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Article

Gelidium amansii Attenuates Hypoxia/Reoxygenation-Induced Oxidative Injury in Primary Hippocampal Neurons through Suppressing GluN2B Expression

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Abstract: Oxidative stress is known to be critically implicated in the pathophysiology of several neurological disorders, including Alzheimer's disease and ischemic stroke. The remarkable neurotrophic activity of *Gelidium amansii*, has been reported consistently in a series of our previous studies, inspired us to investigate whether this popular agarophyte could protect against hypoxia/reoxygenation (H/R)-induced oxidative injury in hippocampal neurons. The primary culture of hippocampal neurons challenged with H/R suffered from a significant loss of cell survival, accompanied by apoptosis and necrosis, DNA damage, generation of reactive oxygen species (ROS), and dissipation of mitochondrial membrane potential (MMP) which were successfully attenuated when the neuronal cultures were preconditioned with GAE, an optimized ethanolic extract of *G. amansii*. Moreover, the expression of *N*-methyl-*D*-acetate receptor subunit 2B (GluN2B), an extrasynaptic glutamate receptor, was significantly repressed in GAE-treated neurons as compared to those without GAE intervention. Together, this study demonstrates that GAE attenuated H/R-induced oxidative injury in hippocampal neurons through, at least in part, a potential neuroprotective mechanism that involves inhibition of GluN2B-mediated excitotoxicity and suppression of ROS production, and suggest that this edible seaweed could be a potential source of bioactive metabolites having therapeutic significance against oxidative stress-related neurodegeneration, including ischemic stroke and neurodegenerative diseases.

Keywords: Oxidative stress; reactive oxygen species; hypoxia-reoxygenation; GluN2B; CNS neuron; Gelidium amansii

1. Introduction

Ischemia/reperfusion (I/R) installs a cascade of pathological events that culminate in several clinical conditions, including ischemic stroke and degenerative brain disease [1]. The I/R provokes a deleterious mechanism that involves excess production of reactive oxygen species (ROS), resulting in the oxidative stress in cells [2]. With high metabolic demand and peroxidizable lipid contents, neurons are potentially vulnerable to I/R-induced oxidative injury, which is accompanied by apoptosis, necrosis and DNA damage. In reperfused cells, mitochondria play a critical role in

initiating apoptosis through contributing excess ROS generation. During I/R, there is an involvement of glutamate excitotoxicity to which the expression of extrasynaptic glutamate receptors such as GluN2B has been crucially implicated. This I/R-induced excitotoxicity initiates a cascade mechanism that results in the cellular oxidative stress and loss of mitochondrial membrane potential (MMP). Targeting excitotoxicity-mediated oxidative stress might, therefore, be a potential therapeutic strategy in neurodegenerative diseases.

A neuronal model of hypoxia/re-oxygenation (H/R) provides a useful tool for the study of ROS-mediated mechanisms of cellular dysfunction in I/R injury in the brain [1]. In this study, a cellular model of H/R-induced oxidative injury that can simulate the pathophysiological events of cerebral I/R was, therefore, employed to investigate the neuroprotective effect of GAE in primary hippocampal neurons. In several of our previous studies, we reported a very potential neurotrophic activity of GAE that spans every stages of neuronal developments [3], including early neuronal differentiation, axonal sprouting, dendritic arborization, axonal maturation and synaptic modulation [4-6]. In addition, GAE has shown various other pharmacological activities such as immunomodulation [7] and antioxidation [8]. Having all these pharmacological effects, we hypothesized that GAE could protect against H/R-induced oxidative injury in primary hippocampal neurons.

2. Materials and Methods

2.1. Sample Collection and Extract Preparation

The mature thalli of *G. amansii* were collected along the coast of the southern part of the Korean peninsula and processed as described in our previous study [4]. An ethanolic extract of *G. amansii* (GAE) was then prepared following the protocol as previously described [4]. The extract was reconstituted in dimethyl sulfoxide (DMSO) to make an aliquot of 8 mg/mL.

2.2. Primary neuronal culture and GAE treatment

All the reagents used for cell cultures were purchased from Invitrogen (Carlsbad, CA, USA) unless otherwise stated. The animal experiment was approved by the Institutional Animal Care and Use Committee of the Dongguk University College of Medicine (approval certificate number IACUC-2016-001). Time-pregnant rats (Sprague-Dawley) were ordered on the 13th day of pregnancy and housed in controlled temperature with a light/dark cycle of 12/12h and with access to food and water *ad libitum*. On the 19th day of pregnancy, the pregnant rat was euthanized with isofluorane and the fetuses were collected. The dissociated cultures of primary hippocampal neurons from the fetal brain were prepared as previously described [9]. The cells were seeded at a density of 3.0×10^4 cells/cm^2 onto poly-DL-lysine-coated (PDL, Sigma-Aldrich, St. Louis, MO) 12-mm glass coverslips in 24-well culture plates for morphological and viability analysis, or 3.0×10^6 cells/cm^2 and 1.2×105 cells/cm^2 onto PDL-coated six-well culture plates for agarose gel electrophoresis and Western blot, respectively. The culture medium was preincubated with GAE or vehicle (DMSO, final concentration < 0.5%).

2.3. Hypoxia/reoxygenation (H/R) injury

Neurons were exposed to H/R following the protocol as described previously [10], with a slight modification. Briefly, at the indicated time, cultured neurons were transferred to a hypoxic chamber (Modular Incubator Chamber MIC-101; Billups-Rothenberg Inc., Del Mar, CA, USA) containing 94% N_2, 5% CO_2, and 1% O_2 and incubated for 4 hr at 37^{0}C. The culture plates were then returned to normoxic conditions (95% air and 5% CO_2 at 37^{o}C) and incubated for the indicated time.

