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Use of donor bone marrow mesenchymal stem cells for treatment of skin allograft rejection in a preclinical rat model

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Abstract Recent studies indicate that mesenchymal stem cells (MSC) exhibit a degree of immune privilege due to their ability to suppress T cell mediated responses causing tissue rejection; however, the impact of allogeneic MSC in the setting of organ transplantation has been poorly investigated so far. The aim of our study was to evaluate the effect of intravenous donor MSC infusion for clinical tolerance induction in allogeneic skin graft transplantations in rats. MSC were isolated from Wistar rats and administered in Sprague-Dawley rats receiving Wistar skin graft with or without cyclosporine A (CsA). Graft biopsies were performed at day 10 post transplantation in all experimental

groups for histological and gene expression studies. Intravenous infusion with donor MSC in CsA-treated transplanted rats resulted in prolongation of skin allograft survival compared to control animals. Unexpectedly, donor MSC infusion in immunocompetent rats resulted in a faster rejection as compared to control group. Cytokine expression analysis at the site of skin graft showed that CsA treatment significantly decreased pro-inflammatory cytokines IFN- γ and IL-2 and reduced TNF- α gene expression; however, the level of TNF- α is high in MSC-treated and not immunosuppressed rats. Results of our study in a rat tissue transplantation model demonstrated a possible immunogenic role for donor (allogeneic) MSC, confirming the need of adequate preclinical experimentation before clinical use.

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Introduction

The introduction of modern immunosuppressive therapies has improved the survival rates for solid organ allo-transplantation in humans. However, immunosuppressive drug toxicity and side effects lead to late allograft loss. Thus, the induction of a state of permanent tolerance to an allograft, defined as a state of unresponsiveness to donor antigens in the absence of long-term immunosuppressive therapy, is an elusive goal in human solid organ transplantation. Several approaches of cellular therapy have been used in an attempt to achieve immunological tolerance in non-human primate and human studies [11]. Stem cell mediated tolerance was experienced with the use of donor whole bone marrow cell (DBMC) infusions [2, 24, 26, 35, 39]. Results of published experiences suggest that donor bone marrow cells infusion

is safe and has a positive impact on chimerism and on the outcome after transplantation [32]. Patients who show a full chimerism after myeloablative therapy and bone marrow (BM) transplantation for treatment of haematopoietic malignancy will accept renal transplants and other tissue transplants from their specific BM donor without requirement for immunosuppressive therapy [6].

Mesenchymal stem cells (MSC) are cells derived from varying fetal and adult organs and have the capacity of self-renewal and of differentiating in several tissues including bone, cartilage, stroma, fat, muscle, and tendon [29]. Numerous *in vitro* studies demonstrate that MSC from various species can suppress T-cell proliferation, in autologous and alloreactive conditions, in response to various stimuli with cell contact dependent and independent mechanisms [1, 25, 31, 38].

In support of their *in vivo* immunosuppressive features are the observations that allogeneic MSC may prolong skin allograft survival in immunocompetent baboons [16], prevent the rejection of allogeneic B16 mouse melanoma cells in immunocompetent mice [7], attenuate graft versus host disease (GvHD) in mice and humans [4, 19], and have a role in the treatment of autoimmune disorders [40]. However, the impact of allogeneic MSC in the setting of organ transplantation has been poorly investigated to date. A recent work by Inoue et al. [16] on a rat organ transplant model confirms the MSC immunomodulatory properties *in vitro* but suggests caution for their use *in vivo*, as MSC injections were not effective in prolonging heart allograft survival inducing rejection instead of tolerance.

The immunogenicity of skin, the most antigenic tissue in the body, is the major obstacle for the skin allograft survival, resulting in rejection within 10–12 days without immunosuppressive therapy. Tolerance to skin allografts is very difficult to induce except under particular conditions. Recently, it has been demonstrated that skin allograft survival is prolonged by the injection of donor epidermal cells together with bone marrow cells [28]. The potential for the use of BM-derived MSC in prolonging skin graft survival was reported by the study of Bartholomew et al. [3]. The authors demonstrated that infusion of major histocompatibility

complex (MHC)-mismatched MSC into baboons had been well tolerated and prolonged skin graft survival *in vivo*. Furthermore, baboon MSC suppress the proliferative activity of allogeneic peripheral blood lymphocytes (PBL) *in vitro*.

Based on the above-mentioned findings, our aim was to evaluate the role of donor MSC in tolerance induction in a rat model of skin transplantation. In particular, we evaluated the effects of intravenous donor MSC infusion on skin allograft survival in an experimental model using Wistar rats as donors and Sprague-Dawley (SD) rats as recipients; both as a comparison with, and in addition to, the conventional immunosuppressive treatment with cyclosporine A (CsA). In addition, we evaluated whether MSC infusion could affect the gene expression profile of some pro- and anti-inflammatory cytokines that could play a role in the modulation of the immune response for skin allograft tolerance or rejection.

Materials and methods

Animals

Wistar and Sprague-Dawley (CD) rats (Charles River Laboratories) were used in this study. Adult male Wistar rats weighing 300–350 g were used as skin graft and MSC donors. Adult male Sprague-Dawley rats weighing 300–350 g were used as skin graft recipients. For each experimental arm, we used three donors and at least 20 recipients.

Rats were housed in an accredited animal facility (Istituto Biologici-San Miniato Stabularium, Siena, Italy) and treated under conditions approved by the Local Ethical Committee of the University of Siena, Italy.

Study design

We performed a case-control study to assess the effect of intravenous administration of MSC in rats that had undergone skin allograft transplantation. The experimental design (Table 1) included four arms; in each arm we performed an autograft in two animals and an allograft in at

Table 1 Summary of graft rejection and survival after MSC injection

Group	Donor	Recipient	MSC injection (day 0 and +3)	CsA	Number of transplanted rats	Percent of not rejected grafts (%)	Percent of rejected grafts (%)	Graft survival* (days)
A	Wistar	Sprague-Dawley	No	No	13	0	100	17 ± 1.8
B	Wistar	Sprague-Dawley	No	Yes	14	43	57	15 ± 3.8
C	Wistar	Sprague-Dawley	Wistar MSC	Yes	14	57	43	19 ± 3
D	Wistar	Sprague-Dawley	Wistar MSC	No	21	0	100	13 ± 1

* Numbers represent mean ± SD days of graft survival among the animals that rejected the graft during the 30-day observation period. Immunosuppression was performed with intramuscular administration of CsA at 5 mg/kg per day. MSC were infused in the tail vein with a dosage of 5.7×10^6 /kg at day 0 and 10.3×10^6 /kg at day +3

least 20 animals. Group A is the control arm and comprises rats that received a skin transplantation only; rats of arm B received skin transplantation and immunosuppressive therapy with CsA; rats of arm C received skin transplantation, immunosuppressive therapy, and intravenous infusion of donor MSC; rats of arm D received skin transplantation and intravenous donor MSC infusion. For each arm, half the number of animals were inspected daily to evaluate skin graft survival (days between transplantation and rejection) and the others were sacrificed on day 10 post transplantation in order to perform two punch biopsies for histopathology and gene expression profile of the graft.

