

A Comparison of Neural Differentiation and Retinal Transplantation with Bone Marrow-Derived Cells and Retinal Progenitor Cells

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ABSTRACT

Retinal progenitor cells (RPCs) are immature precursors that can differentiate into retinal neurons, including photoreceptors. Recently, it has been reported that bone marrow-derived cells may also be capable of differentiation into cells of central nervous system lineage, including retinal neurons. We compared these two cell types to evaluate their potential as a source of cells for retinal transplantation. Marrow stromal cells (MSCs) and macrophages were isolated from enhanced green fluorescence protein mice. MSCs were cultured with brain-derived neurotrophic factor, nerve growth factor, and basic fibroblast growth factor to induce neuronal differentiation. RPCs were cultured under the same conditions or with 10% fetal bovine serum. Neuronal marker expression was examined and compared between MSCs and RPCs. MSCs, macrophages, and RPCs were also cultured

with explanted retinas from rhodopsin knockout mice to study their potential for retinal integration. MSCs expressed neuronal and retina-specific markers by reverse transcription-polymerase chain reaction and immunocytochemistry. Both types of cells migrated into retinal explants and expressed neurofilament 200, glial fibrillary acidic protein, protein kinase C- α , and recoverin. RPCs expressed rhodopsin, a photoreceptor marker we never detected in MSCs. A majority of bone marrow derived-macrophages differentiated into cells that resembled microglia, rather than neural cells, in the explanted retina. This study shows that RPCs are likely to be a preferred cell type for retinal transplantation studies, compared with MSCs. However, MSCs may remain an attractive candidate for autologous transplantation. *STEM CELLS* 2006;24:2270–2278

INTRODUCTION

Marrow stromal cells (MSCs) are a population of multipotent mesenchymal stem cells distinct from hematopoietic stem cells. MSCs were originally reported to contribute to the microenvironment of bone marrow and to be necessary for the proliferation of hematopoietic stem cells [1]. It has recently been shown that MSCs can differentiate into various cell lineages, including bone [2, 3], muscle [4], fat [5], cartilage [6], cardiomyocytes [7–9], and hepatocytes [10]. Recently, some studies claimed that MSCs could differentiate cells expressing markers of neurons and glia in vitro [11–17]. MSCs also have the capacity to migrate into the uninjured [18] and diseased brain [19, 20] and spinal cord [21, 22]. Interestingly, studies show that MSCs differentiate into cells expressing markers of photoreceptors and glia in the retina [23, 24].

The two major clinical subtypes of retinal degeneration (RD) are retinitis pigmentosa and age-related macular degeneration. A hallmark of these diseases is photoreceptor cell degeneration, resulting in visual loss. No effective restorative treatment exists for either RD subtype. Previously, we reported that brain-derived progenitor cells can migrate and differentiate into cells expressing markers of mature neurons and glia when grafted to the retina of mice and rats with RD [25–29]. Despite incorporation into the host retina and morphological similarities to various retinal cell types, the transplanted cells failed to express retina-specific markers in each of these studies. Recently, the transplantation of stem and progenitor cells isolated from retina has shown promise as a strategy for photoreceptor replacement [26, 28, 30–32]. Many mammalian tissues, including the retina, contain stem or progenitor cells that can be

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isolated, propagated, and grafted into animal models of RD [26, 32]. The goal of retinal transplantation is the replacement of dead or diseased host cells with healthy, functional donor cells. In the present study, we investigated whether MSCs could effectively differentiate into retinal cells by using a cocktail of brain-derived neurotrophic factor (BDNF), nerve growth factor (NGF), and basic fibroblast growth factor (bFGF), which (as we previously reported) induces MSC differentiation into neurons [17]. Because there are reports of the differentiation of microglial cells into neurons [33] and bone marrow-derived macrophages into brain microglia [34, 35], we examined the differentiation of macrophages when grafted into the retina. Here, we compared the potential of retinal progenitor cells (RPCs) and MSCs for use in retinal transplantation studies.

