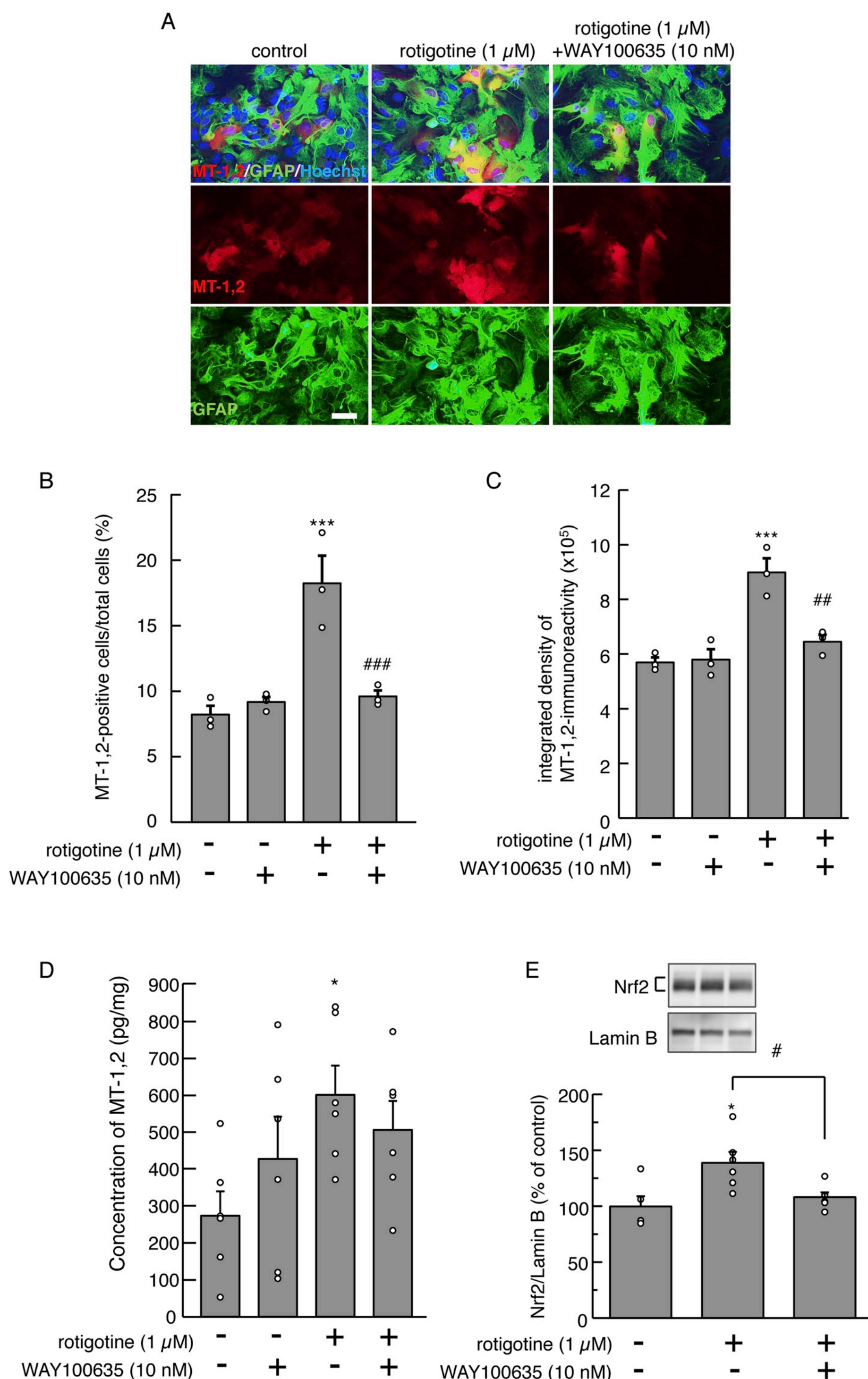

Fig. 2. Rotigotine upregulated MT-1,2 expression and promoted nuclear translocation of Nrf2 in astrocytes via 5-HT1A receptors. (A–D) Effects of treatment with rotigotine and/or WAY100635 on MT-1,2 expression in astrocytes. Cultured striatal astrocytes were treated with rotigotine (1 μM) and/or WAY100635 (10 nM) for 24 h. (A) Representative photomicrographs of MT-1,2 and GFAP double immunostaining. Scale bar: 50 μm. (B) Ratio of MT-1,2-immunopositive astrocytes to total cells. (C) Integrated density of MT-1,2 immunoreactivity. Data are expressed as means ± SEM (n = 3). (D) Changes in MT-1 content in cultured astrocytes after treatment with rotigotine (1 μM) and/or WAY100635 (10 nM) for 24 h. MT-1 content was determined by ELISA. Data expressed as means ± SEM (n = 6). (E) Effects of treatment with rotigotine and/or WAY100635 on nuclear Nrf2 expression in astrocytes. Data are means ± SEM (n = 4–6). *$p < 0.05$, ***$p < 0.001$ vs. control group, $^{\#}p < 0.05$, $^{\#\#}p < 0.01$, $^{\#\#\#}p < 0.001$ vs. the rotigotine-treated group.

channel sites (Forster et al., 1995). Simultaneous treatment with WAY100635 almost completely blocked rotigotine-induced MT-1,2 expression as shown in the results of MT-1,2- and GFAP-double immunostaining (Fig. 2A–C). In this study, we measured MT-1,2 levels using total cell lysates from cultured astrocytes by ELISA. Rotigotine significantly upregulated MT levels in astrocytes, but the MT upregulation was not significantly inhibited by WAY100635. (Fig. 2D). MT-1,2 gene expression is regulated by the transcriptional factor Nrf2 (Shih et al., 2003). In the present study, we examined Nrf2 levels in nuclei of astrocytes after 6 h treatment with rotigotine (1 μM) and WAY100635 (10 nM) by Westernblot analysis. Nrf2 levels were significantly increased by rotigotine treatment, and nuclear translocation of Nrf2 was completely blocked by WAY100635 (Fig. 2E). These results suggested that rotigotine-induced Nrf2 nuclear translocation and MT upregulation occurred through astrocyte 5-HT1A receptor signaling.

3.3. Rotigotine required striatal astrocytes to protect dopaminergic neurons

To examine the role of astrocytes on neuroprotective effects of rotigotine against dopaminergic neurodegeneration, enriched mesencephalic neuronal cultures or mesencephalic neuronal and striatal astrocyte cocultures were treated with rotigotine following by oxidative stress induced by 6-OHDA exposure (Fig. 3A). In enriched neuronal cultures, rotigotine failed to prevent reduction of TH-positive dopaminergic neurons following 6-OHDA exposure (Fig. 3B and C and Suppl. Fig. 1). Conversely, in neuronal and astrocyte cocultures, rotigotine exerted protective effects against 6-OHDA-induced damage of neuritis and reduction of dopaminergic neurons (Fig. 3B, D and Suppl. Fig. 1). These results suggested that neuroprotective effects of rotigotine are mediated by astrocytes.

