Intrapulmonary Delivery of Bone Marrow-Derived Mesenchymal Stem Cells Improves Survival and Attenuates Endotoxin-Induced Acute Lung Injury in Mice

Naveen Gupta, Xiao Su, Boris Popov, Jae Woo Lee, Vladimir Serikov and Michael A. Matthay

*J Immunol* 2007; 179:1855-1863; doi: 10.4049/jimmunol.179.3.1855

http://www.jimmunol.org/content/179/3/1855

References

This article cites 35 articles, 14 of which you can access for free at: http://www.jimmunol.org/content/179/3/1855.full#ref-list-1

Subscription

Information about subscribing to *The Journal of Immunology* is online at: http://jimmunol.org/subscription

Permissions

Submit copyright permission requests at: http://www.aai.org/About/Publications/JI/copyright.html

Email Alerts

Receive free email-alerts when new articles cite this article. Sign up at: http://jimmunol.org/alerts
Intrapulmonary Delivery of Bone Marrow-Derived Mesenchymal Stem Cells Improves Survival and Attenuates Endotoxin-Induced Acute Lung Injury in Mice

Naveen Gupta,2* Xiao Su,† Boris Popov, † Jae Woo Lee,* Vladimir Serikov, † and Michael A. Matthay* 

Recent in vivo and in vitro work suggests that mesenchymal stem cells (MSC) have anti-inflammatory properties. In this study, we tested the effect of administering MSC directly into the airspaces of the lung 4 h after the intrapulmonary administration of Escherichia coli endotoxin (5 mg/kg). MSC increased survival compared with PBS-treated control mice at 48 h (80 vs 42%; p < 0.01). There was also a significant decrease in excess lung water, a measure of pulmonary edema (145 ± 50 vs 87 ± 20 μl; p < 0.01), and bronchoalveolar lavage protein, a measure of endothelial and alveolar epithelial permeability (3.1 ± 0.4 vs 2.2 ± 0.8 mg/ml; p < 0.01), in the MSC-treated mice. These protective effects were not replicated by the use of further controls including fibroblasts and apoptotic MSC. The beneficial effect of MSC was independent of the ability of the cells to engraft in the lung and was not related to clearance of the endotoxin by the MSC. MSC administration mediated a down-regulation of proinflammatory responses to endotoxin (reducing TNF-α and MIP-2 in the bronchoalveolar lavage and plasma) while increasing the anti-inflammatory cytokine IL-10. In vitro coculture studies of MSC with alveolar macrophages provided evidence that the anti-inflammatory effect was paracrine and was not cell contact dependent. In conclusion, treatment with intrapulmonary MSC markedly decreases the severity of endotoxin-induced acute lung injury and improves survival in mice. The Journal of Immunology, 2007, 179: 1855–1863.
instilled i.t. 4 h after the instillation of endotoxin as additional controls (750,000 cells in 30 μl of PBS). MSC were made nonviable by incubating with an apoptosis induction kit containing cycloheximide, actinomycin-D, camptothecin, etoposide, and dexamethasone for 24 h in culture (Chemi-con). Cells were then stained with 0.4% trypan blue to ascertain viability. Mice were then similarly recovered in a 100% oxygen chamber, and were subsequently followed for 24–72 h. Survival in each group was noted as well as body temperature and activity in the two groups. At the end of either 24 or 48 h, samples were collected from each mouse for assessment of lung injury, biochemical analysis, and histology.

Mouse MSC cultures

MSC cultures were obtained from GFP<sup>+</sup>-C57BL/6 mice. Bone marrow was obtained by flushing the tibias and femurs using 1 ml of growth medium (GM)-DMEM with 25 mM HEPES and 10% FBS (Invitrogen Life Technologies). The cells were washed, counted with trypan blue for evaluation of viability, and resuspended in GM to a density of 5 × 10⁶/ml. The resuspended cells were cultured immediately at a density of 2 × 10⁶/ml in a humidified 5% CO₂ incubator at 37°C. After 72 h of cultivation, the nonadherent cells were removed from the culture by changing the medium. Adherent cells were then subsequently propagated in culture with IMDM containing 10% FBS, 10% horse serum, 1% l-glutamine, and 1% penicillin-streptomycin. Cells were passaged every 3–4 days by trypsinization and were used for in vivo experiments after 15–25 passages.