Skin graft placement and evaluation

Skin transplantation was performed according to the methods described by Taylor and Morris [37] with some modifications: in brief, after tiletamine–zolazepam sedation (Zoletil 20[®]) (30 mg/kg i.p.), 1.5 × 1.5 cm full-thickness skin grafts were harvested from the donor abdominal surface. After removal of the subcutaneous tissue, skin grafts were placed on the abdomen of the recipient rat, fixed with simple separate stitches, and covered with a wet buffered bandage. This procedure supports neo-vascularization and engraftment. The graft was then protected by a zined bandage that was removed on day 7. Grafts that failed up to this point were considered as technical failure and excluded by the study. The graft was inspected daily until rejection or until the end of the experiment (30 days). Grafts were considered rejected when at least 90% of graft tissue had disappeared or had become necrotic.

MSC administration

Sprague-Dawley rats of arm C and D received Wistar MSC in the tail vein after completion of the skin graft procedure (day 0) and on day 3, post transplantation. The administered MSC dose was 5.7×10^6 /kg in 200 μ l of 0.9% NaCl solution at day 0 and 10.3×10^6 /kg in the same conditions at day 3. Animals of arms A and B received intravenous 0.9% NaCl solution in the same volume and with the same timing.

CsA administration

Animals of arms B and C received intramuscular CsA (Sandimmun[®]; Novartis, Novartis Farma S.p.A., Varese, Italy) administration at a dose of 5 mg/kg per day from day 0, as previously described [5].

MSC isolation and culture expansion

Rat BM cells were collected from male Wistar rats following the Dobson procedure [9]. Briefly, once the femurs and

tibiae were extracted, their proximal ends were removed, and the bones were then placed in microcentrifuge tubes supported by plastic inserts cut from 1 ml hypodermic needle casings and briefly centrifuged at 700g for 2 min. The marrow pellet was re-suspended in 10 ml of Hank's balanced salts solution (HBSS, w/o calcium and magnesium; Euroclone, Milan, Italy) + 1% fetal bovine serum (FBS, HyClone, South Logan, Utah, USA) and washed (300g for 7 min). After the cells were passed through a 22-G needle, they were re-suspended in culture medium (DMEM-Low Glucose, with L-glutamine, 25 mM HEPES and pyruvate, GIBCO[™]–Invitrogen, Milan, Italy, supplemented with 10% FBS), counted using a hemocytometer and seeded at 24×10^6 /75 cm² flask. Cells were incubated at 37°C in a humidified atmosphere containing 95% air and 5% CO₂. Half of the complete medium was changed after 1 week and thereafter the whole medium every 3–4 days. When approximately 80% of the flask surface was covered, the adherent cells were incubated with 0.05% trypsin–0.02% EDTA (Eurobio, Courtaboeuf, Cedex B, France) for 5–10 min at 37°C, harvested, washed with HBSS and 10% FBS, and re-suspended in complete medium (primary culture, P0). Cells were then re-seeded at 10^4 cells/cm² in 100-mm \emptyset dishes (P1): expansion of the cells was obtained with successive cycles of trypsinization and reseeded. MSC were identified and characterized according to published studies [20, 21].

CFU-F frequency

The number of colony forming units-fibroblasts (CFU-F) was used as a surrogate marker for MSC progenitors frequency: two 100-mm \emptyset dishes were seeded with 1×10^6 total nucleated cells. After incubation for 14 days at 37°C in 5% CO₂ humidified atmosphere, the dishes were rinsed with HBSS, fixed with methanol and stained with Giemsa: visible colonies formed by 50 or more cells [12] were counted and reported as number of CFU-F/ 10^6 seeded total nucleated cells (TNC).

Osteogenic and adipogenic differentiation of MSC

MSC (10^4 cells/cm²) were grown near confluence in 25 cm² flasks and then incubated in osteogenic medium (DMEM–LG with 10% FBS; 10 nM dexamethasone, 100 μ g/ml ascorbic acid and 10 mM β -glycerophosphate (all from Sigma, St Louis, MO, USA), or in adipogenic medium (DMEM–LG with 10% FBS; 0.5 mM isobutyl methylxanthine, 10 μ M dexamethasone, 10 μ g/ml insulin, and 70 μ M indomethacin, all from Sigma, St Louis, MO, USA). The medium was replaced every 3–4 days and the deposition of mineral nodules or the accumulation of lipid-containing vacuoles was revealed after

21 days with Alizarin Red-S or with Oil Red O staining, respectively.

Immunophenotyping

At the fourth or fifth passage, the morphologically homogeneous population of MSC was analysed for the expression of particular cell surface molecules using flow cytometric procedures: MSC recovered from flasks by trypsin–EDTA treatment and washed in HBSS and FBS 10% were re-suspended in flow cytometry buffer consisting of CellWASH (0.1% sodium azide in PBS; Becton Dickinson, San Jose, CA, USA) with 2% FBS. Aliquots (1.5×10^5 cells/100 μ l) were incubated with the following conjugated monoclonal antibodies: CD45-CyChrome™, CD11b-FITC (in order to quantify hemopoietic-monocytic contamination), CD90-PE, CD106-PE, CD73-PE, CD54-FITC, CD44-FITC (BD Pharmingen, San Diego, CA, USA). Non-specific fluorescence and morphologic parameters of the cells were determined by incubation of the same cell aliquot with isotype-matched mouse monoclonal antibodies (Becton Dickinson, San Diego, CA, USA). All incubations were performed for 20 min and after incubation, cells were washed and re-suspended in 100 μ l of CellWASH; 7-AAD (7-amino-actinomycin D) was added in order to exclude dead cells from the analysis. Flow cytometric acquisition was performed by collecting 10^4 events on a FACSort (488 nm argon laser equipped, Becton Dickinson, San Jose, CA, USA) instrument and data were analysed on DOT-PLOT bi-parametric diagrams using CELL QUEST software (Becton Dickinson, San Jose, CA, USA) on a Macintosh PC.