3.4. Secreted MTs from rotigotine-treated astrocytes via 5-HT1A receptor protected dopaminergic neurons against 6-OHDA toxicity

To investigate whether secreted molecules from rotigotine-treated astrocytes can protect dopaminergic neurons against oxidative stress, enriched neuronal cultures were incubated with conditioned media from striatal astrocytes treated with or without 1 μM rotigotine (rotigotine-ACM/control-ACM) (Fig. 4A). Treatment with rotigotine-ACM significantly inhibited neurite damage and reduction of TH-positive

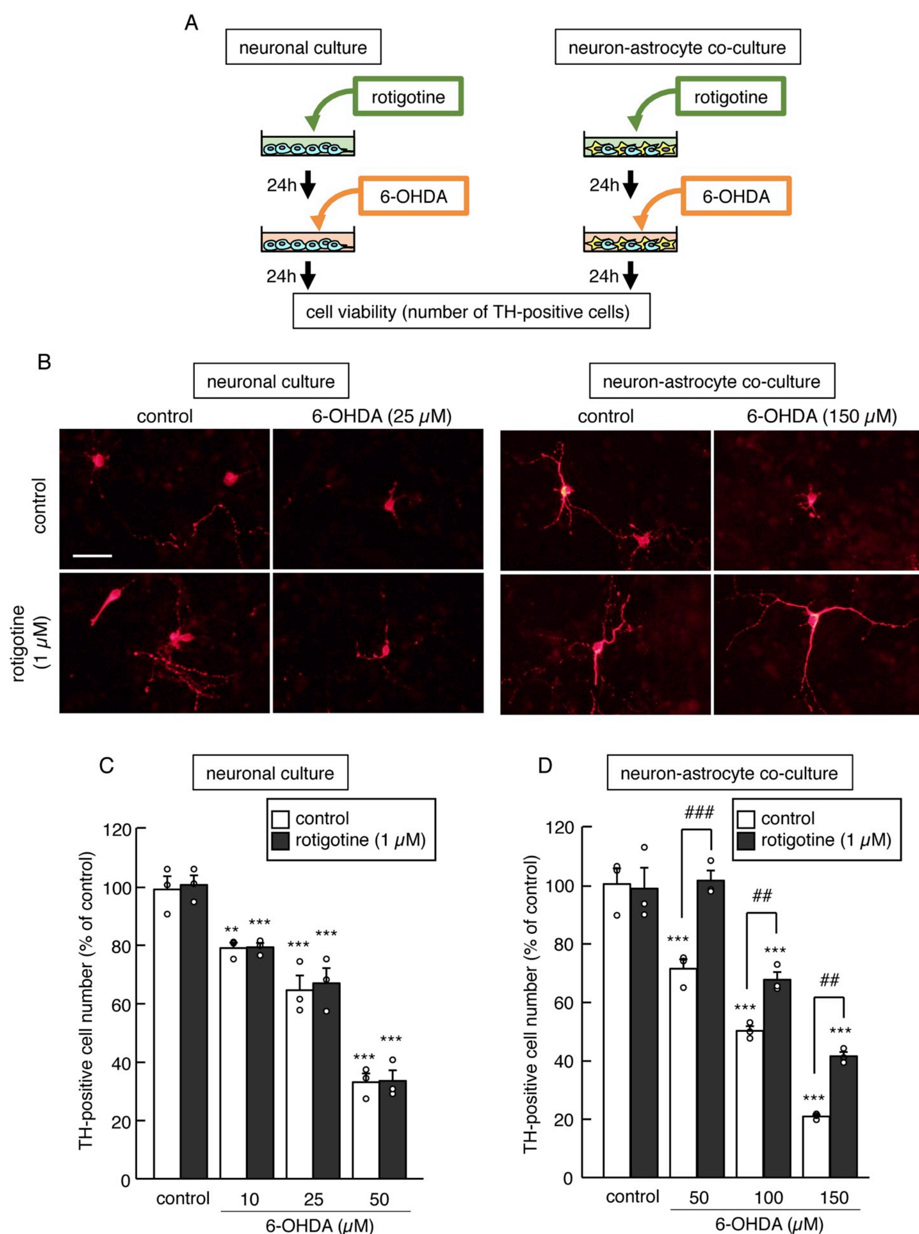

Fig. 3. Rotigotine protected dopaminergic neurons against 6-OHDA toxicity by targeting astrocytes. (A) Flow chart of the study design. Mesencephalic neuronal culture or mesencephalic neuron and striatal astrocyte coculture were treated with rotigotine (1 μM) for 24 h, and then exposed to 6-OHDA for 24 h. Cells were fixed and immunostained for TH. (B) Morphological change of dopaminergic neurons 24 h after 6-OHDA exposure. Scale bar: 50 μm. TH-positive cell number in enriched mesencephalic neuronal cultures (C) or mesencephalic neuronal and striatal astrocyte cocultures (D). Each value is presented as the mean ± SEM (n = 3), expressed as percentage of control. $^{**}p < 0.01$, $^{***}p < 0.001$ vs. each control group, $^{\#\#}p < 0.01$, $^{\#\#\#}p < 0.001$ between the two indicated groups.

neurons following 6-OHDA exposure. Furthermore, the protective effects of rotigotine-ACM were completely annulled by WAY100635 treatment (Fig. 4B, D, F and Suppl. Fig. 2), suggesting that rotigotine promoted secretion of neuroprotective molecules from astrocytes via 5-HT1A receptors. MT-1,2 are produced predominantly in astrocytes, and extracellular MTs secreted from astrocytes protect dopaminergic neurons from damage (Miyazaki et al., 2013). Therefore, we examined involvement of MT-1,2 in rotigotine-mediated neuroprotection. Anti-MT-1,2 antibody was added to rotigotine-ACM, and neuronal cultures were treated with rotigotine-ACM containing MT-1,2 antibody followed by 6-OHDA exposure (Fig. 4C). Incubation of rotigotine-ACM with anti-MT-1,2 antibody completely blocked the neuroprotective effects of rotigotine-ACM (Fig. 4E, G and Suppl. Fig. 3). These results suggested that rotigotine exhibits dopaminergic neuroprotection by promoting MT-1,2 secretion from astrocytes via 5-HT1A receptors on astrocytes.

3.5. Rotigotine upregulated MT-1,2 expression in striatal astrocytes in normal mice

To examine whether rotigotine upregulated MT-1,2 expression in astrocytes *in vivo*, healthy ICR mice were subcutaneously injected with rotigotine (0.125, 0.25, 0.5 mg/kg/day) for 7 days (Fig. 5A). Striatal sections were double immunostained with the astrocyte markers S100β and MT-1,2. MT-1,2 signals were colocalized with S100β-positive astrocytes (Fig. 5B). The number of MT-1,2-positive astrocytes (Fig. 5C and D) and the ratio of MT-1,2-positive cells to S100β-positive astrocytes (Fig. 5E) were significantly increased following repeated rotigotine administration.

