Dysregulation of miR-301a-3p serves as a non-invasive biomarker and is associated with inflammatory responses in traumatic spinal cord injury

Leming Mou, Maoyuan Xin and Enhui Li

Department of Orthopedics, Weifang People’s Hospital, Weifang 261000, Shandong, China

Background: Spinal cord injury (SCI) led by trauma is a serious damage in central nervous system. This study aimed at confirming the expression levels and clinical significance of miRNA-301a-3p (miR-301a-3p) in SCI patients, and exploring the potential mechanisms of miR-301a-3p participating in SCI progression. Methods: One hundred and thirty nine acute spinal trauma patients, included neurologically normal, incomplete and complete SCI cases, were analyzed in this study. Quantitative real-time PCR was used to measure the expression of miR-301a-3p. Receiver operating characteristic (ROC) was used to evaluate the diagnostic accuracy of serum miR-301a-3p in SCI. LPS-treated SH-SY5Y cells were used to mimic SCI inflammatory injury. The levels of IL-1β, IL-6, TNF-α were detected using enzyme-linked immunosorbent assay. Results: Expression of serum miR-301a-3p was significantly higher in both incomplete and complete SCI patients than that in neurologically normal controls, and had a significant ability to distinguish SCI patients from controls. Additionally, complete SCI cases had markedly increased miR-301a-3p compared to incomplete cases, and the two groups of patients could be distinguished based on serum deregulated miR-301a-3p. In the SCI cell model, miR-301a-3p overexpression led to decreased cell viability. The inflammatory responses of the cell model were enhanced by miR-301a-3p, which was consistent with the findings in SCI patients that serum miR-301a-3p was positively correlated with pro-inflammatory cytokines. Conclusion: The expression of miR-301a-3p is increased in SCI patients, and serves as a candidate biomarker for SCI diagnosis. MiR-301a-3p may be involved in SCI progression by affecting neuronal viability and inflammation.

Keywords: Spinal cord injury, miR-301a-3p, neuroinflammation, viability, IL-1β, IL-6, TNF-α

INTRODUCTION

Spinal cord injury (SCI) refers to an injury resulting from the direct or indirect effects of external forces on spinal cord, and is a traumatic injury disease that seriously damages central nervous system (Fehlings et al., 2017; Fan et al., 2018). SCI can be divided into complete SCI and incomplete SCI according to the American Spinal Injury Association (ASIA) Impairment Scale in international Standards for Neurological Classification of Spinal Cord Injury (Vasquez et al., 2013), and a variable damage degree of the two SCI types depends mainly on the primary and secondary mechanisms of injury (Rouanet et al., 2017). Although the clinical repair strategies are different between complete and incomplete SCI (O’Shea et al., 2017), both have devastating consequences for the physical abilities of patients (Ahuja et al., 2017). Studies confirmed that the pathogenesis after the initial occurrence of SCI involved oxidative stress, posttraumatic inflammation, motor neuron apoptosis and necrosis, leading to a secondary neurological damage to the spinal cord and the peripheral nervous system (Rouanet et al., 2017; Wilson et al., 2013; Ahuja et al., 2016). What’s more, SCI leads to spinal inflammatory responses, which is also an important mechanism for aggravating neuronal damage (Sun et al., 2021; Tian et al., 2007). Therefore, the exploration of early diagnostic biomarkers and methods to alleviate neuroinflammation will be beneficial for understanding SCI disease progression and promoting recovery after injury.

MicroRNAs (miRNAs) are small, noncoding RNA particles, and they participate in many biological processes, including inflammation (Xia et al., 2017, Neudecker et al., 2017). miRNA-301a-3p (miR-301a-3p) is an inflammation-related miRNA that promotes inflammatory responses in the development and progression of diseases, such as intestinal mucosal inflammation (He et al., 2016), osteoarthritis (Chen et al., 2017), pulmonary fibrosis (Wang, Li, et al., 2020), or ankylosing spondylitis (Dong et al., 2020). In addition, several studies have demonstrated that miR-301a-3p has the potential to promote the inflammation induced by Japanese encephalitis virus infection in central nervous system (Hazra et al., 2019; Hazra et al., 2017). Kumar et al. have demonstrated that aberrantly expressed miR-301a-3p has a potential diagnostic value for distinguishing patients with the neurodegenerative disease, such as Alzheimer’s disease (Kumar et al., 2013). It is worth mentioning that a recent SCI-related study has explored aberrantly expressed miRNAs in SCI animal models, and the research found that miR-301a-3p was significantly upregulated in SCI mice (Wan et al., 2020). Therefore, it is necessary to analyze the expression levels and clinical significance of miR-301a-3p in SCI patients, to further explore new biomarkers and therapeutic targets for SCI.