Histopathology

Skin graft punch biopsies (6 mm \emptyset) were performed on day 10 post transplantation in ten animals for each group and skin samples were fixed with formalin and stained with haematoxylin–eosin for histological evaluation. Slides were analysed in a blinded fashion. Two parameters, inflammatory infiltrate (*F*) and epidermis thickness (*ET*), were analysed. Inflammatory infiltrate were scored as follows: 0 no inflammation, 1 focal and mild, 2 diffuse and moderate, 3 diffuse and severe. *ET* was calculated as the mean of five thickness measures (μ m) of epidermis from granular to basal layer.

RNA extraction and real-time quantitative RT-PCR

Total RNA from rat skin was isolated by using the RNeasy midi kit (Qiagen, Germany) according to the manufacturer's protocol. Five micrograms of RNA were reverse transcribed separately using M-MLV transcriptase (Gibco BRL) and random hexamer primers (Amersham). In order

to quantify the transcribed interleukin 2 (IL-2, M22899), interleukin 10 (IL-10, L02926), interferon gamma (IFN- γ , AF010466), transforming growth factor beta (TGF- β , AY550025), and tumor necrosis factor alpha (TNF- α , X66539) genes, we performed TaqMan RT-PCR (PE Applied Biosystems, Foster City, CA) in ABI-PE Prism 7700 sequence detection system. VIC-labeled rodent glyceraldehyde-3-phosphate dehydrogenase (GAPDH) (assay-on-demand #4308313) and FAM-labeled rattus IL-2 (assay-on-demand # Rn00587673_m1), IL-10 (assay-on-demand #Rn00563409_m1), IFN- γ (assay-on-demand #Rn00594078_m1), TGF- β (assay-on-demand #Rn00579697_m1), and TNF- α (assay-on-demand # Rn01525860_g1) TaqMan pre-developed assays (Applied Biosystems) were used. The threshold cycles (the PCR cycle at which an increase in reporter fluorescence above a baseline signal can first be detected) of each target product was determined and set in relation to the amplification plot of the housekeeping gene, GAPDH. All experiments were run in duplicate with 50 ng cDNA, and the same thermal cycling parameters were used. Fold change was calculated relative to control skin cycle threshold (Ct). The Ct value is defined as the number of PCR cycles required for the fluorescence signal to exceed the detection threshold value. With the PCR efficiency of 100%, Δ Ct values of the samples were determined by subtracting the average of the Ct values of the target genes from the average of the Ct values of the GAPDH gene. The relative gene expression levels were determined by subtracting the average Δ Ct value of the target from the average Δ Ct value of the calibrator. The amount of target (expressed as fold change), normalised to an endogenous reference and relative to a calibrator, was given by $2^{-\Delta\Delta Ct}$.

Statistical analysis

The survival allograft time in the groups was evaluated by the Kaplan–Meier method and the efficacy of treatment by the Logrank test. Differences in gene expression among different animal groups were tested by using the non-parametric Kruskal–Wallis test. Differences in gene expression between two groups were tested by using the non-parametric Mann–Whitney test. A *P* value of less than 0.05 was considered statistically significant.

Results

rMSC characterisation

Rat BM-derived MSC were successfully culture-expanded. Cells were particularly heterogeneous until the fourth–fifth passage in culture and also comprised numerous lipid

vacuoles. Haematopoietic cells were lost during the medium changes as shown by flow cytometric analysis. Primary culture cells were trypsinised and plated, reaching a cellular expansion up to a mean 10^9 factor in 3 months (Fig. 1a). After the fifth passage, the cells grew exponentially, requiring weekly passages (Fig. 1b). The CFU-F assay was used as a surrogate assay for MSC. In BM total nucleated cell population, the estimated CFU mean count resulted as $56/10^6$ TNC. MSC treated with osteogenic medium formed small deposits of hydroxyapatite intensely red stained with Alizarin S (Fig. 1c). MSC treated with adipogenic medium were successfully differentiated towards adipogenic lineages: lipid vacuoles started to accumulate in the cytoplasm of the cells just after 2–3 days of stimulation and they were orange–red stained after 21 days (Fig. 1d). FACS analysis was used to assess the purity of our MSC and the existence of a homogeneous population of adherent cells (after 4–5 passages). After the exclusion of dead cells, (R1 on 7-AAD negative elements) cell population resulted uniformly positive for CD90, CD44, CD54, CD73, and CD106. There was no significant contamination of haema-

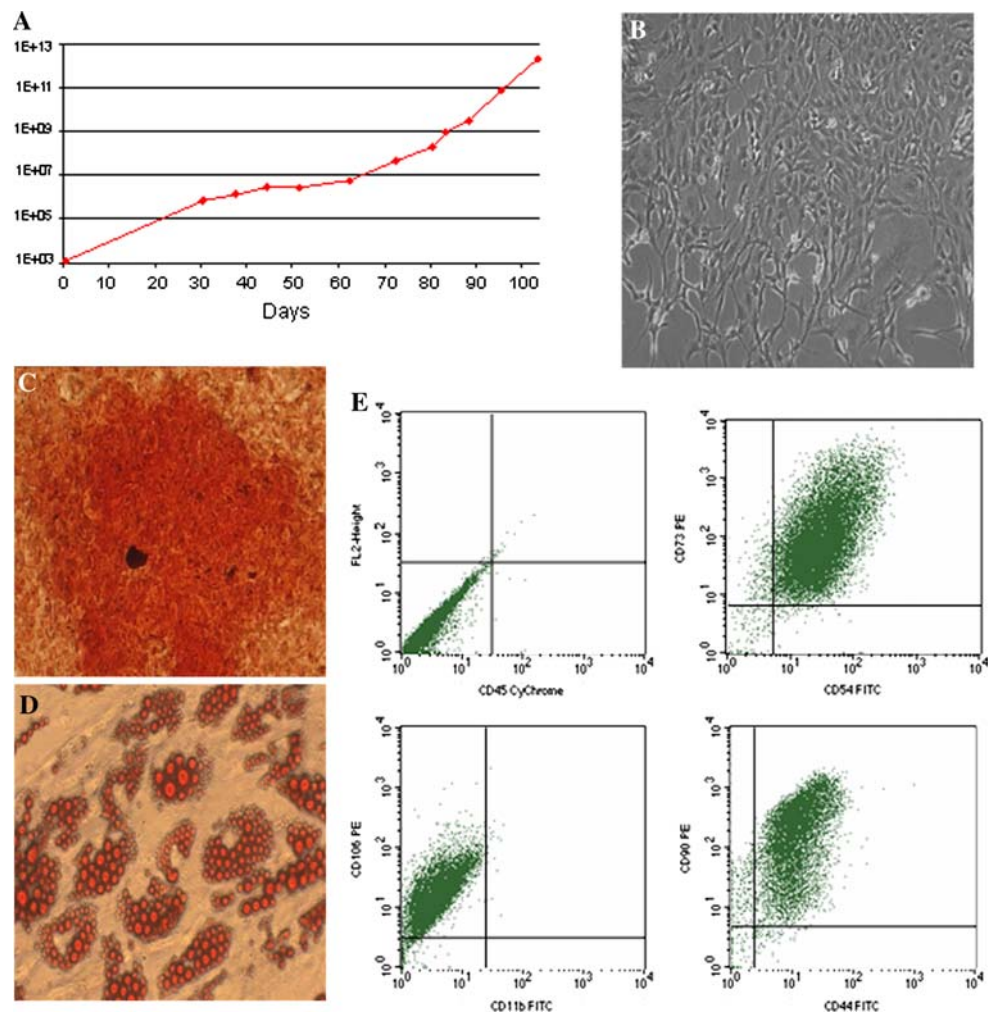
topoietic cells, as flow cytometry was negative for markers of haematopoietic lineage, including CD11b and CD45 (Fig. 1e).