3.6. Rotigotine protected dopaminergic neurons against neurodegeneration in parkinsonian mice via 5-HT1A receptor

Rotigotine (0.125, 0.25, 0.5 mg/kg) was administered to 6-OHDA-

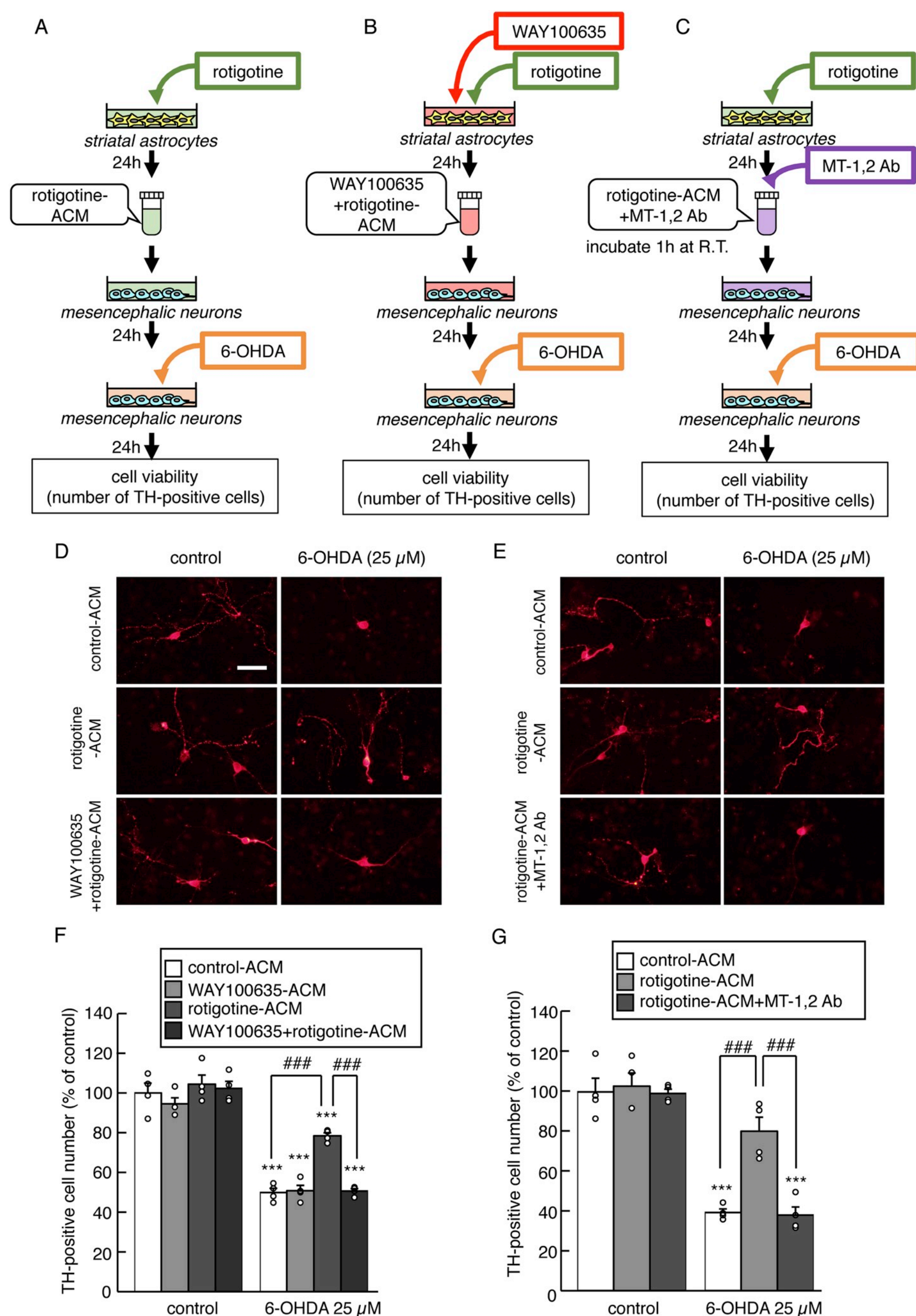

Fig. 4. Rotigotine promoted MT-1,2 secretion from astrocytes to protect dopaminergic neurons via 5-HT1A receptors. (A–C) Flow chart of the study design. Rotigotine and/or WAY100635 were added to astrocytes cultures and incubated for 24 h. Astrocyte conditioned media (ACM) were collected, and mesencephalic neurons were pretreated with ACM (control-ACM, rotigotine-ACM, or WAY100635 + rotigotine-ACM) for 24 h prior to 6-OHDA exposure (A, B). Anti-MT-1,2 antibody was added to rotigotine-ACM to neutralize secreted MT-1,2 from rotigotine-treated astrocytes. Mesencephalic neurons were treated with rotigotine-ACM containing anti-MT-1,2 antibody for 24 h, and then exposed to 6-OHDA (A, C). (D, E) Morphological change of dopaminergic neurons 24 h after 6-OHDA exposure treated with rotigotine-ACM and/or WAY100635 (D) or rotigotine-ACM + MT-1,2 antibody (E). Scale bar: 50 μm. (F) Cell viability of TH-positive dopaminergic neurons after treatment with rotigotine-ACM and/or WAY100635. Neuroprotective effects of conditioned media from rotigotine-treated astrocytes (rotigotine-ACM) were blocked by WAY100635 treatment (WAY100635 + rotigotine-ACM). (G) Incubation of rotigotine-ACM with anti-MT-1,2 antibody (rotigotine-ACM + MT-1,2 Ab) blocked neuroprotective effects of rotigotine-ACM. Data are presented as means ± SEM (n = 4). **$p < 0.01$, ***$p < 0.001$ vs. each control group, ###$p < 0.001$ between the two indicated groups.