2.4. Assessment of neuronal viability

Trypan blue exclusion assay. Neuronal viability was determined by trypan blue exclusion assay in cultures maintained in normoxic and hypoxic conditions. The cultures were stained with 0.4% trypan blue for 15 min at room temperature and then washed with Dulbecco's phosphate-buffered saline

(D-PBS). The neurons were then quantified under a light microscope. Dead neurons are compromised to membrane permeability, and thus, uptake dye and appeared dark-blue in phase-contrast images. Live neurons have intact membrane integrity, and thus, exclude dye. The viability was expressed as the percentage of trypan blue-impermeable cells (live neurons) and results were normalized versus trypan blue-stained non-H/R exposed controls. In each experiment, cells on three coverslips, each with 500 cells were counted randomly.

Measurement of lactate dehydrogenase (LDH) release. The cellular injury was evaluated by measuring the LDH released in the culture media through the damaged cell membrane using the CytoTox96 nonradioactive assay (Promega) and quantitated by measuring the wavelength at 490 nm using a microplate reader. LDH activity is the percentage of the ratio of experimental LDH release with maximum LDH release. Data are normalized to the amount of LDH released from vehicle-treated cells (100%).

2.5. Measurement of apoptotic cell death

Neurons underwent apoptotic and necrotic death were determined by Annexin V binding and propidium iodide (PI) uptake, respectively. Annexin V shows a high affinity for phosphatidylserine, which translocates from the internal to the external surface of the plasma membrane as a characteristic feature of apoptosis. Necrotic cells take up PI due to increased permeability of the damaged cell membrane for this molecule. Neuronal cultures maintained in normoxic and hypoxic conditions were washed with binding buffer and incubated for 15 min in the dark with Annexin V and PI. Apoptotic and necrotic cells were quantitated under a fluorescence microscope and expressed as percentages of total neurons in culture.

2.6. Analysis of DNA fragmentation by agarose gel electrophoresis

Neuronal cells (3×10^6) were rinsed twice with DPBS and lysed in 700 µL of DNA extraction solution (20 mM Tris-HCl, pH 7.4, 0.1M NaCl, 5 mM EDTA, and 0.5% sodium dodecyl sulfate). The lysates were incubated with DNAse free RNAse A (100 µg/mL) and proteinase K (200 µg/mL) at 37 °C in a shaking incubator overnight. After incubation, cell lysates were mixed well with 700 µL of phenol/chloroform/isoamyl alcohol (25:24:1, v/v/v), and then centrifuged at 13000 RPM for 10 min at 4℃. DNA remained in the aqueous phase was extracted twice more with phenol/chloroform/isoamyl alcohol and then with chloroform. DNA was then precipitated overnight at -80℃ with two volumes of absolute ethanol in the presence of $1/10^{th}$ volume of 3M sodium acetate. After centrifugation, the DNA pellets were washed with 70% ethanol and air-dried. The DNA was dissolved in TE buffer (10 mM Tris-HCl and 1 mM EDTA). DNA was electrophoresed on 1.5% agarose gel containing 1 µg/mL ethidium bromide, and DNA fragments were visualized by exposing the gel to UV light.

2.7. Measurement of reactive oxygen species (ROS) generation

Cellular ROS production was confirmed by DCFH-DA staining. DCFH-DA freely crosses cell membranes and is hydrolyzed by cellular esterases to 2′,7′-dichlorodihydrofluorescein (DCFH2). DCFH2 is a non-fluorescent molecule; however, it is oxidized to the fluorescent 2′,7′-dichlorofluorescein (DCF) in the presence of peroxides. To measure ROS production under normoxic and hypoxic conditions, neurons grown in the presence or absence of GAE were rinsed with fresh media and incubated with the fluorescent probe 2′,7′-dichlorodihydrofluorescein diacetate (DCFH-DA, 10 nM; Molecular Probes Inc., Eugene, OR, USA). Cells were then incubated in a CO_2 incubator for 15 min and observed under a fluorescence microscope after rinsing with culture media. The relative fluorescent intensity was measured. The number of ROS positive neurons was also quantitated.

2.8. Determination of mitochondrial membrane potential (MMP)

MMP was measured using 5,5',6,6'-tetrachloro-1,1',3,3'-tetraethyl benzimidazolyl carbocyanine iodide (JC-1) as previously described [10]. The JC-1 dye concentrates in the mitochondria of healthy

cells as J-aggregates, which emit red fluorescence when binding with JC-1. Upon the onset of apoptosis, the MMP dissipates and the JC-1 dye can no longer accumulate in the mitochondria and remains in the cytoplasm as a monomeric form which fluoresces green. To determine the changes in the MMP under normoxic and hypoxic conditions, neurons cultured in the presence or absence of GAE were rinsed with fresh media and incubated with the JC-1 (1μg/mL; Molecular Probes Inc., Eugene, OR, USA) in a CO_2 incubator for 20 min and observed under a fluorescence microscope. MMP was determined as the proportion of red to green fluorescent intensity.