MATERIALS AND METHODS

Experimental Animals

All experiments were performed in adherence with the ARVO (Association for Research in Vision and Ophthalmology) Statement for the Use of Animals in Ophthalmic and Vision Research and with the Schepens Eye Research Institute Animal Care and Use Committee (Boston, MA). Rhodopsin knockout mice ($\rho^{-/-}$ mice; C57/BL6 background, provided by Peter Humphries, University of Dublin, Trinity College, Dublin, Ireland) and postnatal day 1 (P1) enhanced green fluorescence protein (EGFP) mice (C57BL/6 background; Dr. Masaru Okabe, University of Osaka, Osaka, Japan) were euthanized by CO₂ gas.

Isolation of MSCs and Macrophages

Humeri, femurs, and tibias were obtained from P1 EGFP mice and divided into small pieces. These small pieces were cultured in Dulbecco's modified Eagle's medium (DMEM)/F-12 with 10% fetal bovine serum (FBS), and the nonadherent cells were removed by replacement of the media. After approximately 2 weeks, the adherent cells became confluent and were incubated with trypsin for 3 minutes and removed from the flask. All cell cultures were maintained at 37°C, 5% CO₂.

After two or three passages, bone marrow-derived adherent cells were incubated with trypsin for 3 minutes to generate a single-cell suspension. Cells (1×10^6) were labeled with phycoerythrin-conjugated antibody against CD11b (1:50, marker for macrophages; BD Biosciences PharMingen, San Diego, <http://www.bdbiosciences.com>) and Cy-5-conjugated antibody against CD45 (1:50, marker for hematopoietic cells; BD Biosciences PharMingen). To isolate MSCs (CD45⁻, CD11b⁻) and macrophages (CD45⁺, CD11b⁺) from bone marrow-derived adherent cells, cell sorting was performed (data not shown). After sorting, the isolated MSCs and macrophages were cultured in 20% FBS for 2–3 days and then used for the subsequent experiments.

RPC Line

RPCs harvested from the retina of P1 EGFP mice were isolated and maintained in culture as previously described [32]. Briefly, retinas were surgically removed. The tissue was finely minced with two scalpel blades (no. 10), these whole retina homogenates were incubated in 0.1% collagenase, and a single-cell suspension was obtained. Dissociated cells were then cultured in

DMEM/F-12 supplemented with B27 (Invitrogen, Carlsbad, CA, <http://www.invitrogen.com>) and 20 ng/ml of epidermal growth factor (EGF). The neurospheres that were generated could in turn be dissociated and subcultured to generate new spheres [26, 32].

Neural Differentiation and Characterization of MSCs

To examine the differentiation of GFP-expressing MSCs in vitro, MSCs were incubated with trypsin for 3 minutes to generate a single-cell suspension. Cells (1×10^3) were plated on eight-well poly(D-lysine)/laminin-coated chamber slides (BD Biosciences, San Jose, CA, <http://www.bdbiosciences.com>) in DMEM/F-12 medium supplemented with 25 ng/ml BDNF (R&D Systems, Minneapolis, <http://www.rndsystems.com>), 40 ng/ml NGF (R&D Systems), and 20 ng/ml bFGF (R&D Systems) and were fixed with 4% paraformaldehyde (PFA) at 2 weeks after plating. The cells were blocked in 1% bovine serum albumin (Sigma-Aldrich, St. Louis, <http://www.sigmaaldrich.com>) + 0.2% Triton-100 (Sigma-Aldrich) and then incubated for 2 hours with primary antibody to Ki67 (1:100, cell proliferation marker; Vector Laboratories, Burlingame, CA, <http://www.vectorlabs.com>), nestin (1:1, immature neuronal marker; Developmental Studies Hybridoma Bank, Iowa City, IA, <http://www.uiowa.edu/~dshbwww/>), glial fibrillary acidic protein (GFAP) (1:50, astrocyte marker, Dako), MAP-2 (1:500, neuronal markers; Sigma-Aldrich), anti-protein kinase C (PKC)- α (1:200, bipolar cell marker; Santa Cruz Biotechnology, Inc., Santa Cruz, CA, <http://www.scbt.com>), 2D4 rhodopsin (1:500, rod photoreceptor marker; kind gift of Dr. R. Molday, University of British Columbia, Vancouver, BC, Canada), and recoverin antibodies (1:1,000, photoreceptor and bipolar cell marker; Chemicon International, Temecula, CA, <http://www.chemicon.com>). After rinsing in phosphate-buffered saline (PBS [0.1 M]), samples were incubated in Cy3-conjugated species-specific IgG (1:800) for 1 hour. Samples were rinsed again and then coverslipped in polyvinyl alcohol-1,4-diazabicyclo (2.2.2) octane (PVA-Dabco) with 4',6-diamidino-2-phenylindole (DAPI) and viewed under fluorescent illumination. As a control, the untreated MSCs were fixed with 4% PFA and labeled with the same antibodies.