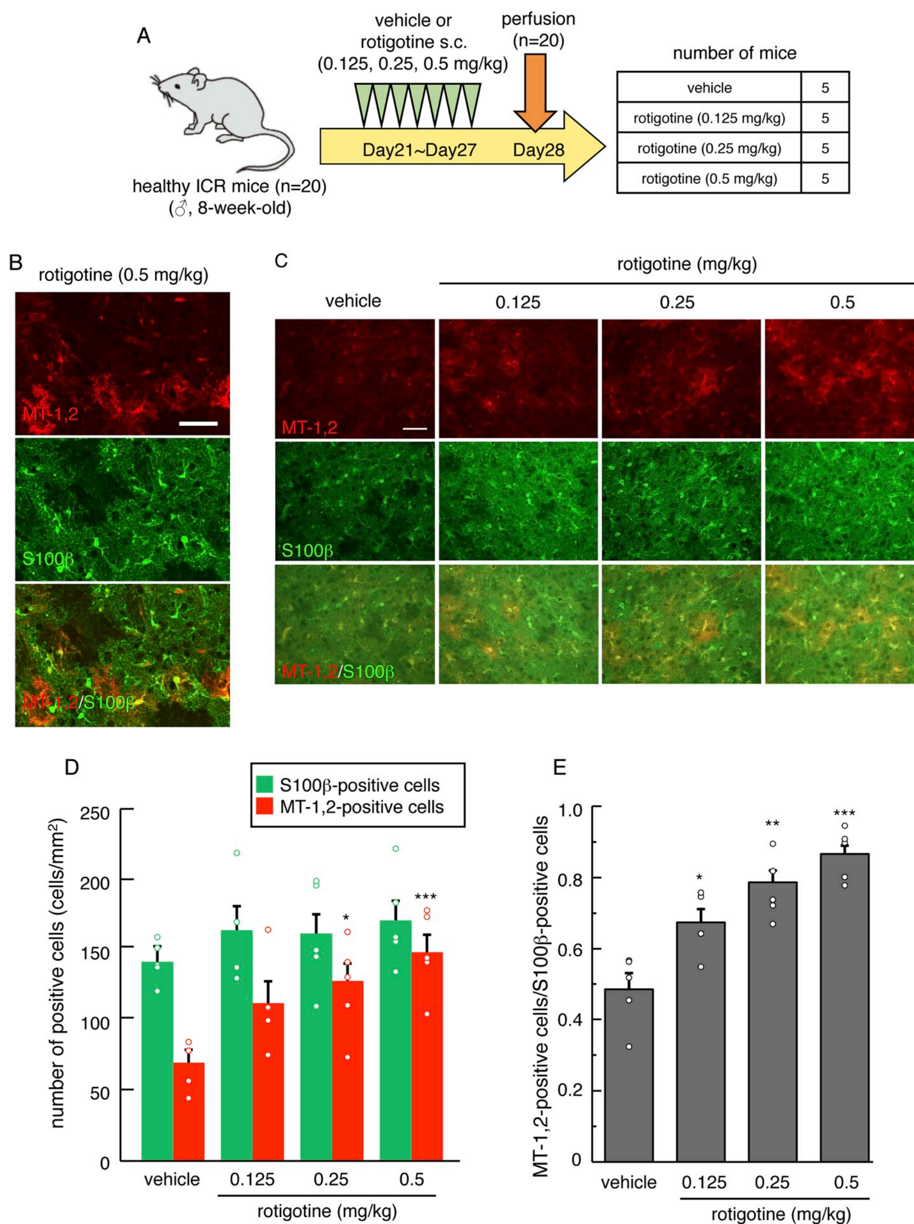

Fig. 5. Effects of rotigotine treatment on MT-1,2 expression in astrocytes in the striatum of normal mice. (A) Flow chart of the study design. Rotigotine (0.125, 0.25, 0.5 mg/kg/day) or vehicle (2% DMSO in corn oil) was administered subcutaneously to healthy ICR mice (male, 8 weeks old) for 7 days. Mice were perfused with a fixative one day after the final administration. (B) Images of confocal laser microscope. Scale bar: 100 μm. (C) Representative photomicrographs of MT-1,2 and S100β double immunostaining using striatal slices. Scale bar: 100 μm. (D) Number of S100β- and MT-1,2-positive cells. (E) Ratio of MT-1,2 immunopositive astrocytes to total cells. Each value is presented as the mean ± SEM (n = 5). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$ vs. the vehicle-treated group.

injected parkinsonian mice to examine neuroprotective effects of rotigotine *in vivo* (Fig. 6A). TH-positive dopaminergic neurons in the SNpc were significantly decreased in the lesioned side of parkinsonian mice. Rotigotine administration (0.5 mg/kg) significantly ameliorated dopaminergic neuronal loss in the SNpc (Fig. 6B and C). To examine whether the 5-HT1A receptor is involved in the neuroprotective effects of rotigotine in parkinsonian mice, rotigotine (0.25 or 0.5 mg/kg/day, s.c.) and/or WAY100635 (0.25 or 0.5 mg/kg/day, i.p.) were administered to 6-OHDA-treated parkinsonian mice for 7 days (Fig. 7A). Rotigotine (0.25, 0.5 mg/kg) prevented reduction of TH-positive neurons in the lesioned side of the SNpc. Neuroprotective effects of rotigotine (0.25, 0.5 mg/kg) were blocked by co-administration of WAY100635 (0.5 mg/kg) (Fig. 7B–G). These results suggested that rotigotine protected dopaminergic neurons in parkinsonian mice by targeting 5-HT1A receptors. We also performed TH Western blot analysis using total cell lysate from midbrain tissues containing SNpc of parkinsonian mice after treatment rotigotine (0.25 mg/kg) and/or WAY100635 (0.25, 0.5 mg/kg). TH expression in the lesioned side of SNpc was decreased by 30% in contrast to control side. Rotigotine treatment showed neuroprotective tendency, but this did not reach significance (Suppl. Fig.4).

3.7. Effects of administration of rotigotine and/or WAY100635 on MT-1,2 expression in astrocytes in the striatum of parkinsonian mice

To examine whether rotigotine increased astrocyte MT-1,2 expression in parkinsonian mice, we double immunostained for S100β and MT-1,2 in striatal sections of parkinsonian mice treated with rotigotine (0.125, 0.25, 0.5 mg/kg). Rotigotine (0.25 mg/kg/day, s.c.) administration for 7 days significantly increased the number of MT-1,2-positive astrocytes (Suppl. Fig. 5A and B) and the ratio of MT-1,2-positive cells/S100β-positive cells in control and lesioned side (Suppl. Fig. 5C). We confirmed colocalization of MT-1,2 and S100β-positive astrocytes in the striatum of parkinsonian mice (Suppl. Fig. 5D). MT induction by rotigotine (0.25 mg/kg/day) treatment in striatal astrocytes was blocked by co-administration of WAY100635 (0.25, 0.5 mg/kg/day, i.p.) (Fig. 8A–D). It is well known that astrocytes become hypertrophic (i.e., reactive astrocytes) and accumulate in the brain during progression of neurodegenerative diseases. Reactive astrocytes express high levels of GFAP *in vivo*. Therefore, we explored MT-1,2 expression in GFAP-positive reactive astrocytes. Accumulation of GFAP-positive astrocytes was observed in the lesioned side of parkinsonian mice, and MT-1,2