2.9. Western blot

Hippocampal cells (1.2 x10^5 cells/cm^2, DIV13) were harvested after H/R treatment and lysed in ice-cold RIPA buffer [50 mM Tris–HCl (pH 8.0), 150 mM NaCl, 1% (v/v) NP-40, 0.5% (w/v) sodium deoxycholate, 1% (w/v) sodium dodecyl sulfate, and protease inhibitor cocktail (Thermo Scientific, Rockford, IL)]. Protein concentrations were measured using the Bradford method [11]. Equal amounts of protein were separated by 8% SDS-PAGE and transferred to PVDF membranes [12], which were incubated with primary antibodies: GluN2B (1:1,000, rabbit polyclonal), anti-phospho-H2AX antibody (1:500; Millipore, Billerica, MA), and anti-actin (JLA20; 1:1,000, mouse monoclonal, Developmental Studies Hybridoma Bank, University of Iowa, IO). After rinsing with TTBS (0.05% Tween-20 in TBS), membranes were incubated with horseradish peroxidase-conjugated secondary antibodies (1:1,000; anti-mouse or -rabbit IgG; Amersham Biosciences). Signals were detected using an ECL detection kit (Invitrogen, Waltham, MA).

2.10. Image acquisition and analysis

A Leica Research Microscope DM IRE2 equipped with I3 S, N2.1 S, and Y5 filter systems (Leica Microsystems AG, Wetzlar, Germany) was used for phase-contrast and epifluorescence microscopy. Images (1388 × 1039 pixels) were acquired using a high-resolution CoolSNAP™ CCD camera (Photometrics, Inc., Tucson, AZ, USA) under the control of a computer running Leica FW4000 software. Digital images were processed using Adobe Photoshop 7.0. The quantifications of cells or puncta were performed using ImageJ (version 1.49) software with the cell counter plugin (National Institute of Health, Bethesda, MA, USA). Gel imaging was processed using the AlphaImager™ HP system (www.alphainnotech.com).

2.11. Statistical analysis

All data are expressed as the mean ± SEM with at least three independent experiments. Statistical comparisons were made by Student's *t*-test and one-way analysis of variance (ANOVA) with *post hoc* Duncan multiple comparisons (SPSS software, version 16.0). Predetermined *p*-values ≤0.05 were considered statistically significant.

3. Results

3.1. GAE attenuates H/R-induced neuronal death

An outline of the experimental protocol is presented in Figure 1. Initially, we evaluated whether GAE showed any toxic effects in the cultured neurons under normoxic conditions. Cytotoxicity analysis using LDH activity assays revealed that concentrations up to 60 μg/mL were nontoxic to cultured neurons (Figure 2A). To evaluate whether GAE could protect neurons from H/R-induced injury, the cultures were exposed to hypoxia followed by reoxygenation. As shown in Figure 2B, the viability of hypoxic neurons was significantly decreased (~20%, $p < 0.01$) compared with normoxic control. In contrast, GAE significantly increased ($p < 0.05$) neuronal viability (Figure 2B and C) in both dose- and time-dependent manner, indicating that GAE successfully attenuated neuronal injury.

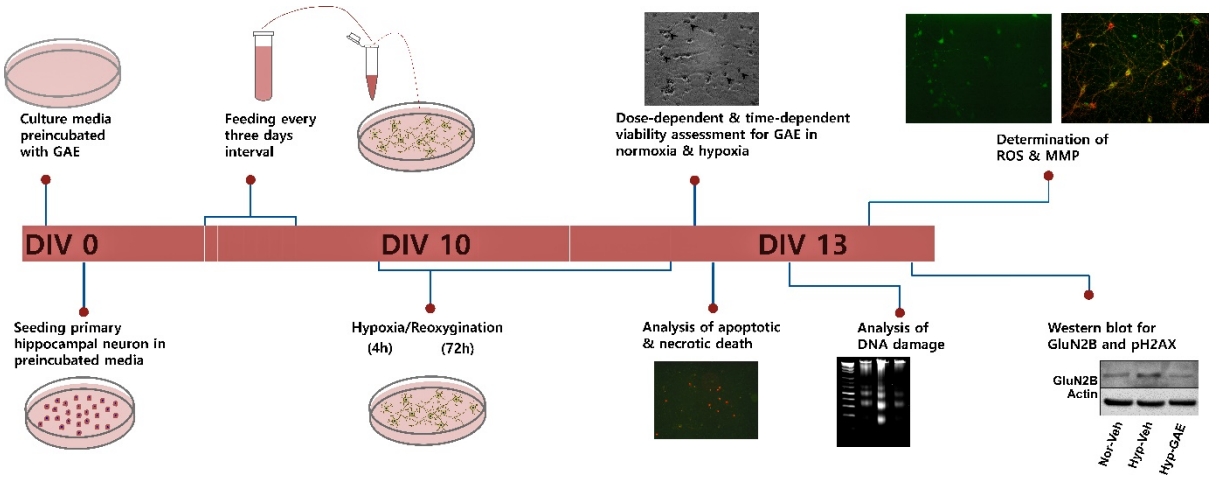

Figure 1. An outline of the experimental protocol. Neuronal cultures were preconditioned with GAE one day prior to cell seeding. Media was first changed four days after culture, and then every three days interval. At DIV10, cultures were exposed to H/R following a protocol consisting of four hours of hypoxia followed by 72 hours of reoxygenation. The analysis was carried out DIV13.