Differentiation and Characterization of RPCs

To examine the differentiation of GFP-expressing RPCs in vitro, RPC spheres were incubated with trypsin for 1 minute to generate a single-cell suspension. In two separate experiments, cells (1×10^3) were plated on eight-well poly(D-lysine)/laminin-coated chamber slides (BD Biosciences) in DMEM/F-12 medium supplemented either with 10% FBS or with BDNF, NGF, and bFGF (the same growth factors used in MSCs differentiation experiments [17]) and were then fixed with 4% PFA at 1 day and 2 weeks after plating. The cells were then reacted and prepared with the antibodies described for MSCs.

Morphometry of Differentiated Cells

In each of the three culture conditions (MSCs with BDNF, NGF, and bFGF; RPCs with 10% FBS; and RPCs with BDNF, NGF, and bFGF), quantitative morphometry was performed by counting positive cells from a total cell number of at least 200 cells per well in randomly selected wells, selected based on DAPI

labeling ($n = 5$). In this counting study, cells (1×10^3) were plated on eight-well poly(D-lysine)/laminin-coated chamber slides (BD Biosciences). Five of eight wells were randomly chosen (by a masked observer), and all cells in the wells were counted. Nestin-positive cells from RPCs were counted at day 1, and MSCs and RPCs positive for other markers were counted after 2 weeks of treatment.

Reverse Transcription-Polymerase Chain Reaction Analysis of MSCs

For reverse transcription-polymerase chain reaction (RT-PCR) analysis, total RNA was extracted using TRIzol (Invitrogen) from MSCs grown in the presence or absence of BDNF, NGF, and bFGF in poly(D-lysine)/laminin-coated culture dishes (BD Biosciences) and from P1 EGFP mice retina for a positive control. First-strand cDNA was prepared from total RNA by reverse transcriptase using oligo(dT) primers. To detect nestin, β -tubulin class III (BT-III; neuronal marker), Map2, GFAP, PKC- α , recoverin, and rhodopsin, primers were used as described in Table 1.

Retinal Organ Culture

Retinal organ culture was performed as previously described [36–38] with minor modifications. Briefly, eyes were enucleated from rhodopsin knockout ($\rho-/-$) mice and transferred to ice-cold Hanks' balanced salt solution (Invitrogen). The retinas were separated from the retinal pigment epithelium and placed onto Millicell-CM membrane culture inserts (diameter 30 mm, pore size 0.4 μ m; Millipore Corporation, Billerica, MA, <http://www.millipore.com>) with the ganglion cell layer downward. The inserts with neural retina were placed in six-well plates containing approximately 1 ml/well of medium containing DMEM/F-12 supplemented with B27 neural supplement (Invitrogen), 2 mM L-glutamine (Sigma-Aldrich), 2,000 U of nystatin (Invitrogen), and 100 μ l/ml penicillin-streptomycin (Sigma-Aldrich). Organ cultures were maintained at 37°C, 5% CO₂ and fed every 2–3 days.

Explant Coculture

The host retinas were explanted from $\rho-/-$ mice (4–8 weeks of age). Cell suspensions (1 μ l, 5×10^3 cells/ μ l) containing (a) RPCs ($n = 12$); (b) MSCs with ($n = 12$) or without ($n = 6$)

pretreatment with BDNF, NGF, and bFGF for 1 week; and (c) macrophages ($n = 6$) were added to the retinas using a pipette immediately after isolation of recipient retinas. We placed the grafted cells onto the surface of retinal explants using a 200- μ l pipette. The cells were spread out over the entire surface of the explant, confirmed by viewing under fluorescent illumination. The explanted retinas were cultured for 1 week.