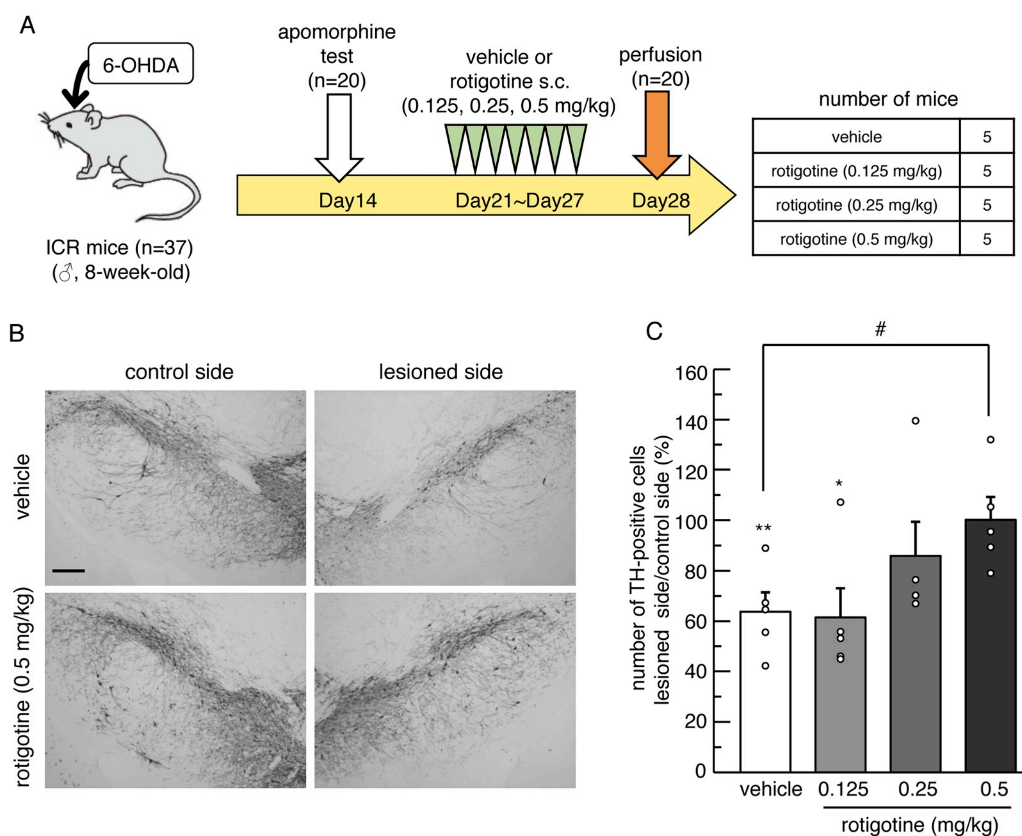

Fig. 6. Neuroprotective effects of rotigotine administration against dopaminergic neurodegeneration in parkinsonian mice. (A) Flow chart of the study design. 6-OHDA was administered to the right striatum of ICR mice (male, 8 weeks old) to prepare parkinsonian mice. Fourteen days after 6-OHDA injection, apomorphine rotation test was performed to confirm development of parkinsonism. Rotigotine (0.125, 0.25, 0.5 mg/kg/day) or vehicle (2% DMSO in corn oil) was administered subcutaneously to the parkinsonian mice for 7 days. Parkinsonian mice were perfused with a fixative one day after the final administration. (B) Representative photomicrographs of TH immunostaining in the SNpc of parkinsonian mice after repeated administration of rotigotine for 7 days. Scale bar: 200 μm. (C) Ratio of nigral TH-immunopositive cells in the lesioned side to the control side of parkinsonian mice after treatment with rotigotine (0.125, 0.25, 0.5 mg/kg/day, s.c.) or vehicle (2% DMSO in corn oil) for 7 days. Each value is presented as the mean ± SEM (n = 5). $^{*}p < 0.05$, $^{**}p < 0.01$ vs. the control side of each group, $^{\#}p < 0.05$ vs. the vehicle-treated group.

signals were colocalized with GFAP-positive astrocytes (Fig. 9A and B). Rotigotine (0.25 mg/kg/day) treatment significantly increased MT-1,2 expression in reactive astrocytes, and WAY100635 (0.25, 0.5 mg/kg/day) completely blocked this effect (Fig. 9C and D). Repeated rotigotine (0.5 mg/kg/day) administration did not induce MT-1,2 expression in the striatum of parkinsonian mice, and WAY100635 (0.5 mg/kg/day) had no effect on MT expression (Suppl. Fig. 6A–C). Furthermore, we measured MT-1 content by ELISA using striatal total cell lysate from tissues of parkinsonian mice treated with rotigotine (0.25 mg/kg) and/or WAY100635 (0.25, 0.5 mg/kg). There was a tendency to increase in MT content on the lesioned side of parkinsonian mice, but rotigotine failed to induce further increase in MT expression (Suppl. Fig. 7). To examine effects of rotigotine administration on astrocytic MT-1,2 expression in the SNpc, we performed double immunostaining of MT-1,2 and S100β or GFAP using slices of SNpc of parkinsonian mice administered with rotigotine (0.25 mg/kg) and WAY100635 (0.25 or 0.5 mg/kg). There was no change in MT-1,2 expression in the astrocytes of SNpc in any groups (Suppl. Figs. 8, 9). These results suggested that rotigotine induced MT-1,2 expression in striatal astrocytes, and protected dopaminergic neurons via 5-HT1A receptor signaling in parkinsonian mice.

4. Discussion

In the present study, we demonstrated dopaminergic neuroprotective effect of rotigotine via 5-HT1A receptor in parkinsonian models. Rotigotine administration prevented dopaminergic neurodegeneration in parkinsonian mice, which were assessed by counting TH-positive cells. However, the results of TH Western blot analysis using tissue samples showed neuroprotective tendency, but there was no significance. By immunohistochemistry, TH-positive signal in each neuron in the lesioned side of 6-OHDA-injected mice was stronger than that in the control side. These observations suggest compensatory increase of TH expression in the lesioned-side SN of parkinsonian mice. Western blot analysis reflects expression of TH protein but not neuronal survival. Therefore, we suppose it is difficult to reproduce the results of TH immunostaining by Western blot analysis.

We showed that upregulation of MT-1,2 in astrocytes could be involved in rotigotine-mediated neuroprotection in this study. MT is a cysteine-rich protein, which has strong antioxidative, anti-apoptotic, and anti-inflammatory properties (Giralt et al., 2002; Murakami et al., 2014; Pan et al., 2013; Penkowa, 2006; Ruttkay-Nedecky et al., 2013). In the brain, two major isoforms, MT-1 and -2, are expressed mainly in astrocytes and secreted in response to oxidative stress (Chung et al., 2004). We previously demonstrated that astrocytes produced MT-1,2 in response to excess DA-induced oxidative stress, and extracellular MT-1,2 protected dopaminergic neurons against DA-induced neurotoxicity (Miyazaki et al., 2011). In addition, MT-1 binds DA quinone, a dopaminergic neuron-specific oxidative stress product formed by DA oxidation, and can protect dopaminergic neurons against DA quinone neurotoxicity (Asanuma et al., 2003; Graham, 1978; Hastings et al., 1996; Miyazaki et al., 2007; Rabinovic and Hastings, 1998). It is well known that 6-OHDA induces dopaminergic neurotoxicity via reactive oxygen species. Previous studies reported that 6-OHDA also produce *p*-quinone by auto-oxidation, played a pivotal role in 6-OHDA-induced neurotoxicity, and glutathione (GSH) conjugated with *p*-quinone and provided neuroprotection (Izumi et al., 2005). Taken together with these previous reports, it is suggested that up-regulation of MT-1,2 expression induced by rotigotine can provide neuroprotection against oxidative stress-induced dopaminergic neurodegeneration. It is also supposed by a previous report, which demonstrated that rotigotine decreased reactive oxygen species in rotenone-treated primary cultured cells from midbrain (Radad et al., 2014). The involvement of up-regulation of anti-oxidative property in neuroprotective effects of rotigotine would be examined in the future study. In this study. In this study, we showed that MT expression was increased after rotigotine treatment via 5-HT1A receptor, which were assessed by counting the number of MT-1,2-positive astrocytes. Unlike the results of immunohistochemistry