Skin graft survival

The mean skin graft survival and percentage of rats with rejected or not rejected skin allograft is summarized in Table 1 and skin graft survival curves are shown in Fig. 2.

The graft from untreated animals (A; $n = 13$) was rejected with a mean \pm standard deviation (SD) of 17 ± 1.8 days. Among CsA-treated rats (B; $n = 14$), 43% (6/14) did not reject and 57% (8/14) had a mean \pm SD skin graft survival of 15 ± 3.8 days. The CsA concentration (5 mg/kg) used for the treatment of the transplanted rats significantly prolongs skin allograft survival compared to control animals (B vs. A $P < 0.01$) but it cannot induce complete engraftment in all animals. The administration of MSC in CsA-treated rats increased skin allograft survival in comparison with untreated animals (C vs. A $P < 0.001$) as 57% (8/14) rats receiving combined treatment of MSC and

Fig. 1 Characteristics of MSC. Cells were enumerated using a haemocytometer at each passage and reached a cellular expansion up to a factor of 10^9 in 3 months: **a** Growth curve, **b** typical morphology. Differentiation into respective lineages was identified under specific conditions: **c** deposits of hydroxyapatite intensely red stained with Alizarin S after culture in osteogenic medium, **d** orange–red stained lipid vacuoles of the cytoplasm of MSC treated with adipogenic medium. Flow cytometric analysis including CD11b and CD45 antibodies showed no contamination of haematopoietic cells and positivity for classical mesenchymal markers CD44, CD54, CD73, CD90, CD106 (e)



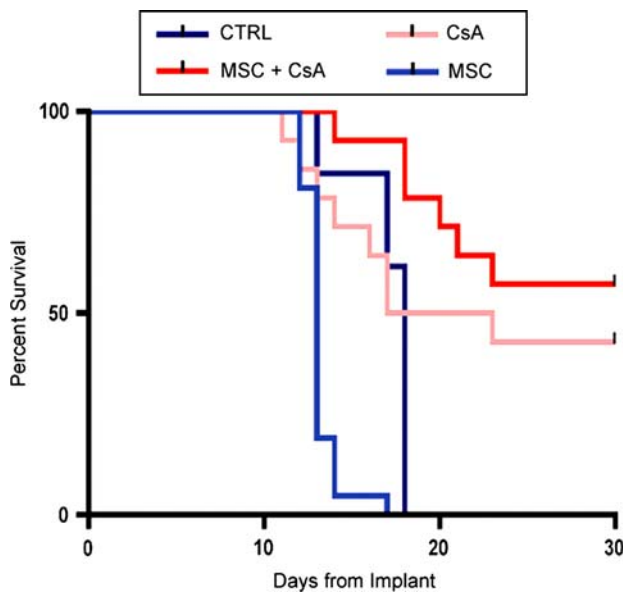


Fig. 2 Kaplan–Meier allograft survival curves for rats receiving skin allograft only (CTRL control, blue line, $n = 13$), skin allograft and CsA treatment (CsA, pink line, $n = 14$), skin allograft, CsA treatment and donor MSC infusion (MSC + CsA, red line, $n = 14$), skin allograft and donor MSC infusion (MSC, azure line, $n = 21$). Observation period: 30 days. Logrank test showed a significant difference among the groups ($P < 0.001$)

CsA (C, $n = 14$) had no allograft rejection and 43% (6/14) rejected the graft with a mean graft survival time of 19 ± 3.0 days. Some rats of this group were observed for 2 months and showed no allograft rejection. In contrast, rats treated with MSC only (D, $n = 21$) rejected the graft with a mean \pm SD skin graft survival of 13 ± 1 days, indicating that donor MSC accelerate graft rejection (D vs. A $P < 0.001$). Kaplan–Meier curves (Fig. 2) indicate a detrimental effect of MSC administration on skin allograft survival in comparison with the other groups. Logrank analysis showed a significant difference among the four groups ($P < 0.001$). On the other hand, MSC infusion in immunosuppressed animals improved skin graft survival in comparison to the control (C vs. A $P < 0.001$) as well as MSC group (C vs. D $P < 0.001$). Combined treatment (MSC and CsA) decreased graft rejection compared with the group treated with CsA only, although the difference was not statistically significant ($P = 0.2$).

Histological evaluation

Histological analysis of skin biopsies from arm A rats showed a dense lymphocytic infiltrate in dermis, particularly in peri-follicular areas, with apoptotic keratinocytes, that is a typical graft rejection pattern (Fig. 3a). Inflammatory infiltrate (F) and epidermis thickness (ET) were analysed. Mean F value was 2.7 while mean ET value was $73.6 \mu\text{m}$. In arm B, histological qualitative examination of

skin graft showed mild-low dense lymphocytes dermal infiltrate and signs of re-epithelization in the epidermis. The graft rejection pattern was less evident and apoptotic keratinocytes were present almost exclusively in the follicular epithelium (Fig. 3b). Mean F value was 2.2, while mean ET value was $80.7 \mu\text{m}$. In Group C, signs of mild-low graft rejection were evident, with a lichenoid infiltrate in the upper dermis and apoptotic keratinocytes in the epidermis (Fig. 3c). Signs of re-epithelization in the epidermis were also present. Mean F value was 2.2, and mean ET value was $77.6 \mu\text{m}$. Group D was qualitatively very heterogeneous with processes of regeneration (fibroblastic activation) and with evident signs of epidermal degeneration and graft rejection only in some samples (Fig. 3d). In some fragments, the inflammatory infiltrate did not allow a clear evaluation of the type of reaction. Mean F value was 2.9 while mean ET value was $48 \mu\text{m}$. Differences among groups were not statistically significant.