**Differentiation assays**

MSC from 20 to 25 passages were cultured at an initial concentration of 2 × 10⁴/ml in GM in dishes containing sterile cover glasses. Adipogenic differentiation was induced by seeding the MSC for 21 days in GM supplemented with 10⁻⁶ M dexamethasone (Sigma-Aldrich) and 5 μg/ml insulin (Sigma-Aldrich). The cells containing drops of fat were identified by staining the culture with 3.75% Oil Red. Osteogenic differentiation was induced by cultivation of the MSC in GM containing 10 mM β-glycerol phosphate, 50 μg/ml ascorbic acid, and 10⁻⁸ M dexamethasone for 21 days. The calcium containing precipitates were visualized after staining with 2% Alizarin Red S (Sigma-Aldrich) adjusted to a pH of 4.2 with ammonium hydroxide. Myogenic differentiation was induced by culturing MSC for 14 days in GM containing 1.5 μg/ml amphotericin B, and then for 1 wk in the medium without amphotericin. The cells were then fixed for 10 min in 4% paraformaldehyde and in 70% ethanol overnight at 4°C followed by evaluation of expression of the early (desmin) and late (myosin H chain) markers of muscle differentiation by immunohistochemistry with D3 and MF20 mAbs (Developmental Studies Hybridoma Bank, University of Iowa, Iowa City, IA).

**Flow cytometry**

Flow cytometry for expression of a panel of surface markers was done using a BD Biosciences FACS machine using standard techniques. MSC were harvested by trypsinization, washed in PBS, and stained by PE- or allophycocyanin-labeled Abs to CD11b, CD31, CD34, and CD45. This analysis was done at passages 15–25, concurrent with the time MSC were used in the in vivo model of ALI.

**Intrapulmonary delivery of instillate**

The details of this method have been previously published by our group (16). Briefly, mice were anesthetized with ketamine and xylazine, and then fixed at a 60° angle. A fiber optic light source was placed immediately over the neck, and the oropharynx was opened with forceps, allowing for the visualization of the trachea. The instillate (endotoxin, PBS, MSC, fibroblasts, or nonviable MSC) was then injected into the trachea using a PE-10 catheter attached to a 0.5-ml syringe.

**Excess lung water/lung wet-to-dry ratio**

Gravimetric lung water determination was done as follows: the whole lung was excised, weighed, and then homogenized after the addition of 1 ml of double distilled H₂O. The homogenate was centrifuged at 12,000 rpm for 10 min to obtain the supernatant, which was weighed; the hemoglobin of the supernatant was also measured. A blood sample was obtained by needle puncture of the right ventricle, and the wet weight, hemoglobin, and hematocrit of the blood sample was obtained. All samples were placed in a drying oven at 55°C for 24 h, and the dry weights were subsequently determined. The final excess lung water and lung wet-to-dry ratio were calculated as described in our previous publications (17–19).