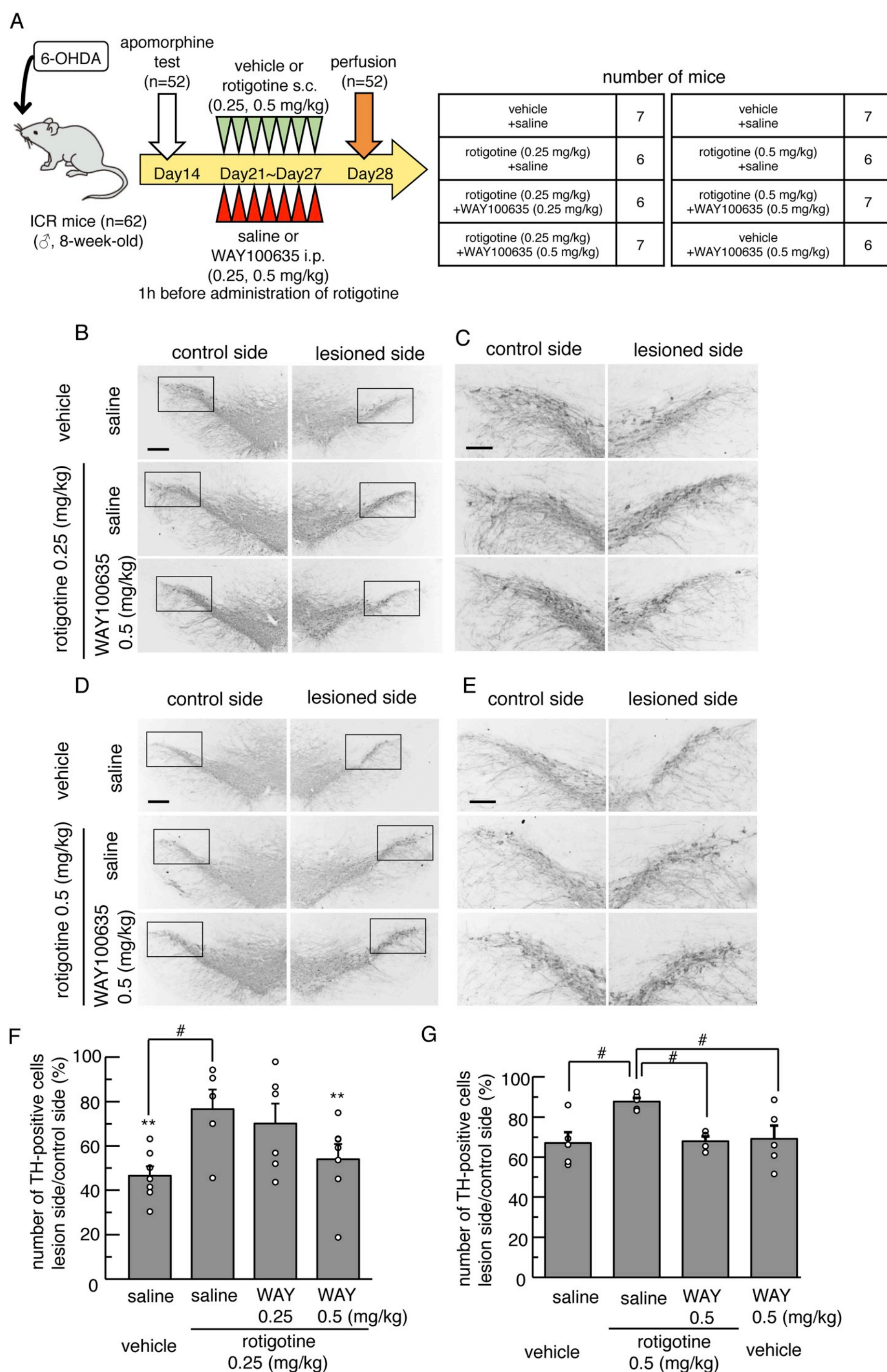

Fig. 7. Rotigotine protected dopaminergic neurons via 5-HT1A receptors in parkinsonian mice. (A) Flow chart of the study design. Parkinsonian mice were administrated with WAY100635 (0.25, 0.5 mg/kg/day, i.p.) or vehicle (saline) 1 h prior to rotigotine treatment (0.25, 0.5 mg/kg/day, s.c.). One day after the final administration, mice were perfused with a fixative. (B, C, F) Effects of administration of rotigotine (0.25 mg/kg/day, s.c.) and/or WAY100635 (0.25, 0.5 mg/kg/day, i.p.) for 7 days on nigral TH-positive neurons in parkinsonian mice. (B) Representative photomicrographs of TH immunostaining in the SNpc. Scale bar: 200 μm. (C) High magnification images of (B). Scale bar: 100 μm. (F) Ratio of TH-immunopositive cells in the lesioned side to the control side. Each value is presented as the mean ± SEM (n = 6–7 mice per group from one independent experiment). $^{**}p < 0.01$ vs. the control side of each group, $^{\#}p < 0.05$ between the two indicated groups. (D, E, G) Effects of administration of rotigotine (0.5 mg/kg/day, s.c.) and/or WAY100635 (0.5 mg/kg/day, i.p.) for 7 days on nigral TH-positive neurons in parkinsonian mice. (D) Representative micrographs of TH immunostaining in the SNpc. Scale bar: 200 μm. (E) High magnification images of (D). Scale bar: 100 μm. (G) Ratio of TH-immunopositive cells in the lesion side to the control side. Each value is presented as the mean ± SEM (n = 5). $^{\#}p < 0.05$ between the two indicated groups.

using brain slices, ELISA showed increasing tendency of MT content in the lesioned-side striatum of parkinsonian mice, and rotigotine (0.25 mg/kg) failed to induce further increase in MT expression. As mentioned above, MT-1,2 are expressed mainly in astrocytes and protein secreted from astrocytes are consumed by neurons to reduce oxidative stress. Therefore, we suppose that it is difficult to detect changes in MT expression using tissue homogenates of parkinsonian mice. As shown in this study, MT-1,2 were induced specifically in GFAP-positive reactive astrocyte. Because astrocytes were activated dramatically in the lesioned-side striatum of 6-OHDA-injected mice, we could observe MT upregulated at least in the lesioned side.