Histochemical stains were performed to exclude bacterial infections. No bacteria were identifiable in the tissue sections by Gram and Warthin–Starry stains. Neutrophils were attracted by the necrotic epidermis.

Cytokine expression analysis

Using a real-time quantitative RT-PCR method, we examined the mRNA expression of different genes in rat skin allograft on day 10 after transplantation. Figure 4 summarizes the data of mRNA levels expressed as fold changes in relation to the control group (untreated). We studied the expression of pro-inflammatory cytokine genes such as $\text{IFN-}\gamma$, IL-2 and $\text{TNF-}\alpha$. $\text{IFN-}\gamma$ and IL-2 gene expression were significantly different among the four groups ($P < 0.0001$ and $P = 0.023$, respectively). In particular, $\text{IFN-}\gamma$ mRNA levels were significantly lower in CsA group (4.3-fold, $P = 0.004$) and MSC group (3.6-fold, $P = 0.002$) in comparison with the control group. Moreover, CsA + MSC group showed significantly higher $\text{IFN-}\gamma$ mRNA levels in comparison to CsA and MSC groups ($P = 0.07$ and 0.008 , respectively). IL-2 mRNA levels among the four groups showed an expression pattern similar to that observed for $\text{IFN-}\gamma$; the difference is statistically significant both in CsA and MSC groups in comparison with the untreated group ($P = 0.039$ and 0.010 , respectively). The overall $\text{TNF-}\alpha$ mRNA levels among the four groups were statistically different ($P = 0.04$). $\text{TNF-}\alpha$ mRNA gene expression was lower in CsA and in CsA + MSC groups, where it reached statistical significance ($P = 0.023$) in comparison with the control group.

Analysis of anti-inflammatory molecules such as IL-10 showed no differences between MSC and untreated animals. IL-10 mRNA levels in all groups were not statistically different. Interestingly, in CsA + MSC group there

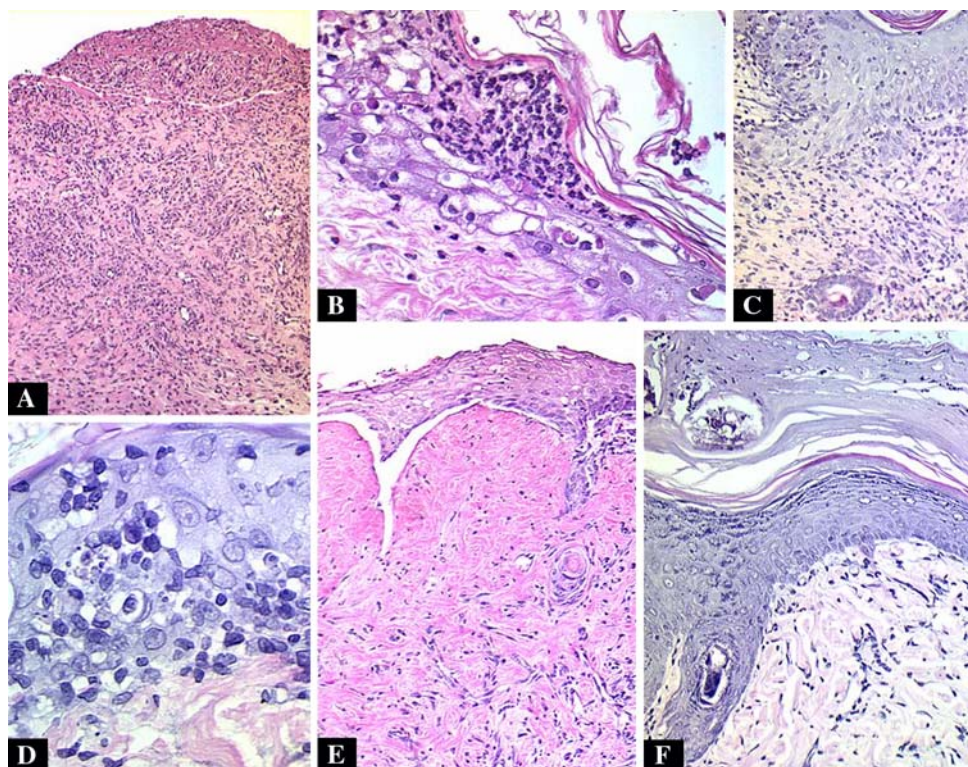


Fig. 3 **a** Haematoxylin–eosin $\times 50$, **b** haematoxylin–eosin $\times 200$; arm D (MSC): evident signs of epidermal degeneration and sometimes ulceration; necrotic apoptotic keratinocytes and neutrophil granulocytes recall are frequent findings; a dense lymphocytic infiltrate is present in the entire dermis. **c** Haematoxylin–eosin $\times 100$; arm A (control): epidermis is conserved with lichenoid graft rejection and diffuse mononuclear infiltrates in the dermis. **d** Haematoxylin–eosin $\times 400$; particular

of lymphocytic satellitosis. **e** Haematoxylin–eosin $\times 50$, **f** haematoxylin–eosin $\times 200$; arms B (CsA) and C (MSC + CsA) graft rejection pattern is less evident and apoptotic keratinocytes are present almost in the follicular epithelium, a mild–low dense lymphocytes dermal infiltrate is present and remnants of the pre-existing epidermis are detectable above a thickened corneum layer

was an up-regulation of IL-10 gene expression in relation to controls (1.6-fold), even if it did not reach statistical significance.

TGF- β gene is a well-known regulator of a number of cellular activities including tissue fibrogenesis, chondrogenic differentiation and immunomodulation. The overall difference of TGF- β mRNA levels among the four groups was statistically different ($P = 0.002$). TGF- β mRNA levels were lower in CsA + MSC group than in CsA ($P = 0.002$), untreated ($P = 0.019$) and MSC ($P = 0.02$) groups.

