

Research Article

The Cotransplantation of Olfactory Ensheathing Cells with Bone Marrow Mesenchymal Stem Cells Exerts Antiapoptotic Effects in Adult Rats after Spinal Cord Injury

Shifeng Wu,¹ Guanqun Cui,² Hua Shao,³ Zhongjun Du,³ Jack C. Ng,⁴ and Cheng Peng⁴

¹Department of Orthopedics, Linyi People's Hospital Affiliated to Shandong University, Linyi, Shandong 276000, China

²Respiratory Department, Qilu Children's Hospital of Shandong University, Jinan, Shandong 250022, China

³Department of Toxicology, Shandong Academy of Occupational Health and Occupational Medicine, Shandong Academy of Medical Sciences, Jinan, Shandong 250062, China

⁴National Research Centre for Environmental Toxicology (Entox), The University of Queensland, Brisbane, QLD 4108, Australia

Correspondence should be addressed to Hua Shao; chinashaohua5888@163.com and Zhongjun Du; duzj1981@163.com

Received 18 April 2015; Revised 24 June 2015; Accepted 29 June 2015

Academic Editor: Jianglin Fan

Copyright © 2015 Shifeng Wu et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The mechanisms behind the repairing effects of the cotransplantation of olfactory ensheathing cells (OECs) with bone marrow mesenchymal stromal cells (BMSCs) have not been fully understood. Therefore, we investigated the effects of the cotransplantation of OECs with BMSCs on antiapoptotic effects in adult rats for which the models of SCI are induced. We examined the changes in body weight, histopathological changes, apoptosis, and the expressions of apoptosis-related proteins after 14 days and 28 days after transplantation. We also assessed animal locomotion using BBB test. We found that treatment with OECs and BMSCs had a remissive effect on behavioral outcome and histopathological changes induced SCI. Furthermore, we observed the significant antiapoptotic effect on cotransplant treated group. In addition, cotransplantation of OECs with BMSCs was found to have more significant repairing effect than that of OECs or BMSCs alone. Furthermore, the recovery of hind limb could be related to antiapoptotic effect of OECs and BMSCs through downregulating the apoptotic pathways. Finally, our data suggested the cotransplantation of OECs with BMSCs holds promise for a potential cure after SCI through the ability to incorporate into the spinal cord.

1. Introduction

Spinal cord injury (SCI) is a destructive neurologic injury resulting in functional deficits due to the loss of spinal cord neurons and axons. Extensive attempts have been made to promote repair and recovery cells from the injury for potential treatments of SCI among which the use of stem cells as transplant tissue shows particular promise since they may replace endogenous destroyed cells through facilitating cell regeneration and differentiate into neurons [1]. Cell-based therapies have demonstrated beneficial effects using different types of cells in preclinical models [2, 3]. Olfactory ensheathing cells (OECs) and bone marrow mesenchymal stromal stem cells (BMSCs) are two of the most studied cells

for SCI repair in experimental models and showed good perspectives for clinical applications of cell therapy.

OECs are unique glial cells found in the olfactory systems that support olfactory neurogenesis and the retargeting across the peripheral nervous system/the central nervous system boundary in the olfactory system. These cells are able to stimulate tissue sparing and neuroprotection, enhance outgrowth of both intact and lesioned axons, activate angiogenesis, and remyelinate axons after a range of demyelinating insults [4]. Recent studies have shown that OEC can promote the differentiation of stem cells into the olfactory system toward the olfactory neurons [5, 6]. Acute transplantation of OECs into partial or complete spinal cord lesions has been found to reduce the volume of injured tissue, promote axonal

regeneration, and recover some functions [7]. The proposed mechanisms of action of grafted OECs include their interaction with astrocytes [8], modulation of the early neuroinflammatory response [9], remyelination and enhancement of axonal regeneration [10], and promotion of angiogenesis. Therefore, progenitor OECs have been proposed as one of the most promising cell sources for SCI therapy. BMSCs have been shown to be able to promote functional recovery [11, 12], by intrathecal injection or intravenous perfusion. The mechanisms underlying the beneficial effects of BMSCs transplants may include neuroprotection by secreting or inducing the expression of neuroprotective molecules in the injured tissues [12], contribution to a permissive environment for axonal regeneration and neural tissue reconstruction [13], acceleration of the tissue repair process [9], and modulation of the neuroinflammatory response.

In recent years, much attention has been paid to secondary cord injury since this appears to be susceptible for therapeutic intervention. Apoptosis and inflammatory responses and some other neurological toxicity events may signify the secondary injury after primary insult in the spinal cord [1]. Apoptosis includes both a receptor-dependent extrinsic pathway and mitochondria associated in spinal cord injuries, which are activated in spinal cord injuries [14]. Several studies have implicated the apoptotic role of caspases in the injured spinal cord [15–17]. Activation of Caspase-3 and Caspase-8 and apoptosis occur in a temporally similar fashion after SCI [18]. Many other genes are involved in apoptosis, such as the antiapoptosis gene Bcl-2 and apoptosis-inducer Bax. Moreover, a study using Bcl-2 overexpressed transgenic mice demonstrated that overexpression of Bcl-2 inhibited neuronal apoptosis after spinal cord injury and improved recovery of neurological function [19]. In contrast, Bax, a cytosolic protein in normal living cells, can induce apoptosis and quickly translocates to mitochondria at an early stage of the apoptotic process. Kotipatruni et al. [20] showed upregulation of Bax and downregulation of Bcl-2 in rat spinal cords after SCI. These results suggested the involvement of a mitochondrial-mediated apoptotic pathway after SCI.

Since the natural capacity of the central nervous system to recover from injury is limited, current SCI research focuses on the use of regenerative potential of OECs or BMSCs to replace the damaged neurons and oligodendrocytes and enhance neuronal plasticity. These studies showed the reduction of neural degeneration and certain functional recovery by transplantation of either OECs or BMSCs. A precious study showed the antiapoptotic effects of transplantation of BMSCs after spinal cord injury [21]. Moreover, OECs and BMSCs could migrate and integrate into damaged organs or tissues, where they differentiate into myocytes and neurons cell lineages [22]. Therefore, we hypothesized that cotransplantation of OECs with BMSCs may have stronger effects on neural degeneration induced by SCI. We further hypothesized that the improved neurological functions by cotransplantation of OECs with BMSCs may be mediated through the regulation of Bax, Bcl-2, Caspase-9, and Caspase-3. To test the hypothesis, we cocultivated OECs and BMSCs for cotransplantation of OECs with BMSCs in rats with SCI and evaluated behavioral activities and histopathological

changes and measured the expression of the protein involved in mitochondria-associated apoptotic pathway.

2. Materials and Methods

2.1. Experimental Animals and Experimental Design. Adult female Wistar rats weighting 250–300 g were purchased from the Department of Experimental Animals, Shandong University, China (the number for certificate of animals is SCXK (Lu) 2013-0009), and maintained under standard housing conditions (temperature: 18–24°C; relative humidity: 45%; light and dark cycle: 12 h:12 h). Food and water were provided ad libitum. All animals were treated according to the protocols evaluated and approved by the ethical committee of Shandong University School of Medicine.

60 adult female Wistar rats were randomly divided into 5 groups which included (1) control group ($n = 12$) in which rats are only treated with laminectomy without SCI for comparison; (2) sham group ($n = 12$) in which DMEM culture medium was administered by intraspinal injection; (3) OECs treated group ($n = 12$) which received 3×10^5 OECs by intraspinal injection; (4) BMSCs treated group ($n = 12$) which received 3×10^5 BMSCs by intraspinal injection; (5) cotransplant treated group ($n = 12$) which received 3×10^5 OECs and BMSCs in the same way. We randomly divided 12 animals in each group into two groups (14-day posttransplantation group and 28-day posttransplantation group). On 14 and 28 days after transplantation, the animals ($n = 6$) from each group were evaluated with different parameters as shown in Figure 1.

2.2. Spinal Cord Injury Model. A standard spinal cord contusion was induced using the New York University (NYU) weight drop device as detailed previously [16]. Briefly, the adult female rats were anesthetized and placed prone on an operating table covered with a warming blanket. After shaving the midthoracic region and prepping with Betadine, an incision was made over the midthoracic region. Laminectomy on each rat was performed at the T9–T11 under chloral hydrate anesthesia. The impact rod of the impactor of 10 g was centered above T10 and dropped from a height of 50 mm to induce a consistent partial SCI. Analgesia was achieved using buprenorphine (0.1 mg/kg) for 2 days after surgery. Gentamicin (0.8 mg/100 g, ip) and Ringer's solution to avoid dehydration (2 mL, ip, after surgery) were administered to prevent urinary tract infection for 3–7 days. Passive mobilization of the hind legs for 15 minutes was undertaken every day for a week after surgery. Postoperative care included manual bladder expression 2 times a day until reflex bladder emptying was established.