We demonstrated that rotigotine promoted Nrf2 nuclear translocation via astrocyte 5-HT1A receptor, resulting in increased MT-1,2 expression. Nrf2 is a master transcription factor, which responds to oxidative stress and induces various antioxidative molecules including MT-1,2 (Miyazaki et al., 2011; Suzuki et al., 2013a, 2013b). GSH is also synthesized in astrocytes regulated by Nrf2 and secreted into the extracellular space to protect neurons against oxidative stress. Previous studies showed that GSH levels are lower in the SN of PD patients compared to those in control subjects (Jenner et al., 1992; Riederer et al., 1989; Sian et al., 1994; Sofic et al., 1992). Therefore, we examined GSH content in conditioned media from roigotine-treated astrocytes. However, GSH levels in rotigotine-ACM were not different from levels in control-ACM (data not shown).

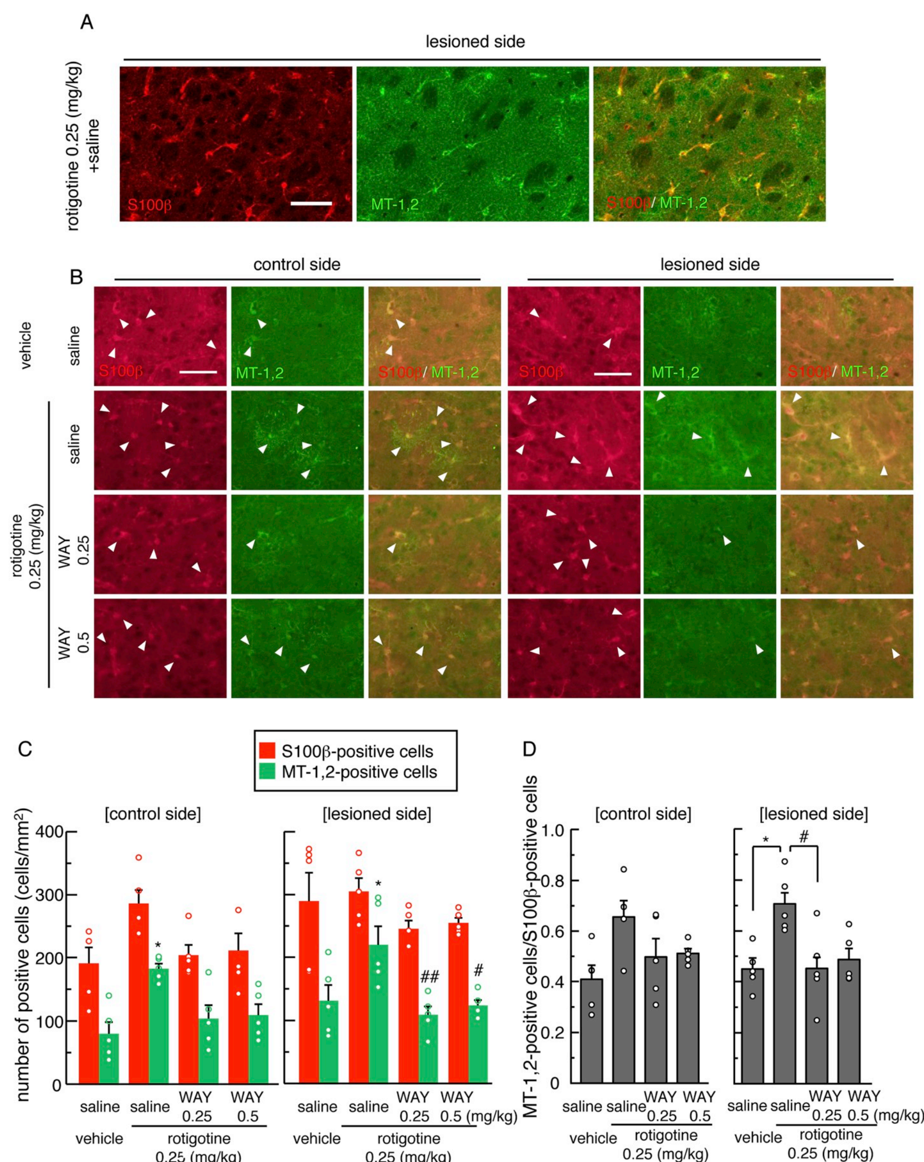

Fig. 8. Rotigotine upregulated MT-1,2 expression in S100β-positive striatal astrocytes in parkinsonian mice via 5-HT1A receptors. Effects of administration of rotigotine (0.25 mg/kg/day, s.c.) and/or WAY100635 (0.25, 0.5 mg/kg/day, i.p.) for 7 days on MT-1,2 expression in striatal astrocytes in parkinsonian mice. We performed double-immunostaining of S100β and MT-1,2. (A) Images of confocal laser microscope. Scale bar: 100 μm. (B) Representative photomicrographs of S100β and MT-1,2 double immunostaining. Scale bar: 50 μm. (C) Number of S100β- and MT-1,2-positive cells in the striatum of parkinsonian mice. (D) Ratio of MT-1,2-positive cells to S100β-positive cells. Data are presented as means ± SEM (n = 5). *$p < 0.05$ vs. the same side of the vehicle-treated group, $^{\#}p < 0.05$, $^{\#\#}p < 0.01$ vs. the same side of the rotigotine-treated group.

Previously, we reported that treatment with 5-HT1A full agonist promoted astrocyte proliferation via secretion of S100β *in vitro* and *in vivo* (Miyazaki et al., 2013). S100β is a calcium binding protein and expressed primarily in astrocytes. Stimulation of 5-HT1A receptor on astrocytes promotes S100β secretion, and extracellular S100β exerts autocrine effects that promote astrocyte proliferation. To assess effect of rotigotine on astrocyte proliferation, we counted astrocytes in cultured cells or normal or parkinsonian mice. In the present study, we used anti-GFAP and anti-S100β antibodies to detect astrocytes by immunohistochemistry. In cell cultures, all astrocytes express GFAP, so we counted GFAP-positive cells. On the other hands, an anti-GFAP antibody detected mainly fibrous activated astrocytes in the brain of mice. To assess all types of astrocytes, including protoplasmic astrocytes *in vivo*, we used anti-S100β antibody. Treatment with rotigotine (0.1, 1 μM) increased the number of GFAP-positive cultured astrocytes. Rotigotine also showed the increasing tendency of S100β-positive astrocyte number in normal mice and control side of parkinsonian mice. However, the number of GFAP-positive activated astrocytes was not changed by rotigotine. These results suggested that rotigotine has weak proliferation effect of astrocyte, but not astrocyte activation.