Discussion

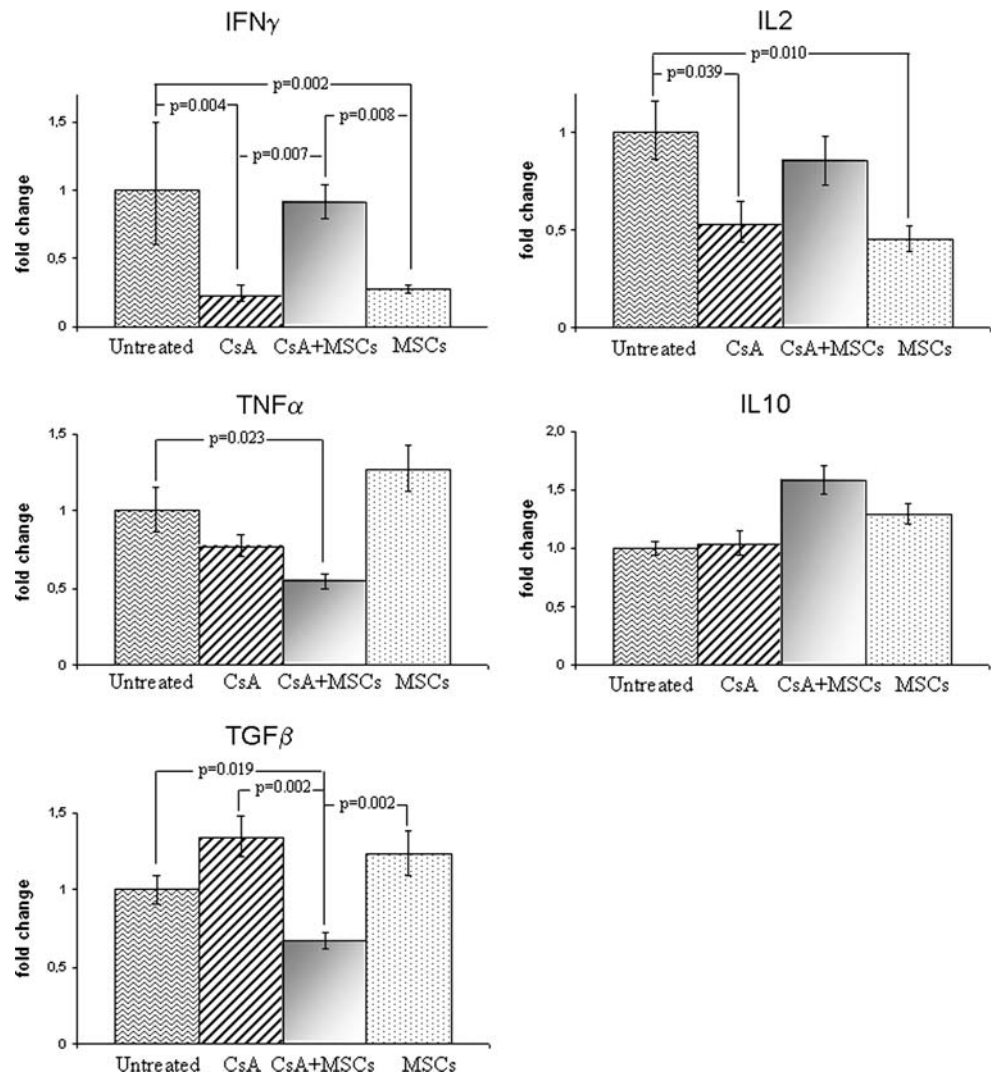
The demonstration of the *in vitro* immunosuppressive effect of MSC raised the issue of whether such property could also be reproduced in the setting of solid organs transplantation.

In this study we have examined the effects of MSC intravenous administration on skin allograft survival in an *in vivo* preclinical rat model. Results obtained from the present study showed that treatment with donor MSC without

immunosuppressive therapy reduced the mean skin graft survival as compared to control animals, suggesting an immunogenic, rather than a tolerogenic role for these cells. CsA treatment resulted in graft survival in 43% of animals. Rats treated with combined therapy (CsA and MSC) showed a better pattern with 57% of graft survival, suggesting a synergistic effect of the two treatments, although the differences between the two groups was not statistically significant. The synergistic immunosuppressive effect of CsA and MSC for the inhibition of lymphocytes proliferation was demonstrated *in vitro* [22].

Accelerated graft rejection upon MSC administration was also recently demonstrated in a heart transplantation preclinical model [16]. The authors confirmed the *in vitro* immunomodulatory properties of MSC but do not support their tolerogenic properties *in vivo*, as MSC injection were ineffective in prolonging allograft survival irrespective of the dose, route of administration and origin (syngeneic or allogeneic). In addition, the authors reported that the administration of MSC, together with low dose delayed CsA administration, accelerates rejection. This discrepancy with our findings may either be due to different dosage and

Fig. 4 mRNA expression of IFN- γ , IL-2, TNF- α , IL-10, and TGF- β genes. Data are expressed as fold changes in relation to the control group (untreated). Statistically significant differences among groups are reported above the columns



time of administration of CsA or due to different immunogenic properties of the organs. Moreover, our data are in agreement with another recent study [10] demonstrating that MHC-mismatched murine MSC led to a robust and specific cellular immune response in non-immunosuppressed allogeneic mice.

Results from histological analysis of skin biopsies correlated with skin graft survival data: inflammatory reaction was more intense in groups A and D which showed a rapid skin graft rejection. Although the epidermis thickness value did not reach statistical significance, in CsA-treated animals (groups B and C) the mean *ET* value was higher in comparison with the control group (A), indicating a correlation with reparative phenomena observed in the histopathological analysis. On the other hand, the MSC treated group (D) showed the lowest *ET* value in comparison to the control group that was in correlation with intense inflammatory infiltrate and sometimes with epidermal ulceration.

Our data on cytokines expression analysis at the site of skin graft showed that CsA treatment significantly

decreased pro-inflammatory cytokines IFN- γ and IL-2 and reduced TNF- α gene expression. Under our conditions, CsA treatment did not affect IL-10 gene expression but the expression of TGF- β was enhanced, in agreement with studies showing that this cytokine is one of the most potent mediators of the immunosuppressive effect of CsA [17]. However, TGF- β is a polyfunctional molecule involved in several biological processes other than immunosuppression [13, 23, 33] TGF- β is a well-known regulator of tissue fibrogenesis by stimulating fibroblast proliferation, promoting collagen synthesis and inhibiting collagen degradation. Our data showed that TGF- β expression is down-regulated in the combined treatment rat group C, where the fibrotic process seems less intense and there are signs of skin regeneration. In addition, cytokine gene expression profile results from a complex network of reactions. All investigated cytokines are synthesized, with peculiar timing, by different cell types present at skin graft biopsies sites and they play a pivotal role in several important processes including angiogenesis, fibrosis inflammatory

reaction and immune modulation. Unfortunately we cannot correlate the cytokine profile with histological examination between graft rejecting and graft accepting rats, as all rats used for these analyses were sacrificed at day 10 post transplantation.