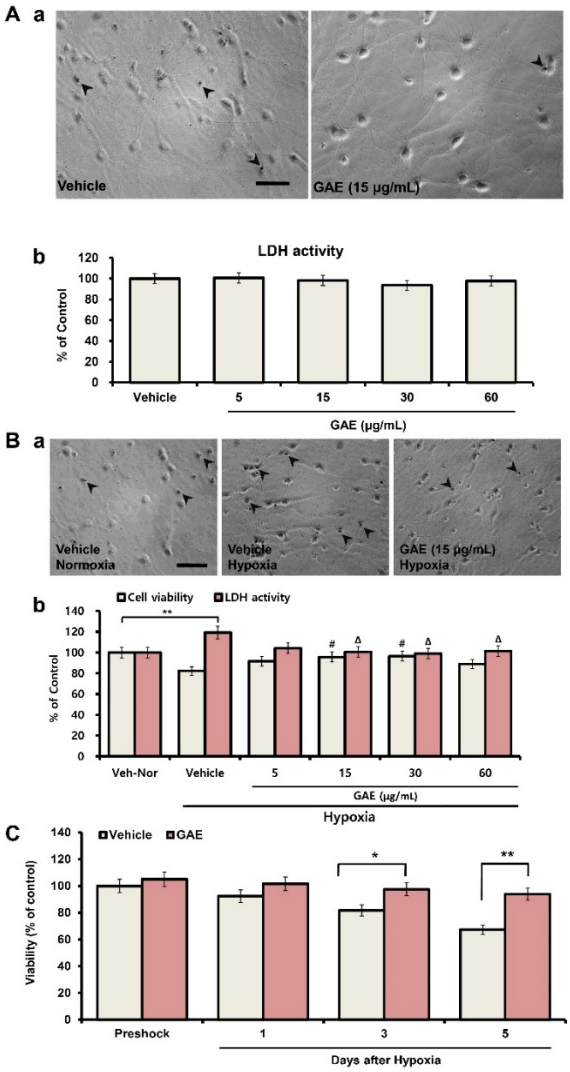

Figure 2. GAE attenuates the decrease in neuronal viability following H/R. A) GAE did not affect neuronal survival during the normoxic condition. Hippocampal neurons were cultured on poly-DL-lysine-coated coverslips for 13 days in vitro (DIV13) in the presence of vehicle or various concentrations of GAE. (a) Typical images for trypan blue staining, indicating no toxic changes in

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GAE-treated neurons. (b) Cytotoxicity was determined by LDH release assay as described in materials and methods, also indicates no change in neuronal viability by GAE. B) GAE protects neurons against hypoxia/reoxygenation injury in a dose-dependent manner. Hippocampal neurons were grown on the same culture conditions, as indicated in Figure 2A for ten days and then kept under hypoxia for 4 hours. After 3 days of re-oxygenation, neuronal viability was determined by trypan blue exclusion and LDH release assay. (a) Typical images for trypan blue staining. (b) The neuronal viability and LDH activity as described in materials and methods. C) GAE protects neurons time-dependently against hypoxia/reoxygenation injury. Hippocampal neurons were grown on the same culture conditions as indicated in above for ten days, and then kept under hypoxia for 4 hours. After 1, 3 and 5 days of reoxygenation, neuronal viability was determined by trypan blue exclusion method. Arrows indicate dead cells. Scale bar, 80 μm, applied to all images. Viability of normoxia control culture is normalized to 100%. Bars represent the mean ± SEM (n = 3). Statistical significance compared to vehicle: *$p < 0.05$, **$p < 0.01$, # $p< 0.05$, and $^{\Delta}p< 0.05$ (ANOVA).

3.2. GAE reduces apoptotic and necrotic death following H/R

Dysfunction of chromatin due to ROS-mediated single and double-strand DNA break has been known to be associated with apoptosis and necrosis. Therefore, to characterize the cell death pattern following hypoxia, we analyzed apoptosis and necrosis as these processes are crucial events in neuronal damage following hypoxia and ischemia. Cell death due to apoptosis and necrosis as revealed by Annexin V and PI staining, respectively, were elicited under hypoxia compared with normoxia (Figure 3). Hypoxic neurons show characteristic symptoms of apoptosis including nuclear condensation, membrane disruption and neuritic disintegration. Neurons stained with Annexin V show a characteristic ring surrounding the cell membrane. On the contrary, pretreatment of neurons with GAE significantly prevented hypoxia-induced apoptosis ($p < 0.01$) and necrosis ($p < 0.05$) compared to hypoxic control. Together, these data indicate the antiapoptotic effect of GAE against hypoxia-induced oxidative stress.