In this study, we used two doses of rotigotine (0.25 or 0.5 mg/kg). In contrast to rotigotine (0.25 mg/kg)-treated group, rotigotine (0.5 mg/kg) did not upregulate MT-1,2 expression, but the drug could inhibit the reduction of nigral dopaminergic neurons in parkinsonian mice. These data suggest that rotigotine may activate several neuroprotective pathways including not only Nrf2-MT pathway but also other pathways, which are not regulated by Nrf2, via 5-HT1A receptor. In addition, rotigotine (0.25 mg/kg) induced MT expression rather than rotigotine (0.5 mg/kg). In the previous study, we reported that effects of 5-HT1A full agonist on astrocytes are not exhibited in a dose-dependent manner (Miyazaki et al., 2013). There is an optimal dose of 5-HT1A agonist to activate astrocytic antioxidative property. Taken together, we suppose rotigotine (0.5 mg/kg) may affect other neuroprotective pathways rather than MT upregulation. WAY100635 (0.25 mg/kg) administration could annul rotigotine (0.25 mg/kg)-induced MT upregulation in astrocytes, but not dopaminergic neuroprotective effect. As mentioned above, we demonstrated that rotigotine induced Nrf2 translocation to nuclei via 5-HT1A receptor. Taken together with these results from *in vivo* and *in vitro*, it is suggested that rotigotine exerts neuroprotective effects by not only MT upregulation but also other mechanisms induced by 5-HT1A receptor stimulation. We supposed that WAY100635 (0.25 mg/kg) is not sufficient to block all neuroprotective mechanisms.

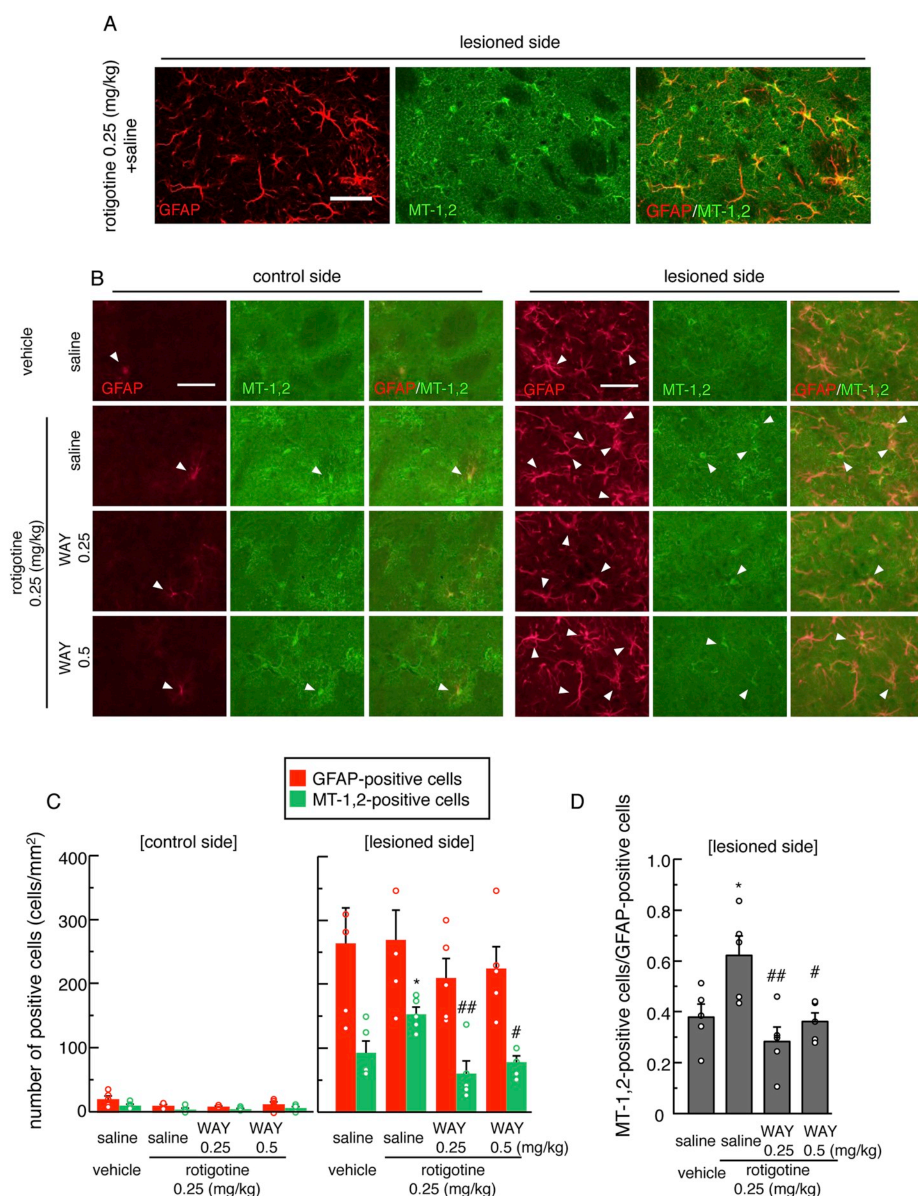

Fig. 9. Rotigotine upregulated MT-1,2 expression in GFAP-positive astrocytes in the striatum of parkinsonian mice via 5-HT1A receptors. Effects of administration of rotigotine (0.25 mg/kg/day, s.c.) and/or WAY100635 (0.25, 0.5 mg/kg/day, i.p.) for 7 days on MT-1,2 expression in striatal astrocytes in parkinsonian mice. We performed double immunostaining of GFAP and MT-1,2. (A) Images of confocal laser microscope. Scale bar: 100 μm. (B) Representative photomicrographs of GFAP and MT-1,2 double immunostaining. Scale bar: 50 μm. (C) Number of GFAP- and MT-1,2-positive cells in the striatum of parkinsonian mice. (D) Ratio of MT-1,2-positive cells to GFAP-positive cells on the lesioned side. Data are presented as means ± SEM (n = 5). *p < 0.05 vs. the same side of the vehicle-treated group, #p < 0.05, ##p < 0.01 vs. the same side of the rotigotine-treated group.

5. Conclusion

The present study demonstrated that the anti-parkinsonian agent, rotigotine, increased expression of antioxidant MTs in astrocytes and protected dopaminergic neurons against oxidative stress via 5-HT1A receptors. Furthermore, administration of rotigotine prevented dopaminergic neurodegeneration in parkinsonian mice. These results suggested that rotigotine upregulates antioxidant molecules by targeting 5-HT1A receptors on astrocytes, resulting in neuroprotection. Our findings suggested that rotigotine may be effective as a disease-modifying treatment for PD.

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All experiments were conducted in compliance with the ARRIVE guidelines.

Author contribution statement

Nami Isooka: performed experiments and analyzed the data, writing paper. **Ikuko Miyazaki**: designed the research, performed experiments and analyzed the data, writing paper. **Ryo Kikuoka**: performed experiments and analyzed the data. **Kouichi Wada**: performed experiments and analyzed the data. **Erika Nakayama**: performed experiments and analyzed the data. **Kotaro Shin**: performed experiments and analyzed the data. **Daichi Yamamoto**: performed experiments and analyzed the data. **Yoshihisa Kitamura**: assisted with some of the *in vivo* experiments. **Masato Asanuma**: designed the research, organized the project, writing paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuint.2019.104608.

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