Results obtained from gene expression analysis suggested a role of cytokine environment in determining the MSC effect on the outcome of solid organ transplantation. In CsA-treated rats, where the level of pro-inflammatory cytokines (TNF- α , IFN- γ) is lower than controls, MSC administration resulted in longer skin graft survival. This pattern is reverted when the MSC are administered in not immunosuppressed rats, where the level of the pro-inflammatory cytokine TNF- α is higher. This hypothesis is supported by a recent work demonstrating reversal of immunosuppressive properties of allogeneic MSC possibly mediated by TNF- α in vitro [8]. However, further investigation at systemic level is necessary. The finding that a high level of inflammation may overcome the immunosuppressive properties of MSC has also been observed in vivo in a preclinical model of allogeneic BM transplantation [36]. In this experimental setting, MSC treatment fails to prevent GvHD.

In our study, mRNA levels of the two pro-inflammatory cytokines, IFN- γ and IL-2, were increased in the combined (MSC + CsA) group with a better skin graft survival. Recently, cardiac tolerated grafts have been demonstrated to have a T cell and macrophage infiltrate with increased mRNA for Th1 cytokines, IL-2, and IFN- γ but not Th2 cytokines [30]. Moreover, in other preclinical models, gene expression of pro-inflammatory cytokines was observed in tolerated allograft [15].

Despite the large amount of data on the immunosuppressive properties of MSC in vitro [18], only few reports suggest that these immunomodulatory properties of allogeneic MSC may be translated to the in vivo setting, as little is known regarding host immune response to MSC. Discordant data are available in vivo on the use of syngeneic and allogeneic MSC in immunosuppressed or non-immunosuppressed animals [10, 14, 16, 27, 34, 36]. Varying results are probably due to different experimental animal models used, the different MSC source (human, rat, mouse) and to the different route of MSC administration (intravenously, in situ implant). In addition, controversy exists on the immunogenicity and immunomodulating potential of MSC in vivo. Few animal studies in vivo and in vitro reported that allogeneic/xenogenic MSC are rejected in an immunocompetent host [14, 16]. Recently Nauta et al. [27] demonstrated that allogeneic murine MSC are not intrinsically immunoprivileged as they can induce a memory T cell response in vivo resulting in graft rejection in a murine allogeneic BM transplantation model through a cellular immune response.

In conclusion, our study in a skin allograft transplantation model demonstrated a clear immunogenic role for donor (allogeneic) MSC as, when administered in immunocompetent rats, they stimulate graft rejection. It may be speculated that immunosuppressive effect of MSC can be fully elicited when the survival of these cells is prolonged by the simultaneous administration of CsA.

The reduction of immunosuppressive drug toxicity and side effects is an important goal in solid organ transplantation but further in-depth studies are necessary to demonstrate the efficacy of MSC treatment in immunosuppressed animals and to reach a clear definition of MSC therapeutic potential.

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References

1. Aggarwal S, Pittenger MF (2005) Human mesenchymal stem cells modulate allogeneic immune cell response. *Blood* 105:1815–1822
2. Barber WH, Mankin JA, Laskow DA, Deierhoi MH, Julian BA, Curtis JJ, Diethelm AG (1991) Long-term results of a controlled prospective study with transfusion of donor-specific bone marrow in 57 cadaveric renal allograft recipients. *Transplantation* 1:70–75
3. Bartholomew A, Sturgeon C, Siatskas M, Ferrer K, McIntosh K, Patil S, Hardy W, Devine S, Ucker D, Deans R, Moseley A, Hoffman R (2002) Mesenchymal stem cells suppress lymphocyte proliferation in vitro and prolong skin graft survival in vivo. *Exp Hematol* 1:42–48
4. Chung NG, Jeong DC, Park SJ, Choi BO, Cho B, Kim HK, Chun CS, Won JH, Han CW (2004) Cotransplantation of marrow stromal cells may prevent lethal graft-versus-host disease in major histocompatibility complex mismatched murine hematopoietic stem cell transplantation. *Int J Hematol* 4:370–376
5. Demir Y, Ozmen S, Klimczak A, Mukherjee AL, Siemionow M (2004) Tolerance induction in composite facial allograft transplantation in the rat model. *Plast Reconstr Surg* 7:1790–1801
6. Dey B, Sykes M, Spitzer TR (1998) Outcomes of recipients of both bone marrow and solid organ transplants. A review. *Medicine (Baltimore)* 5:355–369
7. Djouad F, Plence P, Bony C, Tropel P, Apparailly F, Sany J, Noel D, Jorgensen C (2003) Immunosuppressive effect of mesenchymal stem cells favors tumor growth in allogeneic animals. *Blood* 102:3837–3844
8. Djouad F, Fritz V, Apparailly F, Louis-Plence P, Bony C, Sany J, Jorgensen C, Noel D (2005) Reversal of the immunosuppressive properties of mesenchymal stem cells by tumor necrosis factor alpha in collagen-induced arthritis. *Arthritis Rheum* 5:1595–1603
9. Dobson KR, Reading L, Haberey M, Marine X, Scutt A (1999) Centrifugal isolation of bone marrow from bone: an improved method for the recovery and quantitation of bone marrow osteoprogenitor cells from rat tibiae and femur. *Calcif Tissue Int* 5:411–413
10. Eliopoulos N, Stagg J, Lejeune L, Pommey S, Galipeau J (2005) Allogeneic marrow stromal cells are immune rejected by MHC class I- and class II-mismatched recipient mice. *Blood* 13:4057–4065
11. Fehr T, Sykes M (2004) Tolerance induction in clinical transplantation. *Transpl Immunol* 2:117–130
12. Friedenstein AJ (1976) Precursor cells of mechanocytes. *Int Rev Cytol* 47:327–359