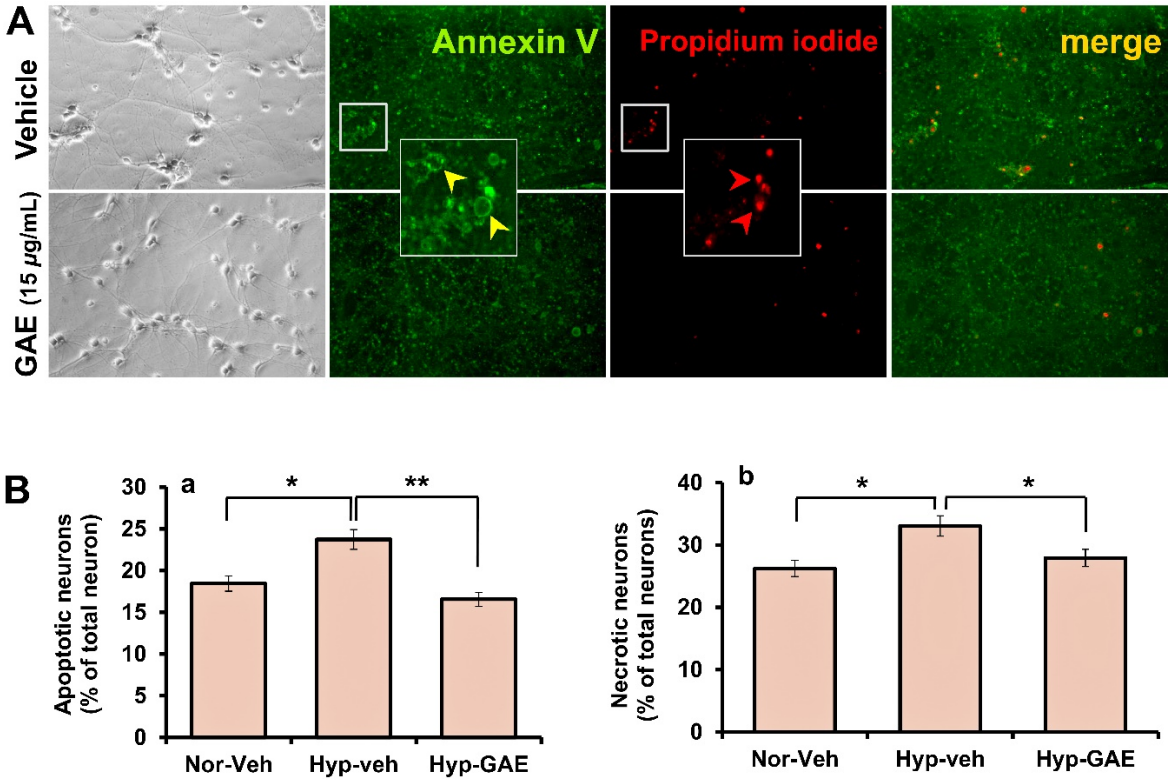

Figure 3. GAE prevents neuronal damage both from apoptosis and necrosis. Hippocampal neurons were grown on the same culture conditions as indicated in Figure 2. Apoptosis and necrosis were determined by Annexin V and PI staining, respectively. (A) Typical images showing apoptotic (yellow arrowhead) and necrotic (red arrowhead) cell damage under hypoxic conditions. Scale bar,

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80 μm, applied to all images. (B) Quantification of apoptotic and necrotic neurons. Data were expressed in percentage of total neurons counted. Nor-Veh, Hyp-Veh and Hyp-GAE for Normoxia-Vehicle, Hypoxia-Vehicle and Hypoxia-GAE, respectively. Bars represent the mean ± SEM (n = 3). Statistical significance compared to vehicle: *$p < 0.05$ and **$p < 0.01$ (ANOVA).

3.3. GAE attenuates H/R-induced DNA damage

To investigate whether GAE could protect against DNA damage, we analyzed DNA fragmentation and double-stranded DNA break using agarose gel electrophoresis and western blot, respectively. Hippocampal cultures exposed to H/R exhibited a nucleosomal laddering, which was attenuated when cultures were preincubated with GAE (Figure 4A). A similar effect was observed with γ-H2AX whose expression was significantly reduced ($p < 0.001$) in GAE-treated culture compared to hypoxic control (Figure 4B), indicating GAE-mediated protection against DNA damage.