Tissue Preparation

After 1 week in explant coculture, the explanted retinas were fixed with 4% PFA, followed by cryoprotection with 20% sucrose. The retinas were sectioned at 12 μ m on a cryostat. Sections were stained with neurofilament (NF) 200 (1:1,000, neuronal marker; Sigma-Aldrich), GFAP, PKC- α , recoverin, and rhodopsin antibodies as described above. After fixation with PFA and sucrose, some whole-mount retinas were stained with biotin-*Griffonia simplicifolia* (GS)-lectin (5 μ g/ml, microglia and macrophages marker; Sigma-Aldrich) for 15 minutes and NF200 antibody for 2 hours. After rinsing in PBS, samples were respectively incubated in Cy3-conjugated streptavidin (Jackson ImmunoResearch Laboratories, Inc., West Grove, PA, <http://www.jacksonimmuno.com>) and Cy3-conjugated species-specific IgG (1:800) for 1 hour. Samples were rinsed again and then coverslipped in PVA-Dabco and viewed under fluorescent illumination.

RESULTS

Characterization of MSCs

When grown on conventional substrates in media supplemented with 10% FBS, GFP-transgenic MSCs exhibited high levels of endogenous green fluorescence (Fig. 1A). The untreated MSCs did not express nestin, Map2, GFAP, PKC- α , recoverin, or rhodopsin (data not shown). To examine differentiation in vitro, medium without 10% FBS was supplemented with BDNF, NGF, and bFGF. After 2 weeks of culture under differentiation conditions, MSCs differentiated into cells with neuronal morphologies and neurite-like processes (Fig. 1B) and also formed spheres (Fig. 1C). Subpopulations of MSCs expressed nestin (Fig. 1D–1F), Map2 (Fig. 1G–1I), GFAP (Fig. 1J–1L), PKC- α (Fig. 1M–1O), and recoverin (Fig. 1P–1R). These markers are consistent, although not conclusive, with differentiation into

Table 1. Primers used for reverse transcription-polymerase chain reaction analysis

Genes	Primer sequences (5'–3')	Product size (bp)	Temperature (°C)
Nestin	F: AACTGGCACACCTCAAGATGT	235	60
	R: TCAAGGGTATTAGCAAGGGG		
GFAP	F: CACGAACGAGTCCCTAGAGC	234	60
	R: ATGGTGATGCGGTTTTCTTC		
TB-III	F: ACCTCAACCACCTGGTATCG	344	60
	R: TGCTGTTCTTGCTCTGGATG		
Map2	F: CTGGACATCAGCCTCACTCA	164	60
	R: AATAGGTGCCCTGTGACCTG		
PKC- α	F: CCCATTCCAGAAGGAGATGA	212	60
	R: TTCCTGTCAAGCAAGCATCAC		
Recoverin	F: ATGGGGAATAGCAAGAGCGG	179	60
	R: GAGTCCGGGAAAACTTGAATA		
Rhodopsin	F: TCACCACCACCTCTACACA	216	60
	R: TGATCCAGGTGAAGACCACA		

Abbreviations: bp, base pair; F, forward; GFAP, glial fibrillary acidic protein; PKC, protein kinase C; R, reverse; TB, tubulin.