**Bronchoalveolar lavage (BAL) and plasma cytokine and protein measurements**

BAL and plasma samples were obtained from mice at 24 and 48 h after endotoxin-induced lung injury in the MSC, fibroblast, apoptotic MSC, and PBS-treated groups. BAL was done after euthanizing the mice and then
for Bn groups (B, Excess lung water was not reduced in the control cell permeability, by the Bio-Rad protein assay kit. fluid from all experimental groups, as a marker of endothelial and epithelial assay (LINCO Diagnostic Services). Protein was measured in the BAL PBS-treated mice were also collected at 8 and 24 h for analysis by luminex ELISA kit (R&D Systems). BAL and plasma samples from MSC- and to be produced by MSC, was measured in selected BAL samples with an Triton X-100 in PBS for 5 min, and then washed with PBS twice again. deparaffinized, washed with PBS, postfixed with ethanol, exposed to 0.2% field, 1; injury to 50% of the field, 2; injury to 75% of the field, 3; diffuse injury, 4 (20). For immunohistochemistry, slides with lung sections were embedded in paraffin, cut into 5- cm of H2O pressure (n = 3 per group per time point). After fixation, lungs were embedded in paraffin, cut into 5-μm sections, and stained with H&E. The degree of hemorrhage and edema was scored in six sections from the lower lobes using the following criteria: no injury, 0; injury to 25% of the field, 1; injury to 50% of the field, 2; injury to 75% of the field, 3; diffuse injury, 4 (20). For immunohistochemistry, slides with lung sections were deparaffinized, washed with PBS, postfixed with ethanol, exposed to 0.2% Triton X-100 in PBS for 5 min, and then washed with PBS twice again. Slides were further blocked with 3% goat serum, 2% horse serum, 3% BSA/0.1% Tween 20 in 4× SSC for 20 min. A primary Ab to GFP (Sigma-Aldrich; in 2× SSC/1% BSA/0.1% Tween 20) was added for 1 h at 37°C at a 1/100 dilution. Slides were washed three times with PBS and then blocked with 3% BSA/0.1% Tween 20 in 4× SSC for 20 min. A FITC-conjugated secondary Ab (in 2× SSC/1% BSA/0.1% Tween 20) was added for 1 h at 37°C. Control slides were stained with isotype Ab. Slides were washed three times with PBS, mounted on glass slides in Fluoro-Guard antifade reagent (Bio-Rad), and coverslips applied. Laser confocal fluorescence microscopy (Axiovert 100, LSM 510; Zeiss) was performed. Histology and immunohistochemistry Lungs from both MSC and PBS groups were excised 24 and 48 h after endotoxin-induced lung injury and fixed with 100% ethanol i.t. under 20 cm of H2O pressure (n = 3 per group per time point). After fixation, lungs were embedded in paraffin, cut into 5-μm sections, and stained with H&E. The level of PGE2, a lipid mediator known to be produced by MSC, was measured in selected BAL samples with an ELISA kit (R&D Systems). BAL and plasma samples from MSC- and PBS-treated mice were also collected at 8 and 24 h for analysis by luminex assay (LINCO Diagnostic Services). Protein was measured in the BAL fluid from all experimental groups, as a marker of endothelial and epithelial permeability, by the Bio-Rad protein assay kit.

Assessment of neutrophil counts and myeloperoxidase (MPO) activity in BAL BAL was done on both MSC- and PBS-treated mice at 8 and 24 h after injury to obtain total cell count and percentage of neutrophils as well as MPO activity. Total cell count was determined with the use of a counter (Beckman Coulter). A cell smear was made using cytopsin (Thermo Shandon), and the cells were visualized using Wright-Giemsa staining (Fisher Scientific). A differential of the white blood cells was then obtained by counting 100 cells from a representative portion of the slide. The activity of MPO was assessed using previously described, standard methods (21).
RNA isolation and RT-PCR for TLR4, CD14, and MD2
RNA was isolated from MSC and RAW 264.7 cells, a macrophage cell line, using the Qiagen RNeasy kit. After isolation, RNA samples were treated with DNase for 60 min at room temperature to remove contaminating DNA. The purity of the RNA was then analyzed by measuring the absorbance ratio at 260 and 280 nm using a spectrophotometer (Beckman Coulter).

Primers for TLR4, MD2, and CD14 were custom made (Sigma Genosys). The sequences were as follows: TLR4, 5′/AACCTGCGTCTCTAAACACCTGGC/3′; MD2, 5′/ATGTTGCCATTTATTCTCTTTTCGACG/3′; and CD14, 5′/GAGAAGCTCGTAACTGGC/3′. RT-PCR was done using the One-Step RT-PCR protocol from Qiagen. Primers for the housekeeping gene, GAPDH, were used as a control (Qiagen). RT-PCR was done using the One-Step RT-PCR protocol from Qiagen. The resulting amplified DNA product was run on a 2% agarose gel, and bands were visualized with the use of ethidium bromide.

Protein isolation and Western blot for TLR4, CD14, and MD2
Protein was isolated from MSC and RAW 264.7, a positive control, using the bicinchoninic acid assay and quantified using a Beckman Coulter spectrophotometer. A total of 40 μg of reduced, denatured protein from each cell type was then loaded and run on a 4–12% gradient Bis-Tris gel (Invitrogen Life Technologies). The gel was run at 100 V for 2 h using a MOPS SDS running buffer (Invitrogen Life Technologies). The proteins were then transferred to a nitrocellulose membrane and incubated with blocking buffer for 1 h. The membrane was then exposed to rabbit polyclonal primary Abs (Abcam) for TLR4, CD14, and MD2 at 1/10000 dilution overnight at 4°C. The membrane was washed and then incubated with an anti-rabbit HRP-labeled Ab (GE Healthcare) at 1/2500 dilution for 30 min. The protein bands were subsequently visualized with an ECL kit (Amer sham Biosciences).