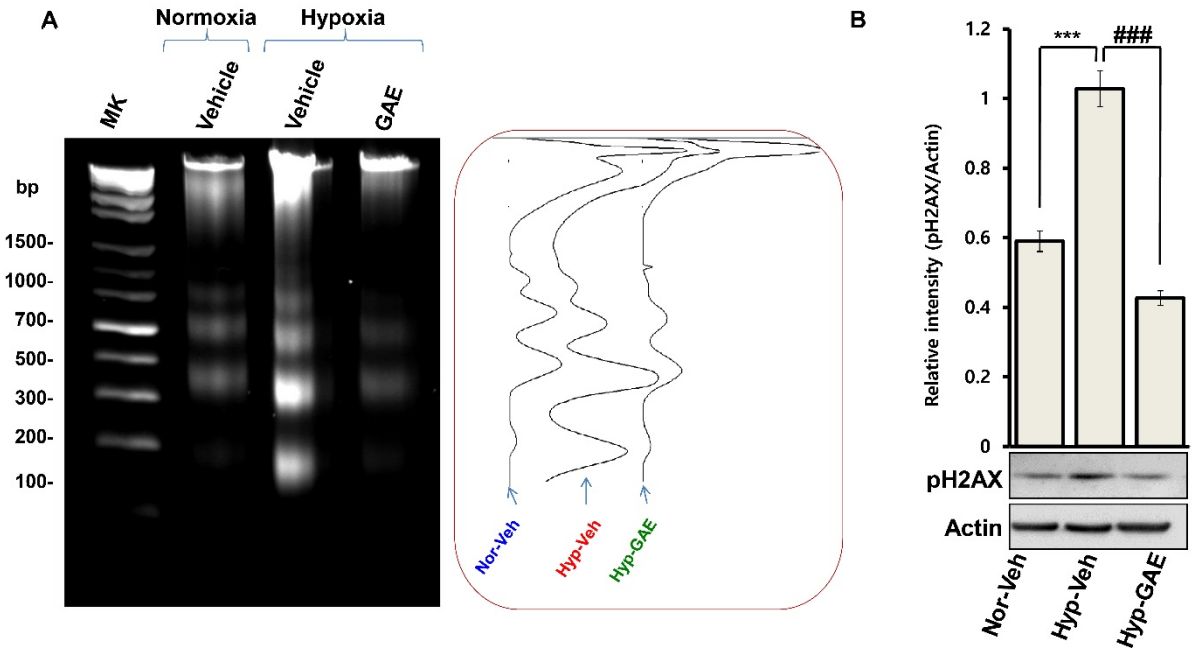

Figure 4. GAE prevents DNA damage. Hippocampal neurons pretreated with either vehicle or GAE were exposed to hypoxia or normoxia for 4 h, and then DNA extracted from neuronal cultures was subjected to conventional agarose gel electrophoresis. Protective effect of GAE on internucleosomal DNA fragmentation after H/R. Hippocampal neurons pretreated with either vehicle or GAE were exposed to hypoxia for 4h on DIV10, followed by normoxia for 72 h. DNA extracted from neuronal cultures was electrophoresed in agarose gel (1.5%), and visualized by EtBr staining. (A) Left panel, representative agarose gel image showing DNA laddering. Molecular sizes are marked on the far left in base pairs (bp). Right panel, comparisons of relative band intensities among groups. (B) Protein expression analysis using Western blot. Hippocampal neurons (plated at 3 × 106 cells/cm^2) were treated with either GAE or vehicle. Proteins were isolated at DIV13 following H/R and immunoblotted. Representative immunoblot bands showing pH2AX and actin expressions. Relative intensities and their test statistics as measured using Image J software and normalized versus actin. Bars represent means ± SEMs (n = 3). ***$p < 0.001$, normoxia vs hypoxia control, and $^{###}p < 0.001$, compared with the hypoxia control (ANOVA).

3.4. GAE suppresses H/R-induced ROS generation

Given that hypoxia followed by re-oxygenation results in excessive production of ROS that imposes oxidative stress to cells, we next investigated whether GAE could prevent ROS generation. There was a significant ($p < 0.01$) accumulation of ROS into H/R-induced neurons compared to normoxic control, whereas GAE significantly suppressed ROS production ($p < 0.01$) compared to treatment naïve control (Figure 5).

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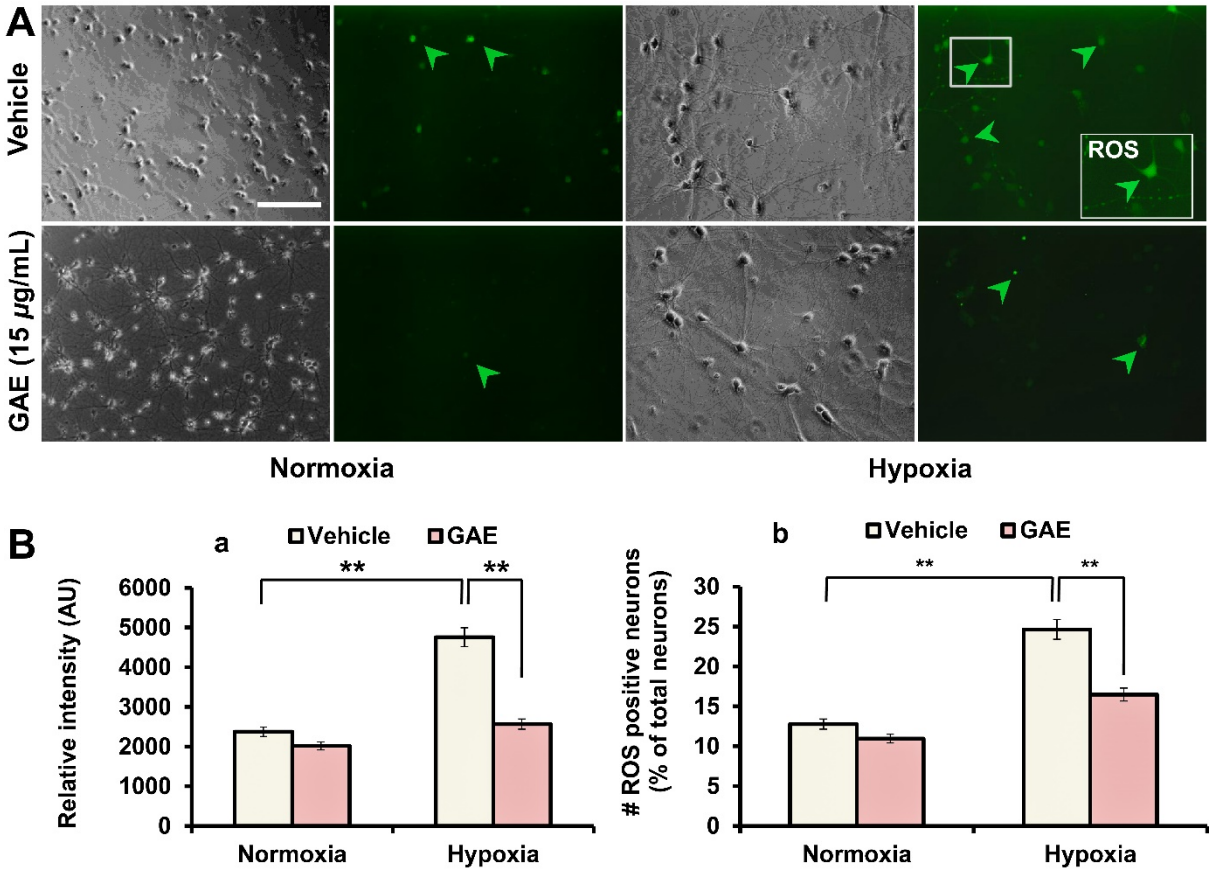

Figure 5. GAE suppresses ROS production. Hippocampal neurons were grown on the same culture conditions as indicated in Figure 2. ROS accumulation was determined by DCF-DA staining. (A) Typical images showing neurons containing ROS (green arrowhead). Scale bar, 80 μm, applied to all images. (B) Measurement of relative intensity (arbitrary units) and ROS positive neurons (expressed in percentage of total neurons). Bars represent the mean ± SEM (n = 3). Statistical significance compared to vehicle: $^{**}p < 0.01$ (ANOVA).

3.5. GAE preserves MMP

The dissipation of MMP is characteristic of early apoptosis. We, therefore, measured MMP using JC-1 dye, which indicates a mixture of green and red fluorescence representing JC-monomer (lower MMP) and JC-aggregate (higher MMP). As shown in Figure 6, MMP of H/R-induced neurons was significantly (p <0.05) reduced compared to that of normoxic control. However, GAE treated neurons significantly (p <0.05) attenuated the loss of MMP when compared with those without GAE intervention.

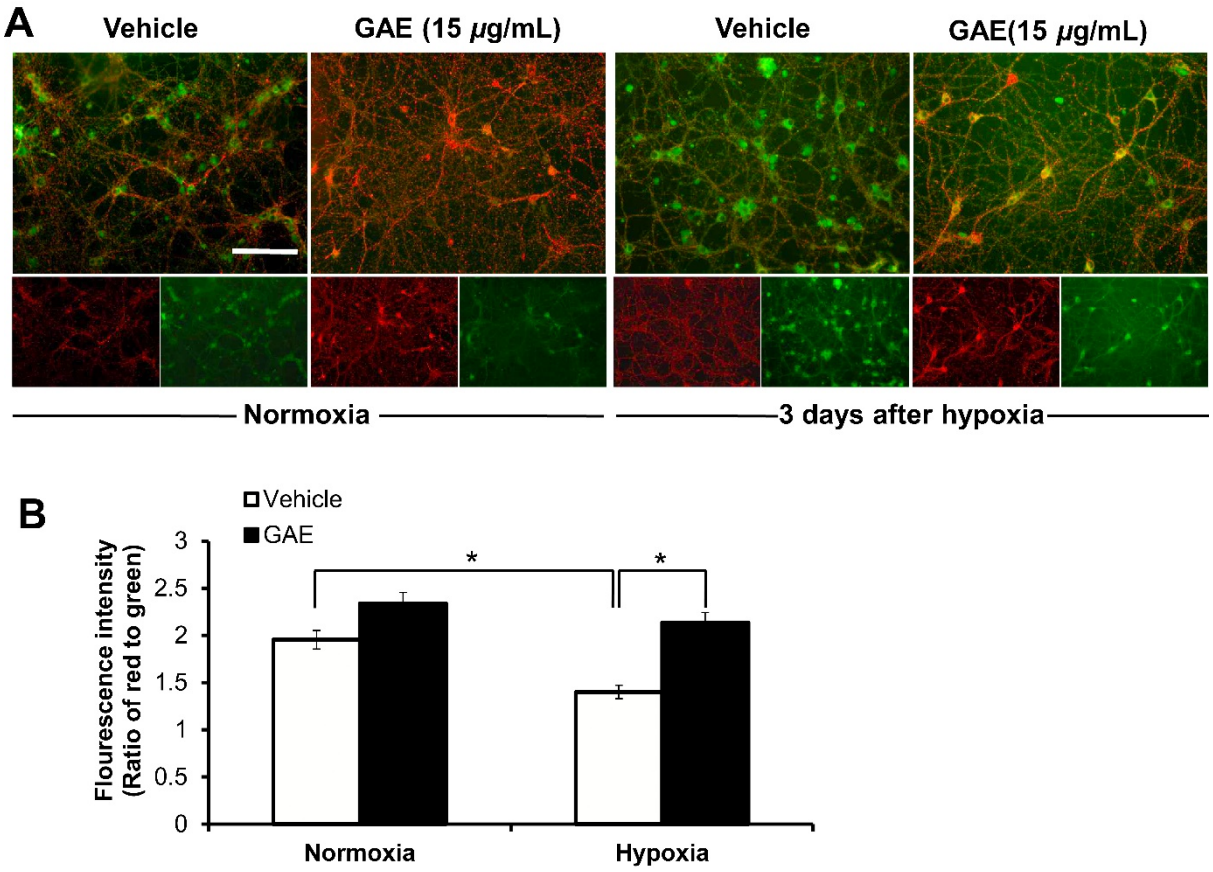

Figure 6. GAE preserves MMP. Hippocampal neurons were grown on the same culture conditions as indicated in Figure 2. MMP was determined by JC-1 staining. (A) Typical images showing red and green fluorescence. Scale bar, 80 μm, applied to all images. (B) MMP was determined as the proportion of red to green fluorescent intensity. Bars represent the mean ± SEM (n = 3). Statistical significance compared to vehicle: *$p < 0.05$ (ANOVA).

3.6. GAE downregulates H/R-induced expression of GluN2B

Next, we analyzed whether GAE could intervene in the expression of GluN2B, an extrasynaptic glutamate receptor that is typically involved in excitotoxicity during hypoxic injury. Neurons challenged with H/R exhibited a significant increase ($p < 0.01$) in GluN2B expression compared to normoxic control (Figure 7). However, GAE-preconditioning remarkably repressed ($p < 0.01$) this expression compared to hypoxic control. Notably, GAE-mediated GluN2B expression was even below the physiological expression in normoxic control. These findings indicate that GAE-mediated attenuation of excitotoxic neuronal death involves, at least in part, the GluN2B-dependent neuroprotective mechanism.

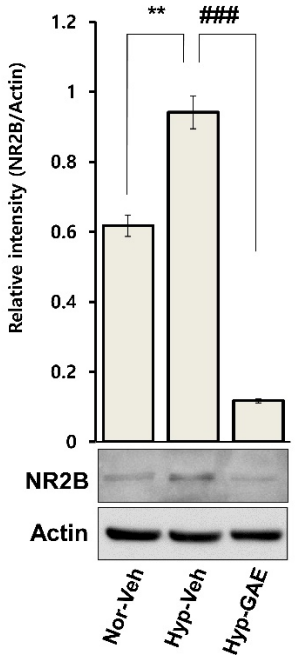

Figure 7. Protein expression analysis using Western blot. Culture condition and immunoblotting technique were followed as in Figure 2 and Figure 4B, respectively. Representative immunoblot bands showing GluN2B and actin expressions. Relative intensities and their test statistics as measured using Image J software and normalized versus actin. Bars represent means ± SEMs (n = 3). $^{**}p < 0.01$, normoxia vs hypoxia control, and $^{###}p < 0.001$, compared with the hypoxia control (ANOVA).

4. Discussion

Oxidative stress-induced neuronal damage following ischemia/reperfusion (I/R) in the brain has been crucially implicated in the pathophysiology of many neurological disorders [13,14]. The neurotrophic support compromised in the aging brain also affects the survival of brain neurons [15]. In light of these phenomena, pharmacological agents that could help overcome these pathological consequences might hold therapeutic promise against the associated brain disorders. In this context, we asked whether an ethanolic extract of *G. amansii* (GAE) that has already proved its neurotrophic potentials in several of our previous investigations could protect against oxidative injury induced by hypoxia/reoxygenation (H/R, an *in vitro* replica of I/R) in hippocampal neurons. Remarkably, in the present study, GAE also exhibited its potentials as a promising neuroprotective substance through defending against H/R-induced oxidative damage.

The massive stroke, referred to as an ischemic stroke, following myocardial infarction or coronary occlusion, very often results in the instant demise of the patients. However, if the patients survive, the damage caused by the reperfusion is much higher than that by ischemia itself [16]. Because the sudden oxygen supply following reperfusion leads to excessive generation of ROS that results in cellular oxidative stress which follows a cascade of pathological events, such as mitochondrial dysfunction, DNA disintegration, apoptosis and necrosis, and ultimately death of neurons [17,18]. In this study, GAE significantly suppressed ROS accumulation in cultured neurons as opposed to the amount of ROS in untreated neurons and successfully attenuated these pathological consequences. A previous report demonstrating that *G. amansii* extract suppresses ROS production, and protects against oxidative stress by activating ROS-scavenging enzymes in 3T3-L1 cells [19] also supports that antioxidant property might contribute, at least in part, to GAE-mediated neuroprotection in our study.

Mitochondria is the powerhouse of cells that fuel every cellular process, including synaptic transmission. However, being a vulnerable target of free radical-induced damage, this essential organelle is also intimately associated with cellular death [20]. Moreover, mitochondrial dysfunction has been crucially implicated in the pathogenesis of several neurodegenerative diseases [21]. In the current study, MMP, a key indicator of mitochondrial function was compromised in cultured

neurons following H/R. In contrast, neurons treated with GAE successfully attenuated MMP dissipation. No previous report supporting the protective action of GAE against MMP loss is available; however, an ethanolic extract of *Gracilariopsis chorda*, also an edible red alga has been shown to preserve MMP [10] contributing a similar neuroprotective mechanism

Primarily expressed in the extrasynaptic domain of postsynaptic neurons, GluN2B takes part in neuronal activity during physiological brain function as well as I/R-induced excitotoxicity [22,23]. During I/R, there is an accumulation of excitatory neurotransmitter, glutamate in the synaptic cleft due to the ionic imbalance (particularly, Ca^{2+} dyshomeostasis) [24] and failure of excess glutamate clearance by reuptake transporters [25]. As a consequence, there is an over-activation of GluN2B that leads to Ca^{2+} overload inside the postsynaptic neurons which induces downstream pro-death signaling cascade such as reactive oxygen species (ROS) generation [26] and mitochondrial damage [24] resulting in neuronal apoptosis. In the present study, GAE significantly suppressed the expression of GluN2B compared to both treatment naïve and normoxic cultures, indicating that GAE-mediated neuroprotection might be due, at least in part, to attenuation of GluN2B-mediated excitotoxicity following H/R.

5. Conclusion

The observations that GAE prevents apoptotic cell death, suppresses ROS production, preserves MMP, attenuates DNA fragmentation and downregulates GluN2B expression support the conclusion that GAE potentially helps the hippocampal neurons to evolve a neuroprotective mechanism that makes them competent against H/R-induced oxidative damage. This novel attribute of *G. amansii* will make this popular agarigenic seaweed as a potential source of neuroprotective agents that could have therapeutic promise against ischemic stroke or other oxidative stress-associated neurodegenerative disorders.

Author Contributions: M.A.H. designed and conducted the experiments, and wrote the manuscript. M.N.H., M.M. and R.D. contributed to conducting the experiments and writing the manuscript. I.S.M. conceived the idea, supervised the experiment, and reviewed the manuscript.

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