This study aimed at confirming the expression levels and clinical significance of miR-301a-3p in SCI progression. Considering a close relationship between miR-301a-3p and inflammation, this study further explores the regulatory effects of miR-301a-3p on the inflammatory responses of a SCI inflammatory injury cell model,
which was expected to preliminarily uncover the mechanisms of miR-301a-3p playing in SCI progression. The results of this study may allow researchers to gain new understanding of the function of miR-301a-3p, and provide novel biomarkers and targets for the diagnosis and therapy of SCI.

MATERIALS AND METHODS

Patients and tissue collection

Blood samples were collected from 139 acute spinal trauma patients treated at Weifang People’s Hospital between September 2017 and September 2020. According to the American Spinal Injury Association (ASIA) Impairment Scale in International Standards for Neurological Classification of Spinal Cord Injury (Vasquez et al., 2013), 139 acute spinal trauma patients were divided into three groups: neurologically normal controls (controls, n=33); incomplete SCI group (n=67); complete SCI group (n=39). Inclusion criteria for acute SCI patients in this study: (1) the onset time of acute SCI was within 24 h before admission in all patients; (2) the age of patient ≥18 years old. Patients with any of the following characteristics were excluded from this study: (1) patients with a history of spinal or craniocerebral related trauma and surgery within a half year period; (2) patients with a severe cardiopulmonary disease including large area myocardial infarction or acute coronary syndrome, severe arrhythmia, and acute respiratory distress syndrome; (3) patients with acute severe head injury (severe brain trauma, massive cerebral hemorrhage, large cerebral infarction and severe brain stem injury, etc.); (4) pregnant women; (5) patients with a previous history of acute SCI or head injury; (6) patients with malignancies, acute and chronic infections, severe hepatic and renal dysfunction, cerebrovascular disease, autoimmune disease and hematological disease. Venous blood samples were collected from the included patients after admission, and clinicopathological characteristics of the patients were recorded. Serum was separated by centrifugation at low temperature and stored at −80°C for subsequent analysis. The protocols for venous blood sample collection and analysis were all in accordance with the guideline of the Ethics Committee, and were approved by the Ethics Committee of Weifang People’s Hospital. A signed informed consent was obtained from each patient before sampling.

Cell culture

Human neuroblastoma SH-SY5Y cells obtained from the Cell Bank of the Chinese Academy of Science (Shanghai, China) were cultured in Dulbecco’s modified Eagle medium (DMEM; Solarbio, Beijing, China), and 10% fetal bovine serum (FBS; Gibco, Grand Island, NY, USA) was added to the medium. The cells were maintained at 37°C in a humidified atmosphere with 5% CO₂.

Cell treatment

To construct a cell model of SCI inflammatory injury, SH-SY5Y cells were treated with 100 ng/mL of LPS (Sigma-Aldrich, Louis, MO, USA) for 24 h at 37°C. To explore the regulatory effects of miR-301a-3p on model cell viability and inflammation, after SH-SY5Y cell reached 80% confluence, the cells were transfected with miR-301a-3p mimic, miR-301a-3p inhibitor, mimic NC or inhibitor NC (GenePharma, Shanghai, China) using Lipofectamine 3000 (Invitrogen, Carlsbad, CA, USA) at 6 h before LPS treatment. Following were the sequences used for transfection: miR-301a-3p mimic: 5'-CAGUG-CAALGUGAUAAAAGGGCAU-3'; miR-301a-3p inhibitor: 5'-AUGAAUUUUAACAUUGCAGU-3'; mimic NC: 5'-UUCCCGAAGCUUGACGU-3'; inhibitor NC: 5'-CAGUAUUUUGUGUACAA-3'.

RNA extraction and reverse transcription-quantitative PCR (RT-qPCR)

TRIzol reagent (Invitrogen) was used to extract total RNA from serum samples, and the purity of RNA was detected by NanoDrop 2000 (Thermo Fisher Scientific, Waltham, MA, USA). The RNA was reverse-transcribed into cDNA using PrimeScript RT reagent kit (TaKaRa, Shiga, Japan) following the manufacturer’s protocols.

Quantitative real-time PCR (qRT-PCR) was performed using SYBR green I Master Mix kit (Invitrogen, Carlsbad, CA, USA) on a 7500 Real-Time PCE System (Applied Biosystems, USA), and U6 was used as an endogenous control for the reaction. All manipulations were performed following the manufacturer’s guidelines. The relative expression results were quantified using the 2⁻ΔΔCt method.

Enzyme-linked immunosorbent assay (ELISA)

To evaluate inflammatory responses in SCI patients and cell model, the levels of interleukin (IL)-1β, IL-6, tumor necrosis factor (TNF)-α (TNF-α) in serum samples and cell supernatants were measured using ELISA kits (R&D Systems, Shanghai, China) following the manufacturer’s protocols.

Cell counting kit (CCK)-8 assay

CCK-8 assay was used to evaluate the proliferation abilities of SH-SY5Y cells. Cells were seeded into a 96-well plate (1×10⁴ cells/well). Then, the 96-well plate was incubated in a humidified incubator at 37°C with 5% CO₂, 10 μL portions of CCK-8 reagent were added to the wells, respectively. After 1 h of incubation, a microplate reader was used to read OD (optical density) values at 450 nm.

Statistical analysis

SPSS 22.0 (IBM Corp.) and GraphPad Prism 7.0 software (GraphPad Software, Inc.) were used to perform the statistical analyses. Differences between multiple groups were compared using one-way ANOVA followed by the Tukey’s test. The chi-square test was used for comparison between categorical variables. Receiver operating characteristic (ROC) was used to evaluate the diagnostic accuracy and discrimination ability of serum miR-301a-3p in SCI patients. The Pearson correlation test was used to evaluate the correlation between serum miR-301a-3p and inflammatory factors (IL-1β, IL-6, TNF-α). All data in the present study were presented as the mean ± standard deviation (S.D.). Each experiment was repeated at least 3 times. P<0.05 was considered statistically significant.

RESULTS

Baseline characteristics of the patients

The baseline characteristics of all participants were included in Table 1, which revealed that there were no significant differences in age, body mass index (BMI), body
temperature and gender between neurologically normal controls and SCI patients (all \( P > 0.05 \)), and SCI patients had significant differences in the site of spinal cord affected (\( P = 0.001 \)) and ASIA grade (\( P < 0.001 \)) compared with neurologically normal controls.

**Overexpression of miR-301a-3p in the serum of SCI patients**

The expression levels of miR-301a-3p in the collected serum samples were detected by qRT-PCR. The expression levels of miR-301a-3p were significantly higher in the serum of both incomplete and complete SCI patients than those in neurologically normal controls (Fig. 1, all \( P < 0.001 \)). In addition, the relative expression of miR-301a-3p was significantly higher in the serum of complete SCI patients compared with that in incomplete SCI patients (\( P < 0.001 \)).

**Diagnostic performance of serum miR-301a-3p in patients with SCI**

The ROC curves were generated according to the expression levels of serum miR-301a-3p. Serum expression levels of miR-301a-3p have high diagnostic performance in distinguishing between SCI patients and neurologically normal controls, with the area under the curve (AUC) of 0.903. At the cut-off value of 0.465, the sensitivity was 80.19% and the specificity was 87.88%, indicating that this was the optimal value of miR-301a-3p to distinguish SCI patients from neurologically normal controls (Fig. 2A).

In addition, the accuracy of serum miR-301a-3p in the differential diagnosis between incomplete SCI and complete SCI patients was analyzed in this study. The ROC result showed that miR-301a-3p had the ability to differentiate complete SCI patients from incomplete SCI patients, and the AUC was 0.836. At a cut-off value of 0.625, the sensitivity was 71.79% and the specificity was 74.63%, which indicated the optimal value of miR-301a-3p.

**Correlation of miR-301a-3p with pro-inflammatory cytokines in patients with SCI**

The inflammatory responses of SCI patients were evaluated by examining the levels of IL-1β, IL-6, TNF-α in serum samples, and the correlation between serum miR-301a-3p and inflammation was analyzed. The results revealed that the expression levels of miR-301a-3p were...
positively correlated with the levels of IL-1β (r=0.702), IL-6 (r=0.618), TNF-α (r=0.712) in patients with SCI (Fig. 3A–C, all P<0.001).

Regulatory effects of miR-301a-3p on LPS-induced inflammatory injury in SH-SY5Y cells

By using LPS stimulation, the human neuroblastoma SH-SY5Y cells were induced as a SCI inflammatory injury cell model, and the potential regulatory role of miR-301a-3p in neuroinflammation was investigated. As shown in Fig. 4A, the expression level of miR-301a-3p was significantly increased in SH-SY5Y cells after treating with LPS compared with untreated (P<0.001), which was consistent with the expression changes observed in SCI patients. After cell transfection in the LPS-induced cell model, we found that the increased miR-301a-3p by LPS was further enhanced by miR-301a-3p mimic compared with the LPS group, while the promoting effects of LPS on miR-301a-3p expression were significantly inhibited by the inhibitor of miR-301a-3p (Fig. 4A, both P<0.001).

In addition, as shown in Fig. 4B, the relative cell proliferation viability was significantly decreased after treating with LPS compared with the untreated cells (P<0.001). In the LPS-induced cell injury model, the inhibited cell viability was further decreased by the overexpression of miR-301a-3p, while silencing miR-301a-3p abolished the restriction in cell viability by LPS (Fig. 4B, both P<0.05).

For cell inflammatory responses to LPS treatment, we found that LPS significantly increased the release concentration of inflammatory factors (IL-1β, IL-6, TNF-α) in SH-SY5Y cells, indicating that the inflammatory response was activated in SH-SY5Y cells (Fig. 4C–E, all P<0.001). By regulating the expression of miR-301a-3p in the cell model, it was found that miR-301a-3p overexpression led to further increases in IL-1β, IL-6, TNF-α levels (all P<0.001), while the promoting effects of LPS on IL-1β, IL-6, TNF-α levels were significantly reversed by the reduction of miR-301a-3p (all P<0.001). Therefore, the expression level of miR-301a-3p reveals an effect on the release concentration of inflammatory factors in the SCI inflammatory injury cell model in vitro.

DISCUSSION

Studies have shown that many abnormally regulated miRNAs are involved in the development of SCI (Zhou
et al., 2020; Zhang et al., 2019). For example, Zhang et al. indicated that downregulation of miRNA-127-5p could aggravate SCI through activating MAPK1 (Zhang et al., 2019). Zhou and others (Zhou et al., 2020b) revealed that the overexpression of miRNA-433-5p protected SCI-induced motor dysfunction and inflammatory responses. According to the research results of Yang and others (Yang et al., 2018) high expression of miR-544a could promote the recovery of spinal cord. In the present study, we have found that the expression levels of miR-301a-3p were significantly higher in the serum of SCI patients and LPS-treated SH-SY5Y cells. Therefore, we reasonably speculate that miR-301a-3p may be involved in the development of SCI.

The aim in treating acute traumatic spinal trauma was to preserve residual neurologic function and avoid secondary injury (Mourelo Farina et al., 2017). Therefore, in the early occurrence of acute spinal trauma, it is quite important to promptly diagnose the situation of damage in patients and conduct appropriate clinical treatment (Mourelo Farina et al., 2017; Ryken et al., 2013; Jones et al., 2015). MiR-301a-3p has been considered as a diagnostic biomarker for several diseases (Wang, Zhao, et al., 2020; Ramirez-Ardila et al., 2016). In previous studies, Wang and others. (Wang et al., 2020b) demonstrated that miR-130 family members (including miR-301a-3p) in serum could effectively distinguish bladder cancer patients from healthy controls. In addition, miR-301a-3p also had the ability to discriminate breast cancer patients from controls (Ramirez-Ardila et al., 2016). In the present study, the results of ROC analysis indicated that miR-301a-3p had the ability to significantly distinguish SCI patients from neurologically normal controls, and complete SCI patients from incomplete SCI patients, with considerable diagnostic accuracy. Therefore, we speculated that miR-301a-3p may have diagnostic implications in SCI patients, and may be a candidate for an early diagnostic biomarker.