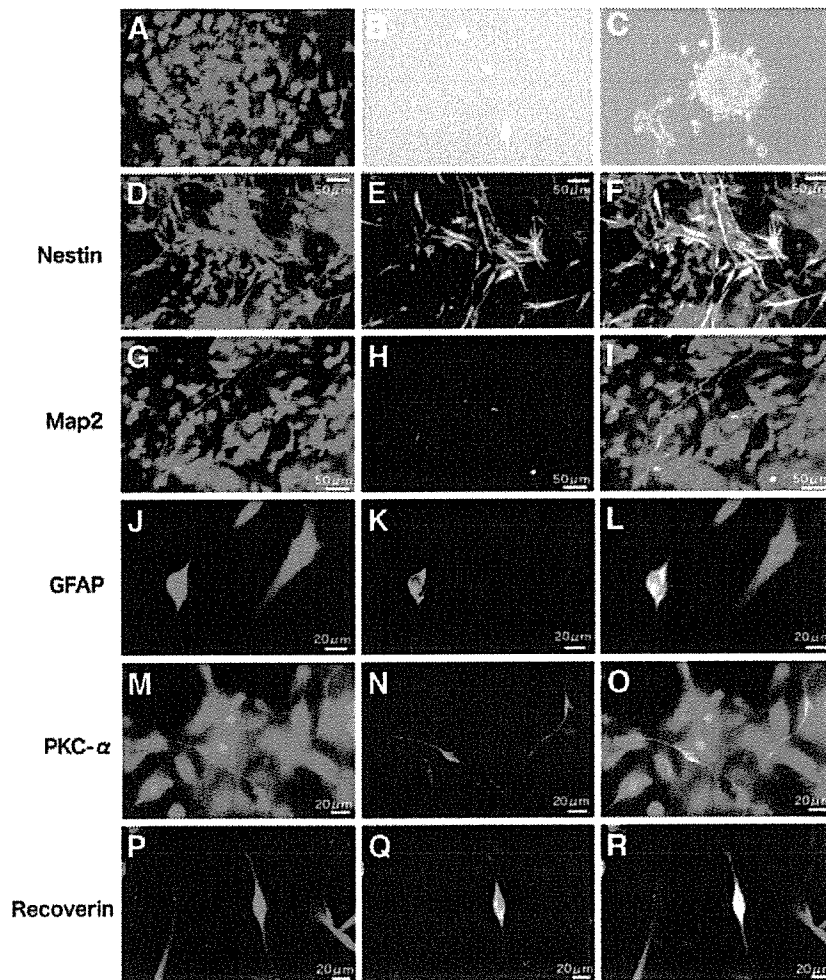


Figure 1. Differentiation and characterization of marrow stromal cell (MSCs) in vitro. Undifferentiated GFP⁺ MSCs grown in Dulbecco's modified Eagle's medium with 10% fetal bovine serum, viewed under fluorescein isothiocyanate illumination (A). MSCs cultured in serum-free medium with brain-derived neurotrophic factor, nerve growth factor, and basic fibroblast growth factor for 14 days (B–R). After 2 weeks of culture under differentiation conditions, MSCs morphologically differentiated into neuronal shape and had neuronal processes (B) and also formed spheres (C). Constitutive GFP expression (D, G, J, M, P), antibody/cytokeratin-3 immunoreactivity for nestin (E), Map2 (H), GFAP (K), PKC- α (N), and recoverin (Q), and merged images (F, I, L, O, R). Abbreviations: GFAP, glial fibrillary acidic protein; GFP, green fluorescent protein; PKC, protein kinase C.

retinal neurons. Interestingly, these immunopositive cells also showed morphological evidence suggestive of differentiation into immature photoreceptors, bipolar cell types, glial cells, and neuronal cells (Fig. 1F, 1I, 1L, 1O, 1R). We could not find any rhodopsin-positive cells from treated MSCs.

Characterization of RPCs

When grown on conventional substrates in medium supplemented with EGF, GFP-transgenic RPCs exhibited high levels of endogenous green fluorescence (Fig. 2A) and maintained an undifferentiated state characterized by ubiquitous Ki67 and nestin immunoreactivity (Fig. 2B, 2C). Cells could be maintained in this state for up to 1 year or 50 passages as neurospheres. To examine differentiation in vitro, medium without EGF was supplemented with 10% FBS. After 2 weeks culture under differentiation conditions, the cells were analyzed immunocytochemically. The number of Ki67⁺ cells markedly decreased (data not shown), and subpopulations expressed GFAP (Fig. 2D), Map2 (Fig. 2E), PKC- α (Fig. 2F), recoverin (Fig. 2G), or rhodopsin (Fig. 2H). These markers are consistent with differentiation into rod photoreceptors, bipolar cells, and Muller glia, all of which are known to be born late in retinogenesis. More-

over, these immunopositive cells also showed morphological evidence suggestive of immature photoreceptor differentiation, as well as of other retinal cell types (Fig. 2D–2H).

Quantitative Evaluation of Differentiated Cell Numbers: MSCs Versus RPCs

To examine the optimal source of cells for retinal transplantation, quantitative evaluation of differentiation into neuronal and retinal cells was carried out using cell counting as previously described [39].

After 2 weeks of BDNF, NGF, and bFGF treatment, the percentages of surviving MSCs expressing nestin, Map2, GFAP, PKC- α , and recoverin were 5.55%, 3.27%, 1.42%, 3.97%, and 13.9%, respectively. The percentages of nestin-, Map2-, GFAP-, PKC- α -, recoverin-, and rhodopsin-positive cells from RPCs treated with 10% FBS were 90.5%, 15.2%, 64.4%, 12.9%, 23.6%, and 3.17%, respectively. The rates of nestin-, Map2-, GFAP-, PKC- α -, recoverin-, and rhodopsin-positive cells from RPCs treated with BDNF, NGF, and bFGF were 89.2%, 29.4%, 10.9%, 28.2%, 22.3%, and 2.25%, respectively (Fig. 3A).