13. Gaciong Z, Koziak K, Religa P, Lisiecka A, Morzycka-Michalik M, Rell K, Kozłowska-Boszkó B, Lao M (1995) Increased expression of growth factors during chronic rejection of human kidney allograft. *Transplant Proc* 27:928–929
14. Grinnemo KH, Mansson A, Dellgren G, Klingberg D, Wardell E, Drvota V, Tammik C, Holgersson J, Ringden, Sylven C, Le Blanc K (2004) Xenoreactivity and engraftment of human mesenchymal stem cells transplanted into infarcted rat myocardium. *J Thorac Cardiovasc Surg* 5:1293–1300
15. Heslan JM, Renaudin K, Thebault P, Josien R, Cuturi MC, Chiffolleau E (2006) New evidence for a role of allograft accommodation in long-term tolerance. *Transplantation* 82:1185–1193
16. Inoue S, Popp FC, Koehl GE, Pisco P, Schlitt HJ, Geisser EK, Dahlke MH (2006) Immunomodulatory effects of mesenchymal stem cells in a rat organ transplant model. *Transplantation* 81:1589–1595
17. Khanna AK, Cairns VR, Becker CG, Hosenpud JD (1998) TGF-beta: a link between immunosuppression, nephrotoxicity, and CsA. *Transplant Proc* 4:944–945
18. Le Blanc K, Tammik L, Sundberg B, Haynesworth SE, Ringden O (2003) Mesenchymal stem cells inhibit and stimulate mixed lymphocyte cultures and mitogenic responses independently of the major histocompatibility complex. *Scand J Immunol* 1:11–20
19. Le Blanc K, Rasmusson I, Sundberg B, Gotherstrom C, Hassan M, Uzunel M, Ringden O (2004) Treatment of severe acute graft-versus-host disease with third party haploidentical mesenchymal stem cells. *Lancet* 9419:1439–1441
20. Lim Yeon J, Jeun SS, Lee KJ, Oh JH, Kim SM, Park SI, Jeong CH, Kang SG (2006) Multiple stem cell traits of expanded rat bone marrow stromal cells. *Exp Neurol* 199:416–426
21. Liu Y, Song J, Liu W, Wan Y, Chen X, Hu C (2003) Growth and differentiation of rat bone marrow stromal cells: does 5-azacytidine trigger their cardiomyogenic differentiation? *Cardiovasc Res* 58:460–468
22. Maccario R, Moretta A, Cometa A, Montagna D, Comoli P, Locatelli F, Podesta M, Frassoni F (2005) Human mesenchymal stem cells and cyclosporin A exert a synergistic suppressive effect on in vitro activation of alloantigen-specific cytotoxic lymphocytes. *Biol Blood Marrow Transplant* 12:1031–1032
23. Mannon RB (2006) Therapeutic targets in the treatment of allograft fibrosis. *Am J Transplant* 6:867–875
24. Mathew JM, Garcia-Morales RO, Carreno M, Jin Y, Fuller L, Blomberg B, Cirocco R, Burke GW, Ciancio G, Ricordi C, Esquenazi V, Tzakis AG, Miller J (2003) Immune responses and their regulation by donor bone marrow cells in clinical organ transplantation. *Transpl Immunol* 3–4:307–321
25. Meisel R, Zibert A, Laryea M, Gobel U, Daubener W, Dilloo D (2004) Human bone marrow stromal cells inhibit allogeneic T-cell responses by indoleamine 2,3-dioxygenase-mediated tryptophan degradation. *Blood* 12:4619–4621
26. Monaco AP, Clark AW, Wood ML, Sahyoun AI, Codish SD, Brown RW (1976) Possible active enhancement of a human cadaver renal allograft with antilymphocyte serum (ALS) and donor bone marrow: case report of an initial attempt. *Surgery* 4:384–392
27. Nauta AJ, Westerhuis G, Kruisselbrink AB, Lurvink EG, Willenze R, Fibbe WE (2006) Donor-derived mesenchymal stem cells are immunogenic in an allogeneic host and stimulate donor graft rejection in a non-myeloablative setting. *Blood* 6:2114–2120
28. Petit F, Minns AB, Nazzari JA, Hettiaratchy SP, Lantieri LL, Randolph MA, Lee WP (2004) Prolongation of skin allograft survival after neonatal injection of donor bone marrow and epidermal cells. *Plast Reconstr Surg* 113:270–276
29. Pittenger MF, Mackay AM, Beck SC, Jaiswal RK, Douglas R, Mosca JD, Moorman MA, Simonetti DW, Craig S, Marshak DR (1999) Multilineage potential of adult human mesenchymal stem cells. *Science* 5411:143–147
30. Plain KM, Boyd R, Verma ND, Robinson CM, Tran GT, Hodgkinson SJ, Hall BM (2007) Transplant tolerance associated with a Th1 response and not broken by IL-4, IL-5, and TGF-beta blockade or Th1 cytokine administration. *Transplantation* 83:764–773
31. Rasmusson I, Ringden O, Sundberg B, Le Blanc K (2005) Mesenchymal stem cells inhibit lymphocyte proliferation by mitogens and alloantigens by different mechanisms. *Exp Cell Res* 1:33–41
32. Shapiro R, Starzl TE (1998) Bone marrow augmentation in renal transplant recipients. *Transplant Proc* 4:1371–1374
33. Sharma VK, Bologa RM, Xu GP, Li B, Mouradian J, Wang J, Serur D, Rao V, Suthanthiran M (1996) Intragraft TGF-beta 1 mRNA: a correlate of interstitial fibrosis and chronic allograft nephropathy. *Kidney Int* 49:1297–1303
34. Stagg J, Pommey S, Eliopoulos N, Galipeau J (2006) Interferon-gamma-stimulated marrow stromal cells: a new type of nonhematopoietic antigen-presenting cell. *Blood* 6:2570–2577
35. Starzl TE, Demetris AJ, Trucco M, Murase N, Ricordi C, Ildstad S, Ramos H, Todo S, Tzakis A, Fung JJ (1993) Cell migration and chimerism after whole-organ transplantation: the basis of graft acceptance. *Hepatology* 6:1127–1152
36. Sudres M, Norol F, Trenado A, Gregoire S, Charlotte F, Levacher B, Lataillade JJ, Bourin P, Holy X, Vernant JP, Klatzmann D, Cohen JL (2006) Bone marrow mesenchymal stem cells suppress lymphocytes proliferation in vitro but fail to prevent graft-versus-host disease in mice. *J Immunol* 176:7761–7767
37. Taylor HR, Morris PJ (1970) Skin grafting in rats. *Am J Med Technol* 4:149–157
38. Tse WT, Pendleton JD, Beyer WM, Egalka MC, Guinan EC (2003) Suppression of allogeneic T-cell proliferation by human marrow stromal cells: implications in transplantation. *Transplantation* 3:389–397
39. Wood ML, Gozzo JJ, Monaco AP (1972) Use of antilymphocyte serum and bone marrow for production of immunological tolerance and enhancement: review and recent experiments. *Transplant Proc* 4:523–529
40. Zappia E, Casazza S, Pedemonte E, Benvenuto F, Bonanni I, Geroni E, Giunti D, Ceravolo A, Cazzanti F, Frassoni F, Mancardi G, Uccelli A (2005) Mesenchymal stem cells ameliorate experimental autoimmune encephalomyelitis inducing T-cell anergy. *Blood* 5:1755–1761