2.3. Culture and Identification of Stem Cells. OECs from olfactory bulbs of healthy female adult Sprague Dawley rats ($n = 6$) weighting 220–300 g were cultured as reported previously with slight modifications [23, 24]. In brief, the Sprague Dawley rats were sacrificed by 3% pentobarbital sodium anesthetic overdose. After being put in 0.5% iodophor solution for about 5 minutes, rats were dissected in the super-clean bench. The cranial cavity was cut along the cranial sagittal

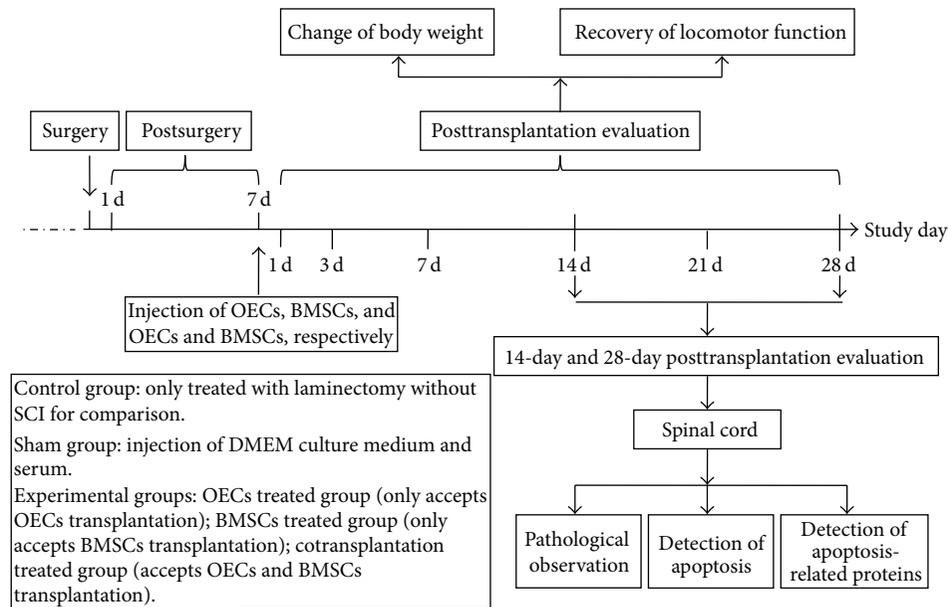


FIGURE 1: Animal experimental design of antiapoptotic effects of cotransplantation of OECs and BMSCs in adult rats.

suture from the foramen magnum. Olfactory bulbs were collected and washed 2 times with PBS and cut to small pieces with sterile ophthalmic scissors. After being washed with 4°C DMEM (with penicillin/streptomycin, 100 μ /mL) (GIBCO, USA) and collected by centrifuge 800 r.p.m (Thermo Fisher, USA), the tissue pieces were digested with 0.125% pancreatin-EDTA at 37°C for 30 minutes. The cell suspension with the cells in 10⁴/mL was obtained and incubated in CO₂ incubator (Thermo Fisher Labserv CO-150, USA) after being washed with DMEM and centrifuged as above.

OECs were identified by immunohistochemistry with p75 antibody. Cells at 60% confluency were washed 3 times with PBS followed by incubation of 4% paraformaldehyde for 20 minutes at room temperature. After being blocked with 5% BSA for 30 minutes, the cells were incubated with p75 antibody (1:100) (Sigma, USA) at 4°C overnight. The cells on slides were placed under microscope to observe under fluorescence microscope (OLYMPUS, Japan) after incubation with secondary antibody (1:200) (Sigma, USA) for 40 minutes at 37°C.

BMSCs were isolated and cultured using the repeated adherent culture method as described by Qian et al. [25]. Bone marrow was isolated in sterile conditions from 8-week-old female healthy Sprague Dawley rats ($n = 6$) weighting 250–300 g. Briefly, after being sacrificed by anesthetic overdose, rats were dissected to get tibia and femur. Under antiseptic conditions, medullar cavity was flushed with DMEM to get single cell suspension which was then washed and incubated in CO₂ incubator (Thermo Fisher Labserv CO-150, USA). The cells were observed daily under inverted microscope (OLYMPUS, Japan).

BrdU (10 μ g/L) (Guangzhou RIBOBIO Co., Ltd, China) was added into the culture flasks after incubation for 48–72 h and the cells were fixed with 4% paraformaldehyde for about 20 minutes. The cell slides were permeabilized

with 1% Triton X-100, digested with 2% HCl and the pepsin for 10 minutes, and blocked with 5% BSA (GIBCO, USA) for 30 minutes followed by incubation of BrdU antibody (Guangzhou RIBOBIO Co., Ltd., China) for 30 minutes. The slides were covered with 90% glycerol and observed under fluorescence microscope (OLYMPUS, Japan).

OECs and BMSCs were digested after they were purified and were mixed together into single cell suspension. The concentration was adjusted to 10⁴/mL and bottles were placed in CO₂ incubator; medium was replaced every 3 to 4 days. When slides were covered more than 60% to start identification, and repeated above steps.

Viability of OECs, BMSCs, and coculture cells was measured using WST-8 cell counting kit (CCK-8, DOJINDO, Japan). The assay was performed according to the manufacturer's instruction with slight modifications. Briefly, cells at 2 \times 10⁴/mL were seeded into a well of a 96-well plate at 90 μ L per well and cultured for different time periods (2, 4, 6, 8, 10, and 12 days). At the end of each incubation time, the cells were tested by addition of 10 μ L CCK-8 solution in each well followed by incubation for 1 h at 37°C. Optical density at 450 nm was detected by a microplate reader (Thermo Fisher, USA). Each experiment was performed in triplicate and repeated independently three times. Cell viability was expressed as the growth rate with respect to the cell number of the day.

2.4. Transplantation Procedure. The rats were randomly divided into 5 groups: (1) control group ($n = 12$) in which rats were only treated with laminectomy without SCI for comparison; (2) sham group ($n = 12$) in which DMEM culture medium was administered by intraspinal injection; (3) OECs treated group ($n = 12$) which received 3 \times 10⁵ OECs by intraspinal injection; (4) BMSCs treated group ($n = 12$) which received 3 \times 10⁵ BMSCs by intraspinal injection;

(5) cotransplant treated group ($n = 12$) which received 3×10^5 OECs and BMSCs in the same way.

BMSCs were resuspended at a concentration of 1×10^6 cells/100 μL , which were used for transplantation. Rats were operated on 7 days later after SCI, and the rats were anesthetized and transplantation was performed using a Hamilton syringe (Sigma, USA) which was attached to a microinjector through a customized needle with a sterile 30-gauge needle. A small hole was made in the dura at the injection site. Then, the customized needle was inserted into the spinal cord at the midline to a depth of 1 to 1.5 mm. 30 μL cell suspension at 1×10^6 cells/100 μL of the cell suspension was then injected over 2 minutes. The needle was left in place for 2 minutes after injection before withdrawal to minimize cell leakage. The OECs and the combination of OECs and BMSCs were transplanted into the spinal cord in the same manner. But the combination of OECs and BMSCs was transplanted into the spinal cord with 15 μL BMSCs cell suspension at 1×10^6 cells/100 μL and 15 μL OECs suspension at 1×10^6 cells/100 μL . The sham group had DMEM culture medium and serum “transplanted” in the same way.

2.5. Histopathological Examination. 14 and 28 days post-transplantation, rats were deeply anesthetized with ketamine/xylazine. The spinal cord tissues were isolated and excised with a razor blade and then fixed in 10% (v/v) neutral phosphate-buffered formalin solution. The tissues were embedded in paraffin blocks, sectioned into 5 μm slice and mounted onto the glass slides, and stained with hematoxylin and eosin (H&E) for histopathological evaluation under the light microscope (Leica DM4000M, Germany). And the photos were taken using optical microscope (Leica DM4000M, Germany). The identity and analysis of the pathology sections were blind to the pathologists. And the results were peer-reviewed by other certified veterinary pathologists.

2.6. Detection of Apoptosis. 14 and 28 days after transplantation, rats were deeply anesthetized with ketamine/xylazine. The spinal cord tissues of the rats were processed as above for a terminal deoxynucleotide transferase dUTP nick end labeling (TUNEL) using in situ cell death detection kit according to the manufacturer's instructions (Chemicon International Inc., Temecula, CA). Briefly, rats ($n = 4$) from normal control, treated, and sham control groups were perfusion-fixed with 4% paraformaldehyde in 0.1 M phosphate buffer (pH 7.4). Then, the sections were incubated with proteinase K (100 $\mu\text{g}/\text{mL}$), rinsed, incubated in 3% H_2O_2 , and washed with PBS for 10 min followed by washing with permeabilization solution (0.1% Triton X-100, 0.1% sodium citrate) for 5 min. After the sections were washed twice with PBS, incubated in TUNEL reaction mixture, and rinsed again, they were visualized using converter-POD with 0.02% 3,3'-diaminobenzidine (DAB). Mayer's hematoxylin was used for counter-staining. The sections were finally mounted onto gelatin-coated slides and then they were air-dried overnight at room temperature. Yellow stained nucleus was TUNEL-positive cells.