Distribution of 51Cr-labeled endotoxin in MSC-treated mice
Endotoxin was labeled with chromium as has been previously described (22, 23). Briefly, 2 mg of dissolved endotoxin was incubated with Na251CrO4 (Amer sham Biosciences) for 24 h. This solution was then dialyzed for 4 days with distilled water until the free 51Cr was near undetectable in the dialyzed solution. Mice were then given 5 mg/kg of endotoxin (15% labeled, 85% unlabeled) i.p. as described previously. MSC or PBS was then given 4 h after the endotoxin, and mice were then euthanized at

**FIGURE 5.** MSC improved lung injury as assessed by histological methods despite the low levels of engraftment detected. A and B, H&E staining of lung sections demonstrated attenuated lung injury in the MSC group (B) vs the PBS group (A) at 48 h after instillation of endotoxin. C, Quantification of lung injury showed a significant reduction in the degree of hemorrhage and edema in the mice receiving MSC (*, p < 0.05; **, p < 0.01). Data are expressed as mean ± SD.

**FIGURE 6.** Levels of the proinflammatory cytokines, TNF-α and MIP-2, were reduced in mice receiving MSC at both 24 and 48 h after endotoxin-induced ALI. A and B, MIP-2 was significantly reduced in the BAL of mice treated with MSC at 24 h, whereas levels of TNF-α in the BAL showed a trend toward reduction in the MSC group (n = 5–6 per group; **, p < 0.01 for MIP-2 in the BAL; p = 0.06 for TNF-α in BAL). C and D, At 48 h, MIP-2 and TNF-α were reduced in the BAL of MSC-treated mice (n = 9–12 per group, *, p < 0.05). Data are expressed as mean ± SD.

MSC and RAW 264.7 cells were plated in six-well plates (Corning) and allowed to reach 50–70% confluency. The cells were then incubated with 4 μg of labeled endotoxin per well for 3 h at 37°C for assessment of uptake and at 4°C for binding. Control wells included one well per plate with no endotoxin, and one well that had polymyxin-B at 50 μg/ml to block endotoxin binding and uptake. The medium was then aspirated from each well, and cells were washed with cold PBS three times. Cells were then harvested with 0.5 ml of 0.5% trypsin, and then solubilized with 0.5 ml of 2% Triton X-100. The radioactivity in the resultant 1-ml suspension was recorded with a gamma scintillation counter (Packard Instrument) as a measure of the endotoxin concentration.

**Binding and uptake of 51Cr-labeled endotoxin by MSC and RAW 264.7 cells**
MSC and RAW 264.7 cells were plated in six-well plates (Corning) and allowed to reach 50–70% confluency. The cells were then incubated with 4 μg of labeled endotoxin per well for 3 h at 37°C for assessment of uptake and at 4°C for binding. Control wells included one well per plate with no endotoxin, and one well that had polymyxin-B at 50 μg/ml to block endotoxin binding and uptake. The medium was then aspirated from each well, and cells were washed with cold PBS three times. Cells were then harvested with 0.5 ml of 0.5% trypsin, and then solubilized with 0.5 ml of 2% Triton X-100. The radioactivity in the resultant 1-ml suspension was recorded with a gamma scintillation counter (Packard Instrument).

**Coculture of LPS-stimulated alveolar macrophages and MSC**
To determine whether MSC are able to regulate production of proinflammatory cytokines by stimulated macrophages by a cell-cell contact-dependent or -independent mechanism, alveolar macrophages were cocultured with MSC in either a standard single well or in a Transwell (0.4-μm pore size; Costar; Corning), and then stimulated with LPS. Alveolar macrophages were isolated from normal C57BL/6 mice by BAL using PBS. After isolation, the cells were washed once, and then resuspended in RPMI 1640 containing 5% FBS and 1% penicillin/streptomycin at a concentration of 20,000 cells/400 μl. MSC were harvested from tissue culture after trypsinization and resuspended in RPMI 1640 medium at a concentration of 20,000 cells/100 μl. Alveolar macrophages and MSC were then coincubated in the presence of LPS (4 μM) for 4 h at 37°C in a standard 24-well plate (Costar; Corning). To test the effects of coculture without cell contact, additional wells were prepared in which a Transwell insert was used with the macrophages cultured in the bottom compartment and the MSC in the upper compartment (see Fig. 11A). Control wells were prepared with only macrophages stimulated with LPS, and MSC stimulated...
with LPS alone. The cell culture supernatants were then collected after the 4-h incubation to assay for the levels of TNF-α, MIP-2, and IL-10 by ELISA (R&D Systems).