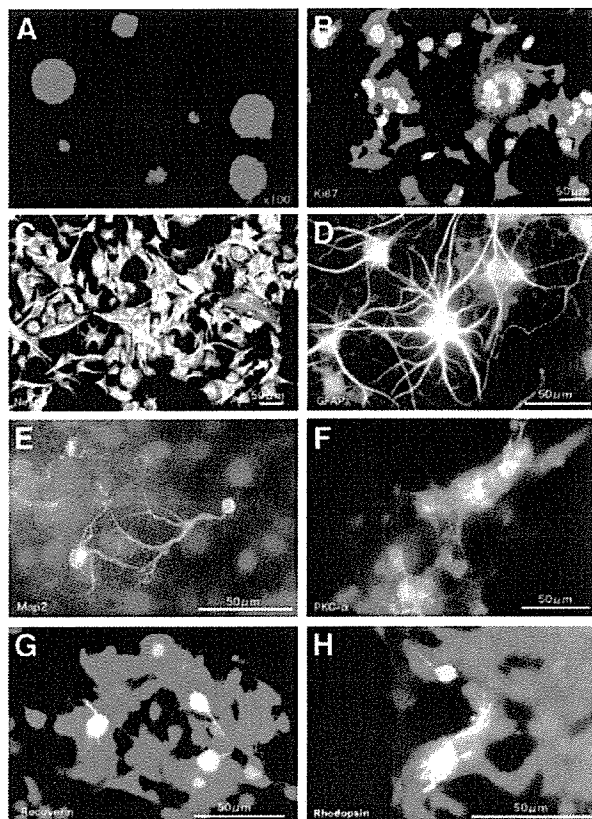


Figure 2. Differentiation and characterization of retinal progenitor cell (RPCs) *in vitro*. RPCs formed green fluorescent protein-positive neurospheres (A). RPCs cultured in the absence of epidermal growth factor and in the presence of 10% fetal bovine serum for 1 (B, C) or 14 (D–H) days. The cells were stained for Ki67 (B), nestin (C), GFAP (D), Map2 (E), PKC- α (F), recoverin (G), and rhodopsin (H). Abbreviations: GFAP, glial fibrillary acidic protein; MSC, marrow stromal cell; PKC, protein kinase C.

RT-PCR Analysis of BDNF, NGF, and bFGF Treatment

Semiquantitative RT-PCR analysis was carried out to determine the effect of BDNF, NGF, and bFGF on MSCs (Fig. 3B). MSCs without treatment showed only weak recoverin expression. (MSCs without treatment did not express nestin, BT-III, Map2, GFAP, PKC- α , or rhodopsin.) After 2 weeks of BDNF, NGF, and bFGF treatment, MSCs expressed nestin, BT-III, Map2, GFAP, PKC- α , and recoverin. Rhodopsin expression was not found. Recoverin expression was increased in treated MSCs.

Macrophages Differentiated into Microglia After Coculture with Explanted Retinas

After coculture with explanted rho^{-/-} mouse retinas, macrophages were viewed by fluorescent illumination at 3 and 7 days. Macrophages migrated into the retina and assumed morphology very reminiscent of microglial cells (Fig. 4A–4C). The cocultured macrophages also expressed GS-lectin, a marker of microglia (Fig. 4D–4F). There was no evidence of neuronal differentiation upon immunocytochemical and morphological analyses (data not shown).