TUNEL-positive cell quantitative method was used. In each group, 5 cases of well-stained sections were selected and magnified 10 times for observation under the microscope objective. 5 high power fields ($\times 400$) in each section were randomly selected, and a total of 25 high power fields were photographed into computer (resolution is 800×600). Q550CW image signal acquisition and analysis system was employed to calculate intestinal epithelial cell apoptosis index. The number of apoptotic cells/the total cell number $\times 100\%$ equals the apoptosis rate of this field, and the average rate of apoptosis of five fields was the apoptosis rate of rat spinal cord cells in the group.

2.7. Western Blot Assay. Western blot was used to detect protein expression of Bax, Bcl-2, Caspase-9, and Caspase-3. After being treated with transplantation (OECs, BMSCs, and OECs and BMSCs, resp.) for 14 days and 28 days, rats were euthanized, and 5 mm lengths of spinal cord centered on T10 were rapidly removed, weighed, and frozen at -70°C until necessary for further experimentation. The tissues were resuspended and homogenized in 0.2 mL of homogenization buffer followed by centrifuge for 10 min (12,000 r/min, at 4°C). The supernatants were collected for protein determination. Protein samples (50 μg) were separated by SDS-PAGE (12% resolving gels, 5% stacking gels) and transferred to PVDF membranes (150 mA, 1.5 h) (Millipore Corporation, USA). After blocking with 5% nonfat dry milk, the membranes were incubated with different primary antibodies including anti-Bax, anti-Bcl-2 (Abcam, USA), anti-Caspase-9, anti-Caspase-3, and anti-GAPDH (Sigma, USA) overnight at 4°C . After washing membranes with TBST, the membranes were incubated with goat anti-mouse IgG-HRP conjugated secondary antibody (Sigma, USA) at a 1:1000 dilution for 1.5 h at room temperature. Finally, the proteins were identified using an enhanced chemiluminescence detection system (ECL detection kit, Pierce). The membranes were exposed to XOMat AR film (Eastman Kodak Company, USA) and the results were quantified through densitometric analysis (MAISIQI HIGH-TECH Co., Ltd, MSD-26, China). Experiments were performed in triplicate to ensure reproducibility.

2.8. Behavioral Assessment after SCI. The recovery of gross motor function was evaluated using Basso, Beattie, and Bresnahan (BBB) locomotor rating scale following the procedure described in Basso et al. [26]. The scale used for measuring hind limb function with these procedures ranges from complete paralysis (score 0) to normal gait (score 21), with an increasing score indicating the degree in use of individual joints, weight-bearing, coordinated limb movement, coordinated joint movement, and other functions. Locomotion was recorded by digital video camera at each time point and analyzed by two blind researchers.

Rats were first gently adapted to the open field for the test. After a rat had walked continuously in the open field, two investigators conducted 4-minute testing sessions on each leg. Two individuals “blinded” to rat treatment status performed the open field test at least once a week from day 1 after SCI to 4 weeks (1, 7, 8, 10, 14, 21, 28, and 35 days after SCI)

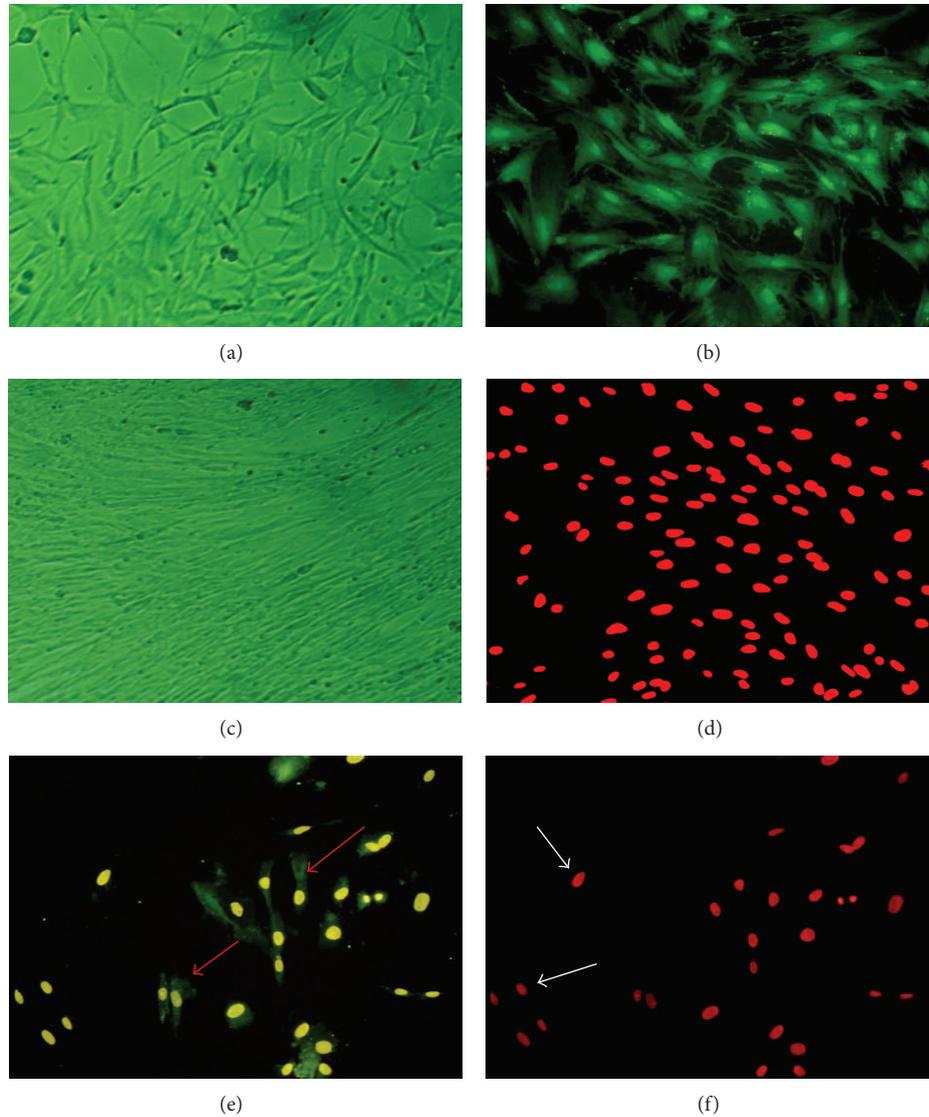


FIGURE 2: Morphological features of OECs, BMSCs, and coculture cells ($\times 200$). OECs were bipolar and multipolar, woven into a net (a). OECs were seen to express p75NTR (green, b). BMSCs were compact and the shape was like spindle (c). BrdU was found to exist in the cell core (red, d). The coculture cells, OECs were identified in the cell membrane (green, e) and cell core (yellow, e) (red arrow); BMSCs were identified in the cell core (red, f) (white arrow) and not in the cell membrane (green, f).

after laminectomy for all animals in the study. Behavioral outcomes and examples of specific BBB locomotor scores were recorded using digital video.

2.9. Statistical Analysis. Quantitative data from open field locomotor scores, detection of apoptosis, and Western blot analysis were evaluated for statistical significance by one-way Analysis of Variance (ANOVA) with replications. Data for each group were represented as mean \pm SD and compared with other groups for significance by ANOVA followed by least significant difference (LSD) test to compare the differences between groups. Results were considered statistically significant at $P < 0.05$.

3. Results

3.1. Culture and Identification of Stem Cells. Under micro-code, the OECs were bipolar or multipolar and cell protrusion became larger and longer, woven into a net on the fifth day. The OECs were identified by positive staining (green, under fluorescent microscope) with p75 antibody (Figures 2(a) and 2(b)). The BMSCs showed the shape of spindle after being cultured and became more compact and longer on the fifth day. Immunofluorescence staining with BrdU showed that the color of nucleus was red (Figures 2(c) and 2(d)). Compared with OECs or BMSCs, the coculture cells were complete adherent 24 h later, and protrusion was short. On fifth day coculture cells became more compact and showed

bipolar triode or multipolar one, but the OECs or BMSCs were small and protrusion was shorter. The cells with green cell membrane and yellow cell nuclear were OECs, and cells with red nuclear were BMSCs without green cell membrane. There was not much difference in rate of these two kinds of cells (Figures 2(e) and 2(f)).

The membrane and cell protrusion of OECs were green under fluorescence, the cells shape showed bipolar triode and multipolar model (Figures 2(a) and 2(b)). And the BMSCs shape was spindle after being cultured and became more compact and longer on the fifth day, the shape was typical of the spindle, and the growth direction was obvious. Immunofluorescence staining showed the color of nucleus was red (Figures 2(c) and 2(d)). We did the morphology observation and identification of coculture cells. Cells were complete adherent 24 h later, and protrusion was short. On fifth day cells became more compact and showed bipolar triode or multipolar model, other cells were small, and protrusion was shorter. The positive cells with green cell membrane and yellow cell nuclear were OECs, cells with red nuclear were BMSCs without green cell membrane. The rate of two kinds of cells was not different significantly (Figures 2(e) and 2(f)).

3.2. The Viability of OECs, BMSCs, and Coculture Cells. All cells showed similar growth rate. Low proliferation of the cells was found in the first two days and it was high during day 2 to day 6 after which it maintained the similar level as shown in Figure 1. But compared with the growth curve of OECs and BMSCs, the coculture cells curve was not entirely consistent (Figure 3).

3.3. The Change of Body Weight for Rats after Surgery. All the rats were recovered 2–4 hours after surgery and were able to drink and eat 6 hours after surgery. The rats' diet returned to normal after three day postsurgery. The body weight of rats in the control group significantly increased during the observation period, but the body weight of rats in the sham group, OECs treated group, BMSCs treated group, and cotransplant treated group decreased until 14 days after surgery (Table 1). The body weight of rats in the OECs treated group, BMSCs treated group, and cotransplant treated group gradually increased. A significant increase in body weight of rats was found in OECs treated group, BMSCs treated group, and cotransplant treated group compared with that in sham group 14 days and 28 days after transplantation ($P < 0.05$) (Table 1). The higher body weight of rats was found in cotransplant treated group 28 days after transplantation ($P < 0.05$) (Table 1). But the body weight of rats had not yet reached the presurgery level until the end of the observation period.

3.4. Pathology Changes in Spinal Cord Tissue. 14 and 28 days after transplantation, no abnormality was found in the control groups. Black and white matter had integrity boundaries. Cavity, liquefaction, and inflammatory cell infiltration were not seen (Figure 4(A), (a₁) $\times 100$; Figure 4(A), (a) $\times 400$; and Figure 4(B), (a₂)). There was no difference in spinal cord stained pictures between 14-day groups (Figure 4(A), (a₁)

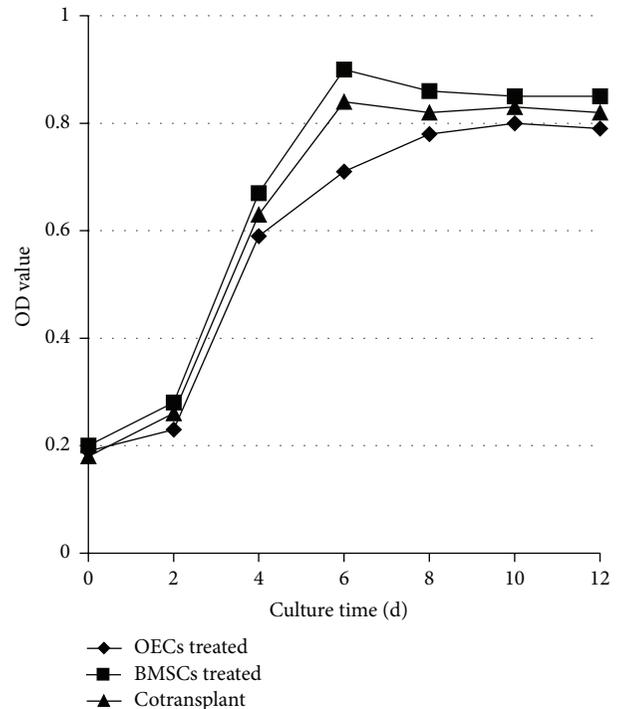


FIGURE 3: The growth curve of OECs, BMSCs, and coculture cells.

$\times 100$) and 28-day groups (Figure 4(B), (a₂) $\times 100$). After spinal cord injury, the spinal cord structure in sham groups was severely damaged. And a lot of cavities, liquefaction, and neurons atrophy could be seen; besides, nerve fibers had arrangement derangement (Figure 4(A), (b₁) $\times 100$; Figure 4(A), (b) $\times 400$; Figure 4(B), (b₂) $\times 100$). The cavity could also be found in the OECs treated group (Figure 4(A), (c₁) $\times 100$), BMSCs groups (Figure 4(A), (d₁) $\times 100$), and cotransplant groups (Figure 4(A), (e₁) $\times 100$). The number of cavities induced by spinal cord injury in these three groups was less than that in the sham group 14 days after transplantation. The cavity induced by spinal cord injury was no significant change (Figure 4(B), (b₂) $\times 100$), but there was a decrease in the number of the cavities and increase in the number of nerve cells (Figure 4(B), (c₂), (d₂), and (e₂) $\times 100$). Moreover, the most and best obvious change was in the cotransplant treated group (Figure 4(B), (e₂) $\times 100$).

3.5. Cellular Apoptosis after Spinal Cord Injury Was Reduced by Olfactory Ensheathing Cells with Bone Marrow Mesenchymal Stem Cells. We used the TUNEL method to confirm the occurrence of apoptosis in the spinal cord after SCI (Figure 5). 14 and 28 days after transplantation, TUNEL staining results of each group can be seen: TUNEL-positive cells were observed to distribute white matter in rats 14 and 28 days after transplantation. And comparison of the spinal cord cell apoptosis rate showed much difference among control group rats and those in the sham groups and OECs treated, BMSCs treated, and cotransplant treated groups 14 and 28 days after transplantation (Figure 5(C)). The higher spinal cord cell apoptosis rate in the sham group and OECs