Statistical analysis
Comparisons between two groups were made using an unpaired t test. For comparisons between multiple groups, ANOVA with Bonferroni’s correction was used (see Fig. 8). The log-rank test was used for comparing survival data at 48 and 72 h. A value of $p < 0.05$ was considered statistically significant. Analyses were done using SPSS software and GraphPad Prism software. Data are shown as mean ± SD.

Results

MSC characterization
Differentiation assays demonstrated that MSC retained their ability to form osteoblasts, adipocytes, and myofibroblasts at passages 15–25 (Fig. 1, A–C). Flow cytometry analysis demonstrated that the cells did not express the cell surface markers CD45, CD11b, CD34, and CD31 (Fig. 1, E and F). Morphologically, the cells expressed GFP (Fig. 1 D) and had a spindled, fibroblast appearance in culture that is consistent with MSC.

MSC improve survival over 72 h and indices of lung injury at 24 and 48 h
Over 48 h, mice that received i.t. MSC had a significantly higher rate of survival vs control mice that received i.t. PBS (80 vs 42%; Fig. 2 A). This difference between the two groups became apparent after the initial 24 h. To determine whether the survival advantage persisted beyond the initial 48 h, additional experiments were done in which mice were followed for 72 h, and those mice that received MSC had a significantly higher rate of survival compared with control mice (Fig. 2 B).

Mice given MSC showed a trend toward lower excess lung water at 24 h, and a significant difference at 48 h (Fig. 3, A and B). In addition, BAL protein, a marker of endothelial and epithelial permeability, was nonsignificantly reduced in the MSC group at 24 h, but significantly reduced in the MSC group at 48 h (Fig. 3, C and D).

In contrast, mice that received the fibroblast cell line, 3T3, or nonviable MSC had no improvement in survival or severity of lung injury (excess lung water and BAL protein) compared with PBS-treated mice at 48 h (Fig. 4).

Table 1. Fibroblasts and apoptotic MSC do not decrease proinflammatory or increase anti-inflammatory cytokines

<table>
<thead>
<tr>
<th></th>
<th>24 h</th>
<th>48 h</th>
<th>24 h</th>
<th>48 h</th>
<th>24 h</th>
<th>48 h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TNF-α</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma</td>
<td>0</td>
<td>78 ± 109</td>
<td>0</td>
<td>105 ± 57</td>
<td>0</td>
<td>60 ± 32</td>
</tr>
<tr>
<td>BAL</td>
<td>918 ± 257</td>
<td>515 ± 266</td>
<td>1149 ± 468</td>
<td>851 ± 268</td>
<td>706 ± 573</td>
<td>865 ± 703</td>
</tr>
<tr>
<td>MIP-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma</td>
<td>799 ± 485</td>
<td>7314 ± 5263</td>
<td>805 ± 684</td>
<td>2365 ± 1366</td>
<td>1030 ± 1442</td>
<td>4775 ± 2879</td>
</tr>
<tr>
<td>BAL</td>
<td>1810 ± 1364</td>
<td>2987 ± 2706</td>
<td>1303 ± 652</td>
<td>1837 ± 1290</td>
<td>974 ± 1107</td>
<td>1598 ± 663</td>
</tr>
<tr>
<td>IL-10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma</td>
<td>615 ± 490</td>
<td>967 ± 789</td>
<td>462 ± 417</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAL</td>
<td>143 ± 144</td>
<td>249 ± 159</td>
<td>88 ± 94</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>24 h</th>
<th>48 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>TNF-α</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MIP-2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IL-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* All comparisons of 3T3 fibroblasts and apoptotic MSC vs PBS are not significant ($p > 0.05$). Units are picograms per milliliter for all measurements. $n = 4–5$ per group for each time point. Data are expressed as mean ± SD.
GFP were seen scattered through the lungs of mice treated with the use of confocal microscopy as described previously. MSC engrafted as clusters or formed clusters of cells in the lung parenchyma. The mice treated with PBS had no evidence for GFP-engrafted cells.