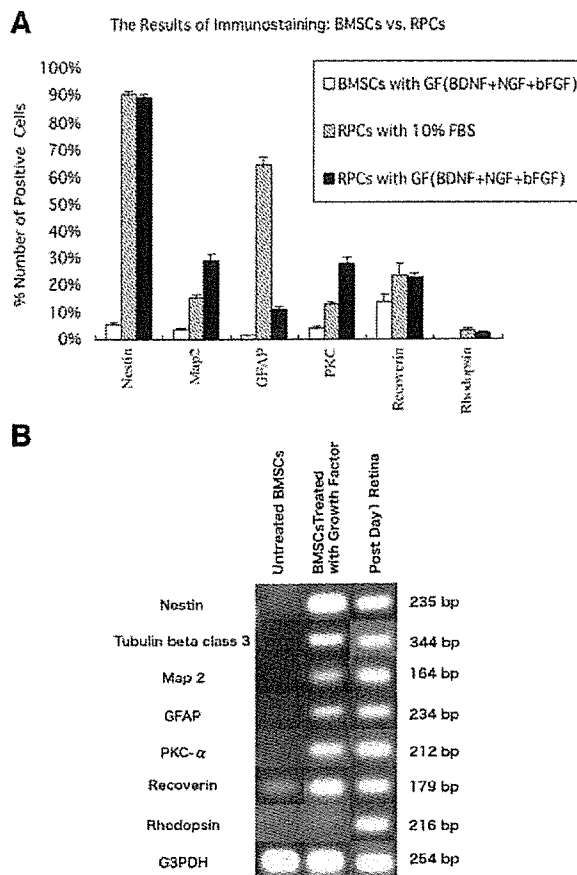


Figure 3. Comparison of BMSCs and RPCs. (A): The number of cells differentiated into retinal cells: comparison of marrow stromal cell (MSC) and RPCs. In this study, nestin-positive cells were counted at day 1, and other markers cells were counted at 2 weeks after treatment. (B): Effect of BDNF, NGF, and bFGF on transcription of retinal cell markers. Semiquantitative reverse transcription-polymerase chain reaction analysis was carried out to determine the effect of BDNF, NGF, and bFGF on MSCs. MSCs without treatment showed only weak recoverin expression. (MSCs without treatment did not express nestin, BT-III, Map2, GFAP, PKC- α , and rhodopsin completely.) After 2 weeks of BDNF, NGF, and bFGF treatment, treated MSCs expressed nestin, BT-III, Map2, GFAP, PKC- α , and recoverin; however, rhodopsin expression was not found. Recoverin expression was increased in treated MSCs. Abbreviations: BDNF, brain-derived neurotrophic factor; bFGF, basic fibroblast growth factor; BMSC, bone marrow stromal cell; bp, base pair; BT-III, β -tubulin class III; FBS, fetal bovine serum; GF, growth factor; GFAP, glial fibrillary acidic protein; NGF, nerve growth factor; PKC, protein kinase C; RPC, retinal progenitor cell.

Migration and Differentiation of MSCs

At 1 week in coculture, MSCs with and without pretreatment of BDNF, NGF, and bFGF migrated into explanted rho^{-/-} retina (Fig. 5A). MSCs without pretreatment did not show morphological or immunocytochemical evidence of neural differentiation (data not shown). On the other hand, pretreated MSCs showed morphological and immunocytochemical evidence of neuronal differentiation. Pretreated MSCs migrated into explanted retinas (Fig. 5A) and expressed NF200 (Fig. 5B–5G), GFAP (Fig. 5H–5J), PKC- α (Fig. 5K–5M), and recoverin (Fig.

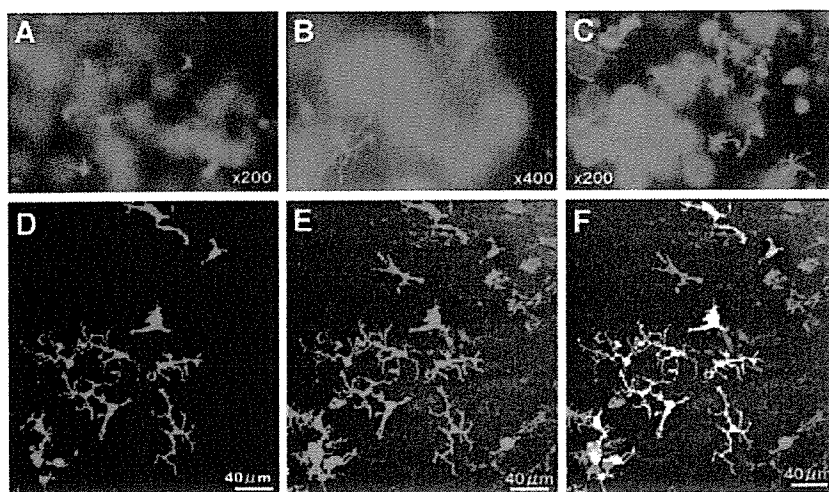


Figure 4. Macrophages differentiated into microglia after transplantation to explanted retinas. *Rho*^{-/-} mice retina at 3 (A) and 7 (B, C) days. Macrophages migrated into retina and morphologically changed their shape to that resembling microglia (A–C). Confocal (D–F) images seen at 1 week after grafting; constitutive green fluorescent protein expression (D), macrophage/microglia antibody/cytokeratin-3 immunoreactivity (E), and merged images (F).

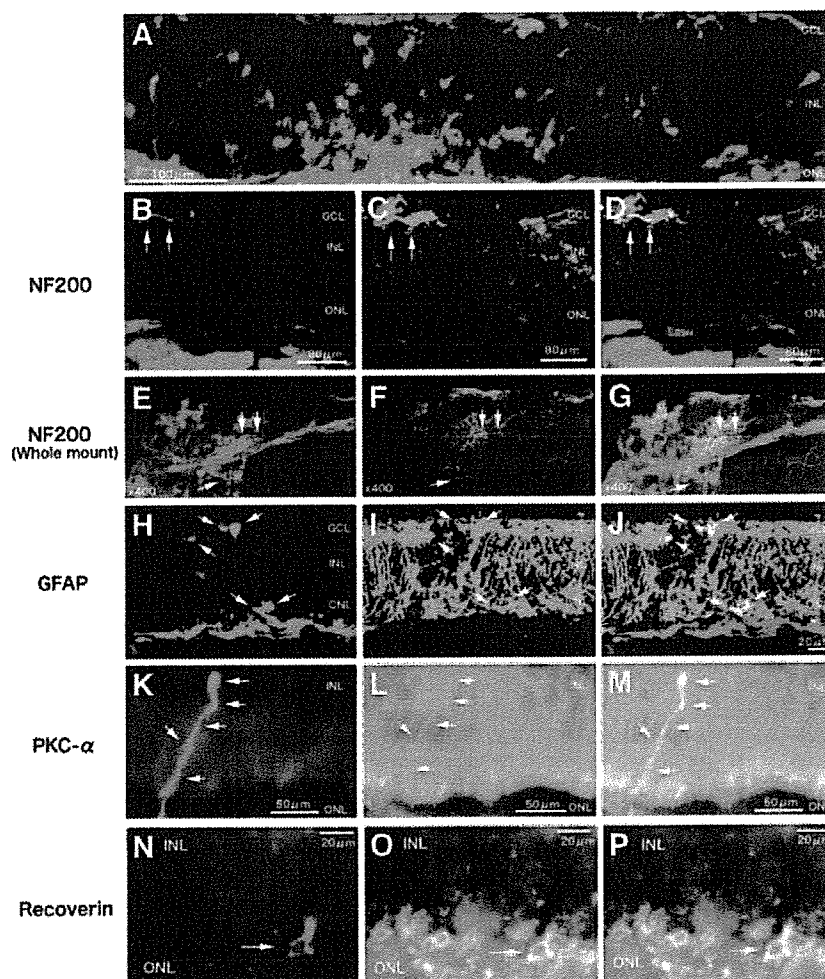


Figure 5. Migration and differentiation of pretreated marrow stromal cell (MSCs) into explanted retinas of *rho*^{-/-} mice. A large number of MSCs migrated into explanted retinas of *rho*^{-/-} mice (A). Epi-fluorescent (K–P) and confocal (B–J) images of the expression of neural and photoreceptor markers by pretreated MSCs that were grafted onto explanted retinas from *rho*^{-/-} mice, seen at 1 week after grafting; constitutive green fluorescent protein expression (B, E, H, K, N), antibody/cytokeratin-3 immunoreactivity for NF200 (C, F) (whole mount), GFAP (I), PKC- α (L), recoverin (O), and merged images (D, G, J, M, P). Abbreviations: GCL, ganglion cell layer; GFAP, glial fibrillary acidic protein; INL, inner nuclear layer; NF, neurofilament; ONL, outer nuclear layer; PKC, protein kinase C.

5N–5P). We also found morphological evidence of neuronal differentiation (Fig. 5B–5P). However, we could not find any rhodopsin-positive cells among coculture, pretreated MSCs.

Migration and Differentiation of RPCs

At 1 week in coculture, RPCs migrated into all retinal lamina adjacent to the graft after addition to the outer retina and showed