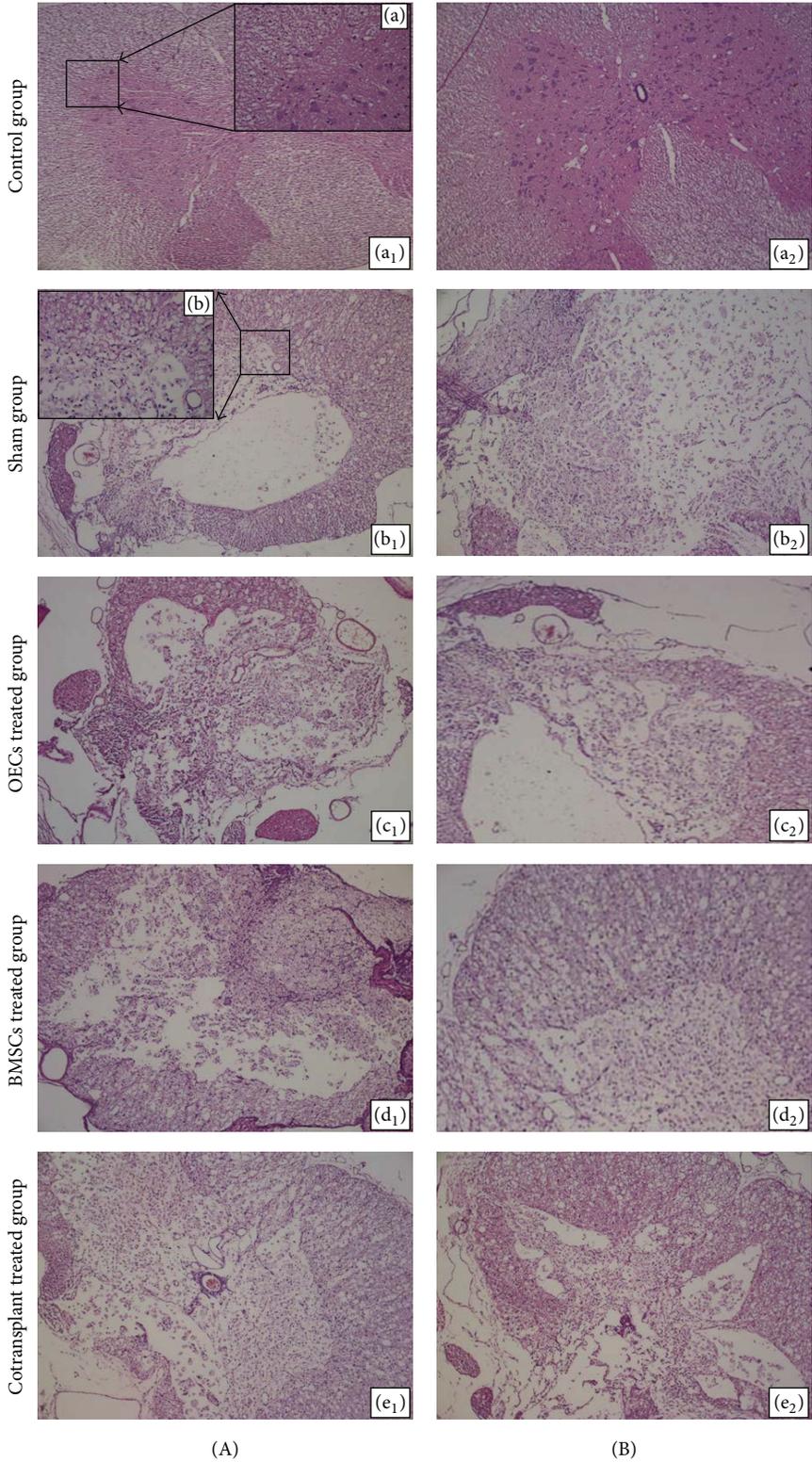


FIGURE 4: H&E staining of spinal cord tissue in each group. (A) 14 days after transplantation; (B) 28 days after transplantation: (a₁, a₂) control group; (b₁, b₂) sham group; (c₁, c₂) OECs treated group; (d₁, d₂) BMSCs treated group; (e₁, e₂) cotransplant treated group.

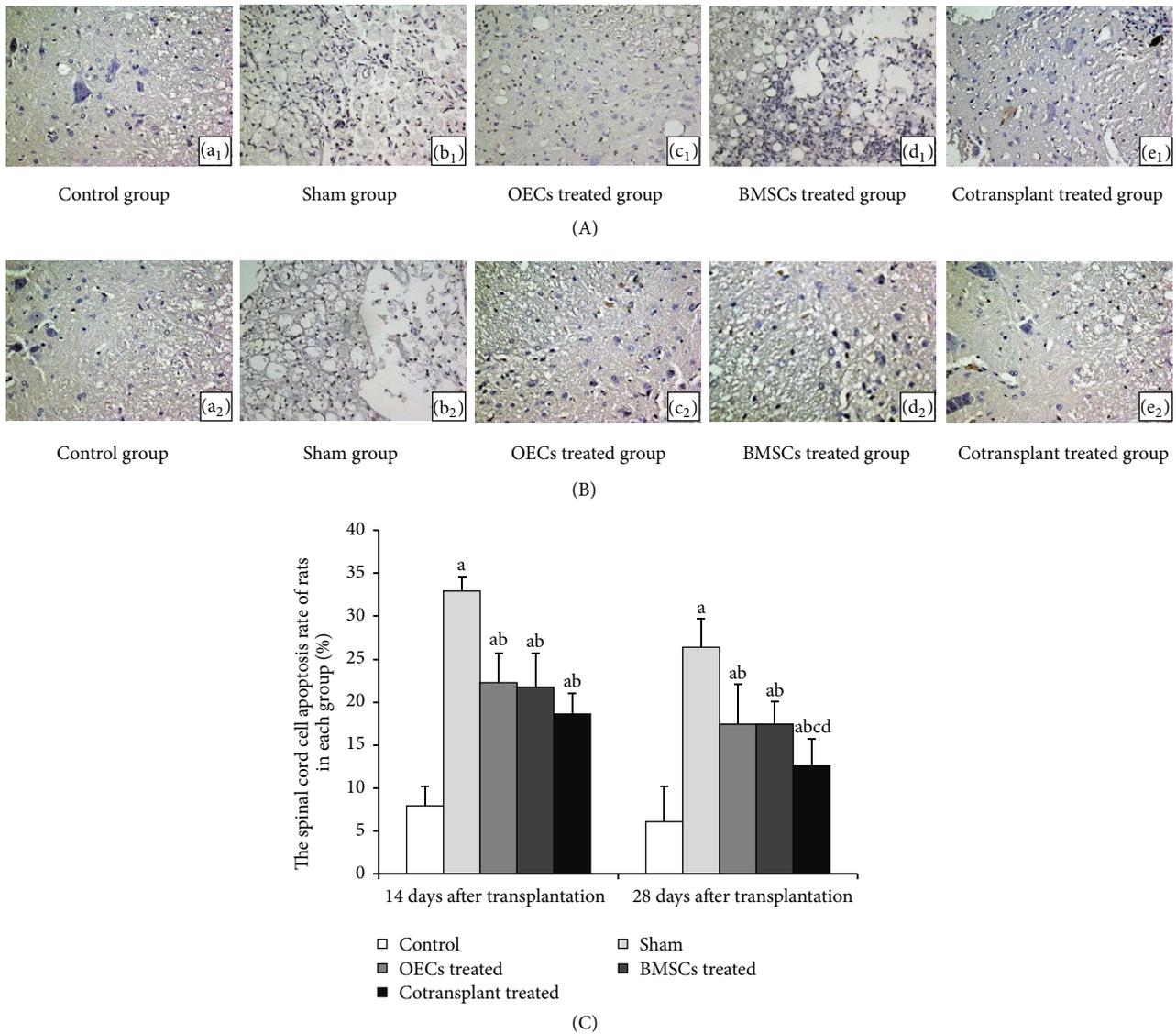


FIGURE 5: Cellular apoptosis after spinal cord injury was reduced by OECs and BMSCs (TUNEL staining, 10×40). Note: (A) 14 days after transplantation; (B) 28 days after transplantation; (a_1, a_2) control group; (b_1, b_2) sham group; (c_1, c_2) OECs treated group; (d_1, d_2) BMSCs treated group; (e_1, e_2) cotransplant treated group. (C) The spinal cord cell apoptosis rate of rats in each group. ^a $P < 0.05$ versus control group; ^b $P < 0.05$ versus sham group; ^c $P < 0.05$ versus OECs treated group; and ^d $P < 0.05$ versus BMSCs treated group.

TABLE 1: The change of body weight for rats after surgery ($g, \bar{x} \pm SD$).

Group	Control group	Sham group	OECs treated group	BMSCs treated group	Cotransplant treated group
Before surgery	263.75 \pm 10.58	264.87 \pm 12.74	259.78 \pm 12.28	263.41 \pm 13.63	262.69 \pm 16.76
1 day after surgery	262.35 \pm 16.53	262.34 \pm 13.44	258.85 \pm 11.76	261.07 \pm 18.23	260.98 \pm 12.06
7 days after surgery	267.74 \pm 14.39	212.38 \pm 15.50 ^a	215.67 \pm 14.57 ^a	220.58 \pm 12.05 ^a	216.10 \pm 15.30 ^a
7 days after transplantation	274.31 \pm 11.97	211.66 \pm 12.19 ^a	212.83 \pm 12.49 ^a	213.18 \pm 14.72 ^a	213.37 \pm 13.75 ^a
14 days after transplantation	286.31 \pm 12.25	213.62 \pm 10.08 ^a	224.65 \pm 13.28 ^{ab}	227.72 \pm 11.05 ^{ab}	229.15 \pm 10.63 ^{ab}
28 days after transplantation	314.67 \pm 15.84	214.11 \pm 17.41 ^a	235.67 \pm 10.50 ^{ab}	239.58 \pm 12.70 ^{ab}	249.10 \pm 10.96 ^{abcd}

^a $P < 0.05$ versus control group; ^b $P < 0.05$ versus sham group; ^c $P < 0.05$ versus OECs treated group; and ^d $P < 0.05$ versus BMSCs treated group.

TABLE 2: BBB scores of rats with SCI before transplantation at 1 day and 7 days after SCI ($\bar{x} \pm SD$).

Group	Control	Sham	OECs treated	BMSCs treated	Cotransplant treated
Before surgery	21	21	21	21	21
1 day after surgery	21	0	0	0	0
7 days after surgery	21	4.47 \pm 0.35 ^a	4.71 \pm 0.63 ^a	4.53 \pm 0.56 ^a	4.68 \pm 0.45 ^a

^a $P < 0.05$ versus control group.

treated, BMSCs treated, and cotransplant treated groups was observed compared with the control group 14 days after transplantation ($P < 0.05$) (Figures 5(A) and 5(C)). The spinal cord cell apoptosis rate in the OECs treated, BMSCs treated, and cotransplant treated groups was significantly lower compared with that in the sham groups ($P < 0.05$) (Figures 5(A) and 5(C)). We also found that the spinal cord cell apoptosis rate in cotransplant treated group was lower than that in the OECs treated and BMSCs treated groups 28 days after transplantation ($P < 0.05$) (Figures 5(B) and 5(C)). The spinal cord cell apoptosis rate in the sham groups, the OECs treated group, BMSCs treated group, and cotransplant treated group had declined, but the higher spinal cord cell apoptosis rate was observed in sham groups compared with the control group, the OECs treated group, BMSCs treated group, and cotransplant treated group 28 days after transplantation ($P < 0.05$) (Figures 5(B) and 5(C)). Based on these results, we are convinced that the cotransplantation of OECs with BMSCs exerts antiapoptotic effects in adult rats after SCI.

3.6. Expressions of Bax, Bcl-2, Caspase-9, and Caspase-3 in Spinal Cord of Rats Transplanted with Olfactory Ensheathing Cells with Bone Marrow Mesenchymal Stem Cells 14 and 28 Days after Transplantation. Figure 6 showed that the expressions of Caspase-9 and Caspase-3 proteins were significantly upregulated and Bcl-2 proteins were significantly downregulated ($P < 0.05$) (Figures 6(c), 6(d), and 6(e)). 14 and 28 days after transplantation, the levels of Caspase-9 and Caspase-3 proteins decreased significantly and Bcl-2 protein increased significantly in the OECs treated groups, BMSCs treated groups, and cotransplant treated groups ($P < 0.05$) (Figures 6(c), 6(d), and 6(e)). The expressions of Caspase-9 and Caspase-3 decreased in cotransplant treated groups were significantly lower than those in OECs treated groups and BMSCs treated groups 28 days after transplantation ($P < 0.05$) (Figures 6(d) and 6(e)). Meanwhile, Caspase-9 and Caspase-3 decreased in cotransplant treated groups, with no significant difference when compared with control groups 28 days after transplantation ($P > 0.05$) (Figures 6(d) and 6(e)). There was higher expression of Bcl-2 protein in cotransplant treated groups 28 days after transplantation ($P < 0.05$) (Figure 6(c)), whereas Bax had little change in each group (Figure 6(b)).

3.7. Recovery of Locomotor Function of Rats Cotransplanted with Olfactory Ensheathing Cells with Bone Marrow Mesenchymal Stem Cells. Finally, we tested whether inhibition of apoptotic by OECs and MSCs can be correlated with

the functional recovery of rats. BBB scores at all time points after transplantation for the cotransplant treated, OECs treated, and BMSCs treated groups and control groups are shown in Tables 2 and 3, which showed that the mean BBB score decreased significantly in the treatment groups compared to that in control groups before transplantation ($P < 0.05$). Recovery of function occurred slowly but steadily over the course of the 14-day observation period in the OECs treated group, BMSCs treated group, and cotransplant treated group. Rats in the transplanted groups showed a significant improvement in the BBB scale relative to the sham injured control group 14, 21, and 28 days after transplantation ($P < 0.05$) (Table 3). The BBB scale in cotransplant treated group increased significantly compared to that in OECs treated group and BMSCs treated group 21 and 28 days after transplantation ($P < 0.05$) (Table 3).

4. Discussion

Transplantation of OECs and BMSCs has been demonstrated as being experimentally promising for therapy of SCI [27–30]. However, clinical application may be constrained by the margin neuronal differentiation capacity of BMSC as well as the limited number of isolatable OECs. To take advantage but obviate the limitations of OECs and BMSCs, the cotransplantation of the two major types of cells has been suggested as therapeutic for SCI. In this study, we successfully coculture the two types of cells *in vitro*. There was no morphological change in cell. We verified the cells immunofluorescence and measured the viability of the individual and cocultured cells. BMSCs showed rapid proliferation with more pronounced increase in the number of cells, while the OECs have low growth rate, with nonsignificant increase in cell number during the culture period. There is a need to ensure that the number of each cell to avoid the imbalance in the proportion of cells in the coculture system.

Consistent with several previous studies [31–33], in this study we demonstrated that transplantation of either of OECs or BMSCs alone is able to promote functional recovery of rats after SCI. Interestingly, the cotransplantation of OECs and BMSCs has been shown to be the most effective in comparison with that of OECs or BMSCs alone, which suggested that the two cell types may interact in a synergistic way to improve the functional recovery of SCI. Deng et al. [34] demonstrated that the cotransplant group was found to have significantly better improvement of gait scaling compared with all other groups after 2 weeks of transplantation. The BMSC group was shown to have higher BBB scores than the OEC group, which is consistent with our findings. Furthermore, the cotransplant

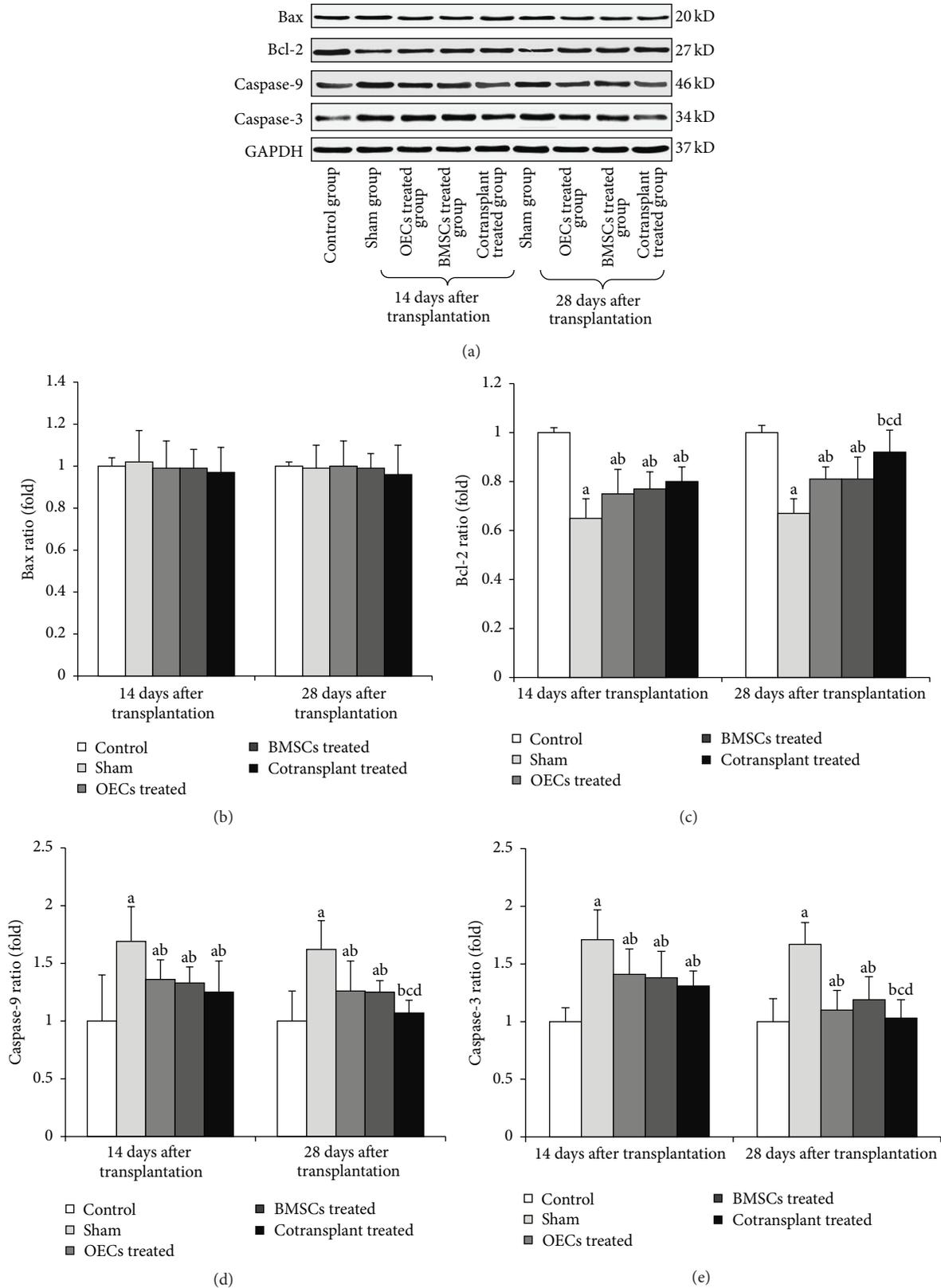


FIGURE 6: The expression on Bax, Bcl-2, Caspase-9, Caspase-3, and GAPDH protein in spinal cord 14 days and 28 days after transplantation. (a) Western blot analysis of Bax, Bcl-2, Caspase-9, Caspase-3, and GAPDH proteins of spinal cord. (b) Relative ratio of Bax protein. (c) Relative ratio of Bcl-2 protein. (d) Relative ratio of Caspase-9 protein. (e) Relative ratio of Caspase-3 protein. ^a*P* < 0.05 versus control group; ^b*P* < 0.05 versus sham group; ^c*P* < 0.05 versus OECs treated group; and ^d*P* < 0.05 versus BMSCs treated group.