Evidences showed that inflammatory response aggravates neuronal injury, and neuronal damage, in turn, promotes neuroinflammation in the pathogenesis of SCI. Studies have indicated that various miRNAs were associated with inflammatory responses in SCI (Sun et al., 2020; Yang et al., 2018). For example, miRNA-411 has been found to attenuate inflammatory damages and apoptosis in SCI (Sun et al., 2020). Additionally, miRNA-544a regulated the inflammation of SCI by inhibiting the expression of NEUROD4 (Yang et al., 2018). The analysis of serum samples collected from SCI patients showed that the expression levels of miR-301a-3p were positively correlated with serum concentration of inflammatory factors (IL-1β, IL-6 and TNF-α) in SCI patients, demonstrating a possible correlation of serum miR-301a-3p with SCI neuroinflammation. However, the effects of miR-301a-3p on SCI neuroinflammation in vitro is unknown. Human neuroblastoma SH-SY5Y cells are recognized as a well-established in vitro model to evaluate neural function (Li et al., 2020; Jia et al., 2021). After cell transfection in the LPS-induced cell model, we found that the miR-301a-3p expression was significantly upregulated by LPS, which was consistent with the expression changes observed in SCI patients. Previous studies concluded that miRNA-301a-3p regulated the inflammation and process of diseases (Jiang & Lv, 2021; Martinez-Gutierrez et al., 2019). For instance, miRNA-301a-3p increased inflammation and apoptosis in ox-LDL-induced HUVECs by targeting KLF7 (Jiang & Lv, 2021). The downregulation of miR-301a-3p was associated with a higher overall survival in metastatic breast cancer (Mar-tinez-Gutierrez et al., 2019). The inflammatory responses were enhanced by miR-301a-3p in the development of ankylosing spondylitis (Dong et al., 2020). In the SCI inflammatory injury cell model of our study, analysis of inflammatory factors levels indicated that miR-301a-3p overexpression led to further increases in IL-1β, IL-6, TNF-α levels, while the promoting effects of LPS on IL-1β, IL-6, and TNF-α levels were significantly reversed by the reduction of miR-301a-3p. Regarding cell viability of the cell model, miR-301a-3p overexpression inhibited cell viability, while miR-301a-3p reduction enhanced this process. Therefore, combining the experimental results and previous studies, we speculate that the dysregulation of miR-301a-3p may be involved in SCI progression by regulating inflammatory responses. After the occurrence of SCI, miR-301a-3p overexpression may promote the progress of neuroinflammation, miR-301a-3p reduction may slow down inflammatory responses, and miR-301a-3p may be regarded as an indicator of inflammatory responses in SCI.

The limitation of this study is that the specific regulatory mechanism of miR-301a-3p in the inflammatory response of SCI was not further explored, thus we give a further perspective on the mechanism of action. Previous studies indicated that miRNA-301a-3p promoted inflammation and apoptosis by targeting KLIF7 in ox-LDL-induced HUVECs (Jiang & Lv, 2021). In addition, Guo et al revealed that miR-301a-3p induced by endoplasmic reticulum stress mediates the occurrence and transmission of trastuzumab resistance in HER2-positive gastric cancer (Guo et al., 2021). The above studies provided us with the ideas that some other inflammation-related pathways or target genes might mediate the regulatory role of miR-301a-3p in the inflammation of SCI pathway. These will be exploratory directions of our future studies, and we will continue to explore the mechanisms of miR-301a-3p acting in the progression of SCI.

In conclusion, the expression of miR-301a-3p was increased in SCI patients, and had the ability to discriminate SCI patients from those neurologically normal patients who also suffered from spinal trauma. The inhibition of miR-301a-3p alleviated inflammatory responses and promoted cell viability in the SCI cell model. All the findings of this research suggest that miR-301a-3p may be a novel biomarker and therapeutic target for traumatic SCI.

Declaration

Ethics approval and consent to participate. The experimental procedures were all in accordance with the guideline of the Ethics Committee of Weifang People’s Hospital and has approved by the Ethics Committee of Weifang People’s Hospital. This study complies with the Declaration of Helsinki. A signed written informed consent was obtained from each patient.

Consent for publication. Written informed consent for publication was obtained from each participant.

Availability of data and materials. The data used to support the findings of this study are available from the corresponding author upon reasonable request.

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Authors’ contributions. LM carried out the research design and conception; MX analyzed and interpreted the data regarding; MX and EL performed the examination of cells; EL and LM delivered essential reagents or
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