Histology

At 48 h, H&E staining of lung sections from MSC-treated mice had significantly less injury compared with mice given PBS (Fig. 5, A and B). Mice treated with MSC also had a significant improvement in the degree of hemorrhage and edema as assessed by the lung injury score (Fig. 5, B). Western blot confirmed that MSC and the RAW cell line express the proteins for TLR4, CD14, and MD2 (lanes 1–3, respectively). To confirm that MSC did not internalize significantly more labeled endotoxin in the lung or BAL compared with PBS at either 8 or 24 h after endotoxin instillation (n = 3 mice per group per time point). Data are expressed as mean ± SD.

MSC express the LPS receptor complex but do not clear endotoxin or affect its distribution

To determine whether MSC expressed the LPS receptor complex, TLR4/CD14/MD2, RT-PCR was done for these genes and the GAPDH was used as a housekeeping gene and was expressed by both MSC and RAW 264.7 (lanes 4 and 8, respectively). GAPDH was used as a housekeeping gene and was expressed by both MSC and RAW 264.7 (lanes 4 and 8, respectively). Western blot confirmed that MSC expressed the proteins for TLR4, CD14, and MD2 (top panel, TLR4 at 90 kDa; middle panel, CD14 at 50 kDa; bottom panel, MD2 at 20 kDa; arrows indicate relevant bands).

MSC administration did not prevent neutrophil chemotaxis to the alveolus

Given the significant reduction in the neutrophil chemokine, MIP-2, in the MSC-treated mice, BAL studies were done at 8, 24, and 48 h after LPS instillation to determine whether neutrophil counts were lower in the MSC-treated vs PBS-treated mice. Total cell counts and absolute neutrophil counts were not different between the two groups at any time point (data not shown). MPO activity was also similar between the MSC- and PBS-treated mice at all time points (Fig. 8).

MSC do not internalize 3H-labeled endotoxin in vitro or affect its distribution in vivo

A, RAW 264.7 cells internalized significantly more labeled endotoxin compared with MSC in culture (n = 4 wells per cell line; **, p < 0.01). B and C, MSC did not affect the distribution of labeled endotoxin in the lung or BAL compared with PBS at either 8 or 24 h after endotoxin instillation (n = 3 mice per group per time point). Data are expressed as mean ± SD.
This demonstrated that MSC and the RAW cell line express all three proteins (Fig. 9B). These results are consistent with recent reports demonstrating that MSC and hemopoietic stem cells do express TLRs (24–26).

Next, it was determined whether MSC could internalize endotoxin in an in vitro system or affect its distribution in vivo. Binding and uptake studies with chromium-labeled endotoxin demonstrated that MSC internalized a significantly smaller amount of endotoxin compared with the control cell line, RAW 264.7 (Fig. 10A). Using the chromium-labeled endotoxin in the in vivo model of ALI, MSC did not alter the kinetics of endotoxin distribution in the mouse (Fig. 10, B and C). These results suggest that clearance of endotoxin is not part of the mechanism by which MSC exert their beneficial effects.

Coculture of alveolar macrophages and MSC reduced level of macrophage stimulation by LPS

The addition of MSC to LPS-stimulated macrophages reduced the level of TNF-α in the cell supernatant compared with only LPS-stimulated macrophages. The degree of reduction was similar in the presence of a Transwell that prevented cell contact between the macrophages and MSC (Fig. 11B). MSC alone did not produce TNF-α in response to LPS stimulation. In contrast to the in vivo data, levels of MIP-2 were not reduced with the addition of MSC to LPS-stimulated macrophages, and IL-10 was not detectable in any of the conditions.

Discussion

There are three major findings of this study: 1) the i.t. administration of MSC demonstrated both a functional and survival benefit in the mouse model of endotoxin-induced ALI when given 4 h after the administration of LPS; 2) there was a significant histological improvement in the severity of lung injury following MSC administration despite a level of MSC engraftment of <5% at 48 h after injury; 3) the beneficial effects with MSC appear to be mediated by a shift from a proinflammatory to an anti-inflammatory response to endotoxin.

Previous studies using MSC in lung injury have used only the bleomycin model of lung injury (3, 4). In these studies, the i.v. administration of cells ameliorated the severity of bleomycin-induced injury despite the low engraftment levels seen. This beneficial effect was primarily demonstrated by an improvement in histology, although Rojas et al. (4) did report a significant survival advantage when the MSC were given to bone marrow-suppressed mice. Despite these interesting results, there is little known of the effects of MSC in experimental models of ALI and of the possible benefit of administering cells by the i.t. route. Our objective was to study the effects of the i.t. delivery of MSC in the mouse model of endotoxin-induced ALI when given as a treatment, and our primary endpoints were functional and survival effects. The data obtained in our study demonstrate, for the first time, a significant beneficial effect of the local delivery of MSC in experimental ALI. MSC therapy reduced lung wet-to-dry ratio and excess lung water, overall markers of severity of lung injury, and BAL protein, a marker of endothelial and epithelial permeability, at 48 h. However, the most striking finding of this study was the significant survival advantage conferred with MSC treatment. In addition, the survival data demonstrate that cell therapy exerted its beneficial effects after the initial 24 h of endotoxin-induced injury, because this is when the survival curves diverge. Furthermore, the benefits with MSC administration were not replicated with the i.t. delivery of fibroblasts or nonviable MSC. This result suggests that undifferentiated, viable MSC are required to produce a functional and survival benefit in endotoxin-induced ALI.

The second major finding of this study was that MSC administration led to a significant histologic improvement in the extent of lung injury despite the low level of engraftment. The improvement in histology was assessed quantitatively by the use of a lung injury score described previously (20). The extent of hemorrhage and edema was significantly reduced in the mice treated with MSC, which supports the findings of less excess lung water in these mice. MSC engraftment was estimated by the use of confocal microscopy. The low level of engraftment seen (<5%) is consistent with prior studies in the field (3, 7), which have reported engraftment levels <1% even in the presence of lung injury. These data support the concept that MSC might be protective against lung injury through mechanisms independent of their ability to engraft in the lung.

Given the rare incorporation of administered MSC into the lung, as well as recent literature reporting the immunomodulatory properties of MSC (9–12), we hypothesized that the benefit with MSC treatment was mediated through a down-regulation of the proinflammatory responses to endotoxin. Analysis of BAL and plasma samples from MSC-treated and control mice confirmed this hypothesis demonstrating lower levels of TNF-α and MIP-2 in the MSC-treated mice. Despite this reduction in the level of the chemokine MIP-2, neutrophil influx into the alveolus was not ameliorated in the MSC-treated mice because the levels of MPO and absolute neutrophil counts were not reduced. This suggests that the protection provided by MSC is not dependent on a reduction in neutrophil recruitment to the lung. This finding may be explained by the fact that MSC are administered 4 h after i.t. endotoxin by
which time there has been activation of alveolar macrophages and recruitment of neutrophils to the lung. In addition, MSC may also have effects on neutrophil function and activity that have yet to be described.

To determine whether the anti-inflammatory effect of MSC was related to an ability to internalize and act as a scavenger of free endotoxin, in vitro and in vivo studies with $^{51}$Cr-labeled endotoxin were done. These studies showed that, despite the expression of TLR-4 by MSC, the cells did not take up endotoxin as well as a macrophage cell line and did not alter the distribution of endotoxin in the mouse. Therefore, the beneficial effects of MSC are not related to clearance of endotoxin and reduction of its free concentration.

Given these results, other potential mechanisms of MSC regulation of the response to endotoxin were investigated. Of these, the possibility that MSC were either producing or up-regulating the production of anti-inflammatory cytokines seemed most likely given previous reports that MSC can modulate the activity of immune cells (9–11). To test for this, the levels of a variety of candidate factors were assessed. These analyses demonstrated that the levels of IL-10 were significantly higher in the BAL at 8 h and in the plasma at 24 h in MSC-treated mice. This result is consistent with recent reports demonstrating that MSC do increase production of IL-10 by APCs (9, 27). Furthermore, this finding may indicate an important mechanism by which MSC produce their beneficial effect because IL-10 has well-described protective effects in lung inflammation (28, 29). In addition to increasing IL-10 levels, MSC administration led to higher levels of IL-13 and IL-1ra. These findings indicate that MSC shift the balance from a pro-inflammatory to an anti-inflammatory cytokine response to endotoxin in part by leading to the production of soluble factors such as IL-1ra and by inducing a Th2 type response. This result is also consistent with recent reports that MSC can down-regulate T cell responses by shifting from a Th1 to Th2 type response (9, 30, 31). However, it is still not known whether the MSC are the source of the regulatory cytokines or whether they are inducing immune cells to secrete them, or both. Separate experiments done with the fibroblast and apoptotic MSC control cells did not demonstrate this shift in the inflammatory response to endotoxin. It is worth noting that the absolute levels of the specific cytokines measured (TNF-α, MIP-2, and IL-10) are different in Table I compared with the levels in Fig. 6, perhaps because the experiments for Table I were done at a later time to provide evidence that the control cells (fibroblasts and apoptotic MSC) did not change the levels of BAL and plasma cytokines. These differences can most likely be ascribed to the inherent variability in the cytokine response to endotoxin, which may be explained by changes in temperature, age, and environmental conditions (32, 33).

Despite these differences, the finding that the two control cell populations did not decrease the pro-inflammatory or increase the anti-inflammatory response to endotoxin, in comparison with PBS, is important and suggests that the immunomodulatory effect observed with MSC is specific.

In vitro co-culture experiments with endotoxin-stimulated alveolar macrophages and MSC were done to determine whether direct cell-to-cell contact is required to down-regulate the acute inflammatory response to endotoxin. Alveolar macrophages were used in these studies because they are the initial innate immune cell in the lung that is exposed to endotoxin in this model and orchestrate the inflammatory response and recruitment of other cells, such as neutrophils (34). Using a Transwell to physically separate the macrophages and MSC and thereby inhibit cell-cell contact, we found that the stem cells can inhibit macrophage production of TNF-α by endotoxin in a contact-independent manner. These experiments suggest that endotoxin-stimulated MSC produce soluble factors that can regulate the macrophage response to endotoxin and may account for the beneficial effects of MSC treatment in the endotoxin model of ALI in vivo.

One of the limitations of using MSC is the lack of specific cell surface markers to isolate and characterize them. There has been significant variability in the methods used to isolate and culture bone marrow-derived MSC in the prior literature (3, 8, 35). Initial studies by Kotton et al. (8) used the plastic adherent fraction of whole bone marrow to select for MSC, whereas Ortiz et al. (3) used bone marrow cells that were immunodepleted for cells expressing CD45, CD11b, and CD34 to isolate a purified population of MSC. More recently, Miyahara et al. (35) isolated MSC from adipose tissue of rats, and similar to Kotton et al. (8), retained only the plastic adherent fraction for propagation. The MSC used in this study were originally isolated by selecting for the adherent fraction of whole mouse bone marrow and then subsequently propagating this subset of cells in culture. To verify that these cells represented a homogenous population of MSC, flow cytometry was done and demonstrated that the cells did not express CD11b, CD31, CD34, or CD45. In addition, differentiation assays were done after 20–25 passages and confirmed that the cells retained the ability to differentiate into osteoblasts, adipocytes, and myofibroblasts. Thus, the cells used in this study do represent a population of MSC that have retained their multipotent capability. However, until there are more specific cell surface markers for MSC, there will be continued difficulty in standardizing the MSC used by investigators in this field.

In summary, this study demonstrates that intrapulmonary treatment with MSC in experimental endotoxin-mediated ALI provides a significant survival advantage that is explained by a reduction in lung vascular permeability and the quantity of lung edema. This protection is mediated by a shift from a pro-inflammatory to an anti-inflammatory response to endotoxin that includes enhanced production of IL-10. These findings are the first evidence that intrapulmonary MSC have beneficial effects in an animal model of ALI and raise the possibility of using cell-based therapy for ALI in patients.

Acknowledgments

We thank Dr. Mark R. Looney, Dr. Xiaohui Fang, and Sandy Brady for their advice and technical assistance.

Disclosures

The authors have no financial conflict of interest.

References