TABLE 3: BBB scores of rats with SCI after OECs and BMSCs transplantation treatments ($\bar{x} \pm SD$).

Group	Control	Sham	OECs treated	BMSCs treated	Cotransplant treated
1 day after transplantation	21	5.07 ± 0.67 ^a	5.19 ± 0.98 ^a	5.20 ± 0.54 ^a	5.38 ± 0.69 ^a
3 days after transplantation	21	5.26 ± 0.82 ^a	5.83 ± 1.05 ^a	5.89 ± 0.91 ^a	6.48 ± 0.90 ^a
7 days after transplantation	21	5.73 ± 0.90 ^a	6.49 ± 0.93 ^a	6.74 ± 1.03 ^a	6.95 ± 1.20 ^a
14 days after transplantation	21	5.88 ± 1.05 ^a	8.87 ± 1.56 ^{ab}	9.31 ± 1.26 ^{ab}	10.96 ± 1.73 ^{ab}
21 days after transplantation	21	6.19 ± 0.97 ^a	10.81 ± 2.00 ^{ab}	11.23 ± 1.87 ^{ab}	13.23 ± 2.22 ^{abcd}
28 days after transplantation	21	6.56 ± 1.22 ^{ab}	12.98 ± 2.11 ^{ab}	13.09 ± 2.01 ^{ab}	15.16 ± 2.31 ^{abcd}

^a $P < 0.05$ versus control group; ^b $P < 0.05$ versus sham group; ^c $P < 0.05$ versus OECs treated group; and ^d $P < 0.05$ versus BMSCs treated group.

of OECs and BMSCs had the most effective change compared with that of OECs and BMSCs alone. In this regard, the cograf of mixed cell types with complementary properties may provide a novel approach for cell transplantation in SCI and even other tissue types.

Recently, much attention has been paid to secondary cord injury since this appears to be susceptible for therapeutic intervention. Apoptosis and inflammatory responses and some other neurological toxicity events may signify the secondary injury after primary insult in the spinal cord [1, 35]. Therefore, this study attempted to test the possible synergistic effects of the two cells for antiapoptotic effects after cotransplantation in rat SCI models. We found decreased apoptosis in rats from group of cotransplantation of OECs and BMSCs from apoptosis study using TUNEL assay which showed. The spinal cord cell apoptosis rate in the OECs treated, BMSCs treated, and cotransplant treated groups was significantly lower compared with that in the sham groups. Importantly, the spinal cord cell apoptosis rate in cotransplant treated group was lower than that in the OECs treated and BMSCs treated groups 28 days after transplantation. Interestingly, we also found that death of injured spinal cord cells in white matter following spinal cord injury involves the regulations processing of Bax, Bcl-2, Caspase-9, and Caspase-3, thus contributing probably to the apoptotic death of cells in the spinal cord. Increased activity of the Caspase family of proteases is associated with apoptosis during which Caspase-3 plays a crucial role in SCI-mediated apoptotic cell death in the white matter [14, 36].

To investigate mechanisms underlying suppression of apoptosis after cotransplantation of OECs and BMSCs after SCI, we also detected the Bax, Bcl-2, Caspase-9, and Caspase-3 expression in apoptosis by Western blot. The results demonstrated that the expression of Caspase-9 and Caspase-3 and the ratio of Bax/Bcl-2 were significantly decreased in the cotransplant treated group compared with those in the sham groups. However, the expression of Bax had little change in each group. Therefore, we speculated that downregulation of Bcl-2 and consequently the higher ratio of Bax/Bcl-2 may be directly associated with the release of Caspase-9 and Caspase-3, and then the latter finally resulted in apoptosis after SCI. The cotransplantation of OECs with BMSCs exerts antiapoptotic effects in adult rats after spinal cord injury by inhibiting downregulation of Bcl-2 expression. Consequently, the decrease in the ratio of Bax/Bcl-2 results

in the suppression of Caspase-9 and Caspase-3, leading to a decrease in the number of apoptotic cells in the cotransplant treated group. These findings further confirmed that OECs and BMSCs appear to show the neuroprotective effects to attenuate apoptotic processes by inhibiting the expression of the mitochondria-associated intrinsic pathway related proteins during secondary damage of SCI.

In this study, we found that transplantation of OECs, BMSCs, and cotransplantation of OECs with BMSCs can significantly recover functional activities of rats after two weeks of transplantation. Importantly, we found that there was significant functional recovery, improvement in the number of intact axons across the injury site, and a decrease in white matter loss in cotransplant treated group compared to that in OECs treated group and BMSCs treated group 21 and 28 days after transplantation. The finding of the locomotor recovery in treated rats suggests that the mitochondria-associated intrinsic pathway provides a potential therapeutic target in the treatment of SCI. Our study further confirmed the previous studies [37–41] indicating that stem cells could migrate and accumulate in the injured areas, differentiate into neural cells, and improve the functional recovery of these animals.

5. Conclusion

In conclusion, cotransplantation of OECs and BMSCs could migrate into injured spinal cord tissue and repair SCI and then contribute to the functional restoration by inhibiting the expression of the mitochondria-associated intrinsic pathway related proteins. While we observed that OECs and BMSCs could migrate successfully into the damaged spinal cord and repair SCI by reducing apoptosis, this repair effect was only observed until 14 days after transplantation. Although the apoptotic pathways that are involved require verification, we have laid sufficient foundation for further study of SCI treatments with OECs and BMSCs. However, successful development of OECs and BMSCs therapy for spinal cord injury will require a better understanding of the intrinsic properties of these stem cells, the microenvironment, host-graft interactions, and subsequently greater functional improvements. Ongoing behavioral and biochemical assessments of the long-term positive effects of OECs and BMSCs will provide further insight regarding the therapeutic potential of these stem cells for SCI.

Disclaimer

The authors alone are responsible for the content and writing of the paper.

Conflict of Interests

The authors declare that there is no conflict of interests.

Acknowledgments

The authors thank the financial support from the National Natural Science Foundation of China (81470145) and Science and Technology Development Plan Project of Shandong Province (2012G0030034).

References

- [1] V. R. Dasari, D. G. Spomar, C. Cady, M. Gujrati, J. S. Rao, and D. H. Dinh, "Mesenchymal stem cells from rat bone marrow downregulate caspase-3-mediated apoptotic pathway after spinal cord injury in rats," *Neurochemical Research*, vol. 32, no. 12, pp. 2080–2093, 2007.
- [2] A. Torres-Espín, E. Redondo-Castro, J. Hernández, and X. Navarro, "Bone marrow mesenchymal stromal cells and olfactory ensheathing cells transplantation after spinal cord injury—a morphological and functional comparison in rats," *European Journal of Neuroscience*, vol. 39, no. 10, pp. 1704–1717, 2014.
- [3] A. J. Mothe and C. H. Tator, "Advances in stem cell therapy for spinal cord injury," *Journal of Clinical Investigation*, vol. 122, no. 11, pp. 3824–3834, 2012.
- [4] J. D. Kocsis, K. L. Lankford, M. Sasaki, and C. Radtke, "Unique in vivo properties of olfactory ensheathing cells that may contribute to neural repair and protection following spinal cord injury," *Neuroscience Letters*, vol. 456, no. 3, pp. 137–142, 2009.
- [5] C. L. Beites, S. Kawauchi, C. E. Crocker, and A. L. Calof, "Identification and molecular regulation of neural stem cells in the olfactory epithelium," *Experimental Cell Research*, vol. 306, no. 2, pp. 309–316, 2005.
- [6] C. T. Marshall, C. Lu, W. Winstead et al., "The therapeutic potential of human olfactory-derived stem cells," *Histology and Histopathology*, vol. 21, no. 4–6, pp. 633–643, 2006.
- [7] R. López-Vales, J. Forés, E. Verdú, and X. Navarro, "Acute and delayed transplantation of olfactory ensheathing cells promote partial recovery after complete transection of the spinal cord," *Neurobiology of Disease*, vol. 21, no. 1, pp. 57–68, 2006.
- [8] M. I. Chuah, D. M. Hale, and A. K. West, "Interaction of olfactory ensheathing cells with other cell types *in vitro* and after transplantation: glial scars and inflammation," *Experimental Neurology*, vol. 229, no. 1, pp. 46–53, 2011.
- [9] A. Torres-Espín, J. Hernández, and X. Navarro, "Gene expression changes in the injured spinal cord following transplantation of mesenchymal stem cells or olfactory ensheathing cells," *PLoS ONE*, vol. 8, no. 10, Article ID e76141, 2013.
- [10] J. C. Stamegna, M. S. Felix, J. Roux-Peyronnet et al., "Nasal OEC transplantation promotes respiratory recovery in a subchronic rat model of cervical spinal cord contusion," *Experimental Neurology*, vol. 229, no. 1, pp. 120–131, 2011.
- [11] M. Boido, D. Garbossa, M. Fontanella, A. Ducati, and A. Vercelli, "Mesenchymal stem cell transplantation reduces glial cyst and improves functional outcome after spinal cord compression," *World Neurosurgery*, vol. 81, no. 1, pp. 183–190, 2014.
- [12] R. Quertainmont, D. Cantinieaux, O. Botman, S. Sid, J. Schoenen, and R. Franzen, "Mesenchymal stem cell graft improves recovery after spinal cord injury in adult rats through neurotrophic and pro-angiogenic actions," *PLoS ONE*, vol. 7, no. 6, Article ID e39500, 2012.
- [13] M. Koda, T. Kamada, M. Hashimoto et al., "Adenovirus vector-mediated ex vivo gene transfer of brain-derived neurotrophic factor to bone marrow stromal cells promotes axonal regeneration after transplantation in completely transected adult rat spinal cord," *European Spine Journal*, vol. 16, no. 12, pp. 2206–2214, 2007.
- [14] J. E. Springer, R. D. Azbill, and P. E. Knapp, "Activation of the caspase-3 apoptotic cascade in traumatic spinal cord injury," *Nature Medicine*, vol. 5, no. 8, pp. 943–946, 1999.
- [15] P. Warden, N. I. Bamber, H. Li et al., "Delayed glial cell death following wallerian degeneration in white matter tracts after spinal cord dorsal column cordotomy in adult rats," *Experimental Neurology*, vol. 168, no. 2, pp. 213–224, 2001.
- [16] S. M. Lee, T. Y. Yune, S. J. Kim et al., "Minocycline reduces cell death and improves functional recovery after traumatic spinal cord injury in the rat," *Journal of Neurotrauma*, vol. 20, no. 10, pp. 1017–1027, 2003.
- [17] S. A. Nottingham and J. E. Springer, "Temporal and spatial distribution of activated caspase-3 after subdural kainic acid infusions in rat spinal cord," *Journal of Comparative Neurology*, vol. 464, no. 4, pp. 463–471, 2003.
- [18] S. Casha, W. R. Yu, and M. G. Fehlings, "Oligodendroglial apoptosis occurs along degenerating axons and is associated with FAS and p75 expression following spinal cord injury in the rat," *Neuroscience*, vol. 103, no. 1, pp. 203–218, 2001.
- [19] Y. Wang, Z. Sun, K. Zhang, G. Xu, and G. Li, "Bcl-2 in suppressing neuronal apoptosis after spinal cord injury," *World Journal of Emergency Medicine*, vol. 2, no. 1, pp. 38–44, 2011.
- [20] R. R. Kotipatruni, V. R. Dasari, K. K. Veeravalli, D. H. Dinh, D. Fassett, and J. S. Rao, "P53- and bax-mediated apoptosis in injured rat spinal cord," *Neurochemical Research*, vol. 36, no. 11, pp. 2063–2074, 2011.
- [21] J. K. Lee, H. K. Jin, and J.-S. Bae, "Bone marrow-derived mesenchymal stem cells attenuate amyloid β -induced memory impairment and apoptosis by inhibiting neuronal cell death," *Current Alzheimer Research*, vol. 7, no. 6, pp. 540–548, 2010.
- [22] F. Yin, L. Guo, C.-Y. Meng et al., "Transplantation of mesenchymal stem cells exerts anti-apoptotic effects in adult rats after spinal cord ischemia-reperfusion injury," *Brain Research*, vol. 1561, pp. 1–10, 2014.
- [23] B. Wang, X.-J. He, Q. Li, H.-P. Li, and D. Wang, "In vitro culture of human fetal olfactory bulb olfactory ensheathing cells by three purification methods," *Journal of Clinical Rehabilitative Tissue Engineering Research*, vol. 12, no. 16, pp. 3089–3091, 2008.
- [24] H. H. Nash, R. C. Borke, and J. J. Anders, "New method of purification for establishing primary cultures of ensheathing cells from the adult olfactory bulb," *Glia*, vol. 34, no. 2, pp. 81–87, 2001.
- [25] W. Qian, Y. Na, J. Yufeng et al., "Culture and biologic characteristics identification of bone marrow stromal cells in rats," *Progress in Modern Biomedicine*, vol. 10, no. 8, pp. 1473–1476, 2010.
- [26] D. M. Basso, M. S. Beattie, and J. C. Bresnahan, "A sensitive and reliable locomotor rating scale for open field testing in rats," *Journal of Neurotrauma*, vol. 12, no. 1, pp. 1–21, 1995.

- [27] E. Syková, P. Jendelová, L. Urdžiková, P. Lesný, and A. Hejčl, "Bone marrow stem cells and polymer hydrogels—two strategies for spinal cord injury repair," *Cellular and Molecular Neurobiology*, vol. 26, no. 7-8, pp. 1113–1129, 2006.
- [28] V. Sahni and J. A. Kessler, "Stem cell therapies for spinal cord injury," *Nature Reviews Neurology*, vol. 6, no. 7, pp. 363–372, 2010.
- [29] J. Hernández, A. Torres-Espín, and X. Navarro, "Adult stem cell transplants for spinal cord injury repair: current state in preclinical research," *Current Stem Cell Research and Therapy*, vol. 6, no. 3, pp. 273–287, 2011.
- [30] A. J. Mothe and C. H. Tator, "Advances in stem cell therapy for spinal cord injury," *The Journal of Clinical Investigation*, vol. 122, no. 11, pp. 3824–3834, 2012.
- [31] D. P. Ankeny, D. M. McTigue, and L. B. Jakeman, "Bone marrow transplants provide tissue protection and directional guidance for axons after contusive spinal cord injury in rats," *Experimental Neurology*, vol. 190, no. 1, pp. 17–31, 2004.
- [32] J. Lee, S. Kuroda, H. Shichinohe et al., "Migration and differentiation of nuclear fluorescence-labeled bone marrow stromal cells after transplantation into cerebral infarct and spinal cord injury in mice," *Neuropathology*, vol. 23, no. 3, pp. 169–180, 2003.
- [33] Y.-B. Deng, X.-G. Liu, Z.-G. Liu, X.-L. Liu, Y. Liu, and G.-Q. Zhou, "Implantation of BM mesenchymal stem cells into injured spinal cord elicits de novo neurogenesis and functional recovery: evidence from a study in rhesus monkeys," *Cytherapy*, vol. 8, no. 3, pp. 210–214, 2006.
- [34] Y. B. Deng, Y. Liu, W. B. Zhu et al., "The co-transplantation of human bone marrow stromal cells and embryo olfactory ensheathing cells as a new approach to treat spinal cord injury in a rat model," *Cytherapy*, vol. 10, no. 6, pp. 551–564, 2008.
- [35] G. L. Li, G. Brodin, M. Farooque et al., "Apoptosis and expression of Bcl-2 after compression trauma to rat spinal cord," *Journal of Neuropathology and Experimental Neurology*, vol. 55, no. 3, pp. 280–289, 1996.
- [36] B. A. Citron, P. M. Arnold, C. Sebastian et al., "Rapid upregulation of caspase-3 in rat spinal cord after injury: mRNA, protein, and cellular localization correlates with apoptotic cell death," *Experimental Neurology*, vol. 166, no. 2, pp. 213–226, 2000.
- [37] S.-U. Kuh, Y.-E. Cho, D.-H. Yoon, K.-N. Kim, and Y. Ha, "Functional recovery after human umbilical cord blood cells transplantation with brain-derived neurotrophic factor into the spinal cord injured rat," *Acta Neurochirurgica*, vol. 147, no. 9, pp. 985–992, 2005.
- [38] S. Liu, Y. Qu, T. J. Stewart et al., "Embryonic stem cells differentiate into oligodendrocytes and myelinate in culture and after spinal cord transplantation," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 97, no. 11, pp. 6126–6131, 2000.
- [39] P. Lu, L. L. Jones, and M. H. Tuszynski, "BDNF-expressing marrow stromal cells support extensive axonal growth at sites of spinal cord injury," *Experimental Neurology*, vol. 191, no. 2, pp. 344–360, 2005.
- [40] P. Lu, L. L. Jones, E. Y. Snyder, and M. H. Tuszynski, "Neural stem cells constitutively secrete neurotrophic factors and promote extensive host axonal growth after spinal cord injury," *Experimental Neurology*, vol. 181, no. 2, pp. 115–129, 2003.
- [41] S. Saporta, J.-J. Kim, A. E. Willing, E. S. Fu, C. D. Davis, and P. R. Sanberg, "Human umbilical cord blood stem cells infusion in spinal cord injury: engraftment and beneficial influence on behavior," *Journal of Hematotherapy and Stem Cell Research*, vol. 12, no. 3, pp. 271–278, 2003.