The endoplasmic reticulum stress transducer old astrocyte specifically induced substance positively regulates glial scar formation in spinal cord injury

Yoshikazu Sumida\textsuperscript{a}, Naosuke Kamei\textsuperscript{a,c}, Norifumi Suga\textsuperscript{a}, Mitsuo Ochi\textsuperscript{b} and Nobuo Adachi\textsuperscript{a}

To investigate the relationship between endoplasmic reticulum (ER) stress mediated by old astrocyte specifically induced substance (OASIS) and astrogliosis in spinal cord injury (SCI). SCI models were established using adult male mice deficient for OASIS and C57BL/6 (wild-type mice) mice. After SCI, recovery and astrogliosis were examined in the mice at specific time points using functional and histological methods. After SCI, functional recovery was better in the OASIS-deficient mice than in the wild-type mice. OASIS deletion did not inhibit astrocyte migration but reduced the excessive accumulation of N-cadherin-expressing reactive astrocytes that formed the glial scar around the injury site. In addition, OASIS deletion increased the number of serotonin-positive axons in spinal cord regions caudal to the injury site. These findings suggested that the OASIS-mediated ER stress response inhibits the repair of the injured spinal cord by promoting the development of N-cadherin-expressing reactive astrocytes that form glial scars following injury. OASIS deletion inhibited the development of N-cadherin-positive reactive astrocytes that form glial scars and promoted axon growth and functional recovery after SCI. These results suggest that the ER stress response mediated by OASIS could be a new target in the treatment of SCI. NeuroReport 29:1443–1448 Copyright © 2018 The Author(s). Published by Wolters Kluwer Health, Inc.

NeuroReport 2018, 29:1443–1448

Keywords: astrocyte, astrogliosis, endoplasmic reticulum stress, old astrocyte specifically induced substance, spinal cord injury

*Department of Orthopaedic Surgery, Graduate School of Biomedical and Health Sciences, Hiroshima University, Higashihiroshima and \textsuperscript{b}Medical Center for Translational and Clinical Research, Hiroshima University Hospital, Hiroshima, Japan

Correspondence to Yoshikazu Sumida, MD, Department of Orthopaedic Surgery, Hiroshima University, 1-2-3 Kasumi, Minami-ku, Hiroshima 734-8551, Japan
Tel: +81 822 575 233; fax: +81 822 575 234; e-mail: mpbs0007@yahoo.co.jp

Received 26 July 2018 accepted 12 August 2018

Introduction

The endoplasmic reticulum (ER) is the entrance site for proteins destined for the secretory pathway or extracellular environment [1]. Various pathophysiological conditions, such as ER-calcium depletion, oxidative stress, hypoglycemia, altered glycosylation, mutated protein expression, and hypoxia, interfere with the correct folding of proteins and increase the accumulation of unfolded or misfolded proteins in the ER [1,2]. This condition is termed ER stress, and excessive and/or long-term stress results in apopotic cell death [1,3]. To manage the accumulation of unfolded proteins, the ER ubiquitously expresses three major transducers, protein kinase R-like ER kinase, inositol-requiring 1, and activating transcription factor 6, which sense unfolded proteins in the ER lumen. They provoke an unfolded protein response (UPR), which leads to the production of ER-resident chaperones and attenuates global protein translation and ER-associated degradation, to remove misfolded or unfolded proteins. Another ER stress transducer is the old astrocyte specifically induced substance (OASIS), which is expressed in specific cells, including astrocytes and osteoblasts [2,4,5]. The activation of OASIS by mild ER stress has been reported to accelerate the differentiation of neural precursor cells into astrocytes in the fetal brain [6]. In this study, we examined the function of OASIS in astrogliosis following spinal cord injury (SCI). SCI is a severe condition that occurs throughout the world with an annual incidence of 15–40 cases per million [7]. SCI consists of two stages. After mechanical injury owing to an external force, the injured area enlarges owing to secondary damage, including the increase in inflammation, hypoxia, ischemia, and demyelination, and disruption of the blood–brain barrier [8]. Previous treatments have included the administration of methylprednisolone, but none were sufficiently clinically effective [9]. Previous studies [10,11] have focused on reactive astrogliosis, which is a pathological hallmark of SCI and is a defense mechanism that minimizes and repairs the initial damage but eventually leads to inhibitory effects through glial scar formation [12]. Controlling astrogliosis is one of the most important steps in the successful treatment of SCI. The function of the ER stress

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response has been reported to be related to apoptosis, but no studies have revealed the relationship between ER stress and astroglialosis in SCI. Here, we show that the OASIS-mediated ER stress response positively regulates reactive astroglialosis, which results in glial scar formation following SCI.

Materials and methods
The experiments described in this study were conducted in accordance with the National Institutes of Health Guidelines for the Care and Use of Laboratory Animals. All protocols were approved by the ethics committee of Hiroshima University.

Old astrocyte specifically induced substance-deficient mice
C57BL/6 and OASIS−/− mice were used in this study. The OASIS−/− mice were supplied from the Department of Biochemistry of the Graduate School of Biomedical and Health Sciences of Hiroshima University [13]. They were bred and maintained at the animal facility of Hiroshima University.

Spinal cord injury model
Adult male mice (10 weeks old) that were deficient for OASIS [OASIS knockout (KO) mice] and C57BL/6 mice [wild-type (WT) mice] were anesthetized by the sustained inhalation of 2.0% isoflurane and air (2.0 l/min). After a T10 thoracic laminectomy, the spinal cord was contused with an Infinite Horizon Impactor (70 kdyn; Precision Systems and Technologies Denmark ApS, Glostrup, Denmark) for 60 min at room temperature. The sections were then dried, and treated with serum-free protein blocker (Agilent Technologies Denmark ApS, Glostrup, Denmark) for 1 min for nuclear staining. All spinal cord sections were stained with primary antibodies. The primary antibodies used in this study were as follows: goat anti-glial fibrillary acidic protein (GFAP, 1: 200; Abcam plc, Cambridge, UK), rat anti-F4/80 (1: 200; BD Biosciences, San Jose, California, USA), mouse anti-nectin (1: 100; BD Biosciences), rabbit anti-N-cadherin (1: 400; Abcam plc), goat anti-serotonin (5-HT; 1: 600; Abcam plc), rabbit anti-cleaved caspase-3 (1: 400; Cell Signaling Technology Inc., Danvers, Massachusetts, USA), and rat anti-myelin basic protein (MBP, 1: 400; Abcam plc). The secondary antibodies were Alexa Fluor 568-conjugated donkey anti-goat IgG (1: 500), Alexa Fluor 594-conjugated donkey anti-rat IgG (1: 500), Alexa Fluor 568-conjugated donkey anti-mouse IgG (1: 500), Alexa Fluor 594-conjugated donkey anti-rabbit IgG (1: 500), Alexa Fluor 488-conjugated goat anti-rabbit IgG (1: 400), and Alexa Fluor 594-conjugated goat anti-rat IgG (1: 400; all from Thermo Fisher Scientific Inc., Waltham, Massachusetts, USA). 4′,6-Diamidino-2-phenylindole dihydrochloride (DAPI) solution was applied for 5 min for nuclear staining. All spinal cord sections were examined using a fluorescent microscope (BZ-9000; Keyence Corporation, Osaka, Japan).

Quantitative assessment of N-cadherin, axons, and apoptotic oligodendrocytes
The N-cadherin- and 5-HT-positive areas were measured using ImageJ software (National Institutes of Health, Maryland, USA), as previously described [16]. The areas of the 5-HT-positive axons were measured at two different sites (caudal region adjacent to the epicenter and 500 µm caudal to the epicenter) [17]. The number of apoptotic oligodendrocytes was calculated at two different regions in the white matter caudal to the injury site [18]. Cells labeled for MBP, cleaved caspase-3, and DAPI were counted by investigators who were blind to the groups in five sections each from five mice from each group. The labeled sections were examined using the BZ-9000 microscope.

Statistical analysis
All measured values other than the BMS scores were expressed as mean ± SD. The data were analyzed using the Statistical Package for Social Sciences (SPSS, IBM Japan, Tokyo, Japan). Unpaired Student’s t-tests were used to compare the two groups. The BMS scores were expressed as mean ± standard error and statistically analyzed using two-way repeated-measures analysis of variance for group and time. P values less than 0.05 were considered statistically significant.

Results
Motor function recovery
All WT and KO mice had BMS scores of 9 (maximum score) before the SCI, and their scores were reduced to ∼1, 1 day after SCI. The scores of both the WT and KO mice gradually improved over time. Significant effects for group were identified using repeated-measures analysis
of variance ($P < 0.0001$ for group, time, and group × time interaction). The scores of the KO mice were significantly higher than those of the WT group on and after day 7 after SCI (Fig. 1). These findings indicated that OASIS deletion improved the functional recovery of mice after SCI.

**Generation and migration of reactive astrocytes following spinal cord injury**

The astrocyte precursor cells expressing GFAP and nestin were mainly observed around the central canal of the spinal cord at almost the same intensity in the WT and KO mice on day 7 after SCI (Supplementary Fig., Supplemental digital content 1, http://links.lww.com/WNR/A491 which demonstrates GFAP- and nestin-positive astrocytes). On day 14 after SCI, accumulation of F4/80-positive macrophages in the central part of the injury site, with surrounding GFAP-positive astrocytes, was observed (Fig. 2). No significant differences were found for the F4/80-negative and GFAP-negative areas between the WT and KO mice. These findings suggested that OASIS deletion did not affect the generation and migration of reactive astrocytes following SCI.

**N-cadherin-positive astrocytes**

N-cadherin-positive astrocytes were located in the region adjacent to the GFAP-negative central part of the injury site in both WT and KO mice (Fig. 3). However, the N-cadherin-positive area in the KO mice was significantly smaller than that in the WT mice. These findings showed that OASIS deletion decreased the development of N-cadherin-expressing reactive astrocytes.

**Axon growth**

To assess the contribution of descending nerve fibers to motor function improvement, immunohistochemistry for 5-HT (marker of descending serotonergic axons) was performed (Supplementary Fig., Supplemental digital content 2, http://links.lww.com/WNR/A492, which shows spinal cord sections on day 42 after SCI). The 5-HT-positive areas were measured in two lesions at the injury site (caudal region adjacent to the epicenter) and 500 µm distal to the lesion. In both lesions, the area of the 5-HT-positive axons in the KO mice was significantly greater than that in the WT mice. These findings suggested that OASIS deletion enhanced axon growth after SCI.

**Apoptotic oligodendrocytes**

Immunohistochemistry for cleaved caspase-3 (apoptotic marker), MBP (oligodendrocyte marker), and DAPI was performed on day 7 after SCI (Fig. 4). The numbers of apoptotic oligodendrocytes (trichrome-stained cells) were counted in two regions of the white matter caudal to the injury site. The numbers in WT mice were significantly higher than those in KO mice.

**Discussion**

Our findings demonstrated that OASIS deletion did not affect the generation and migration of reactive astrocytes but rather inhibited the development of N-cadherin-positive reactive astrocytes around the injury site and enhanced axon growth after SCI.

In this study, we examined astrogliosis following SCI from the aspect of ER stress. The UPR in the ER is a homeostatic response that occurs under ER stress conditions [19]. The ER stress signals are detected by sensors that are located in the membrane and that transmit new signals to deal with the stress. Of the two types of sensors, one is ubiquitous, and the other is expressed in specific cells. We focused on the sensor specifically expressed in astrocytes, OASIS, and examined its...
contribution to astrogliosis. This study is the first report of the relationship of OASIS to astrogliosis after SCI.

Astrogliosis following SCI has two contrasting characteristics. One is beneficial and prevents the spinal cord from expanding owing to inflammation and reconstructs the blood–spinal barrier [12]. The suppression of astrogliosis has been reported to enlarge the damaged lesion, which hampers recovery from the injury [10]. In contrast, astrogliosis also forms a morphological barrier called a glial scar that disturbs axonal regeneration and leads to poor motor function recovery.

The UPR mediated by OASIS has previously been reported to promote astrocyte differentiation in the fetal brain [6]. However, OASIS deletion did not affect the generation of astrocyte precursor cells expressing nestin and GFAP following SCI in the present study. In addition, OASIS deletion did not decrease the proliferation and migration of reactive astrocytes. These findings suggested that OASIS might not contribute to the differentiation of neural precursor cells in SCI. Therefore, OASIS deletion might not inhibit the beneficial effects of astrogliosis in the acute and subacute phases of SCI.

In contrast, these findings revealed that OASIS deletion decreased N-cadherin-positive reactive astrocytes around the injury site and promoted axon growth and functional recovery after SCI. N-cadherin has been reported to play a prominent role in the injury response of astrocytes, including the formation and maintenance of the glial scar [20]. A previous study has shown that the astrocyte-specific
KO of N-cadherin results in impairments in astrogliosis in response to brain injury [21]. Furthermore, another previous study has reported that N-cadherin downregulation in reactive astrocytes prevents glial scar formation and promotes axonal regeneration and functional recovery after SCI [22]. These findings suggested that the ER stress response mediated by OASIS positively regulates the development of N-cadherin-positive scar-forming astrocytes that inhibit axon growth and functional recovery after SCI.

In this study, we also evaluated apoptotic oligodendrocytes at the injury site. Fewer apoptotic oligodendrocytes were observed in OASIS KO mice. Although the detailed mechanisms are unknown, we assumed that the beneficial effects of astrogliosis play a role in protecting oligodendrocytes from apoptosis. Therefore, the ER stress response mediated by OASIS could promote the apoptosis of oligodendrocytes that inhibit improvements in functional recovery after SCI.

Although studies on SCI have been performed for decades, we still do not have a definitive cure for SCI, which sometimes has tragic outcomes. We believe that a better understanding of the relationship between OASIS and astrogliosis will provide new options for the treatment of SCI. Therefore, additional studies are needed to elucidate the detailed mechanisms and roles of OASIS.

Conclusion
The deletion of OASIS inhibited the development of N-cadherin-positive reactive astrocytes that form glial scars and promoted axonal growth and functional recovery after SCI. Thus, the ER stress response mediated by OASIS could be a new target for the treatment of SCI.

Acknowledgements
The authors would like to thank Prof. Kazunori Imaizumi and Dr. Atsushi Saito from Department of Biochemistry,
Hiroshima University for providing OASIS-deficient mice and technical support.

This study was supported by a MEXT/JSPS KAKENHI Grant-in-Aid for Scientific Research (C) awarded to N.K. (grant no. 17K10931).

Conflicts of interest

There are no conflicts of interest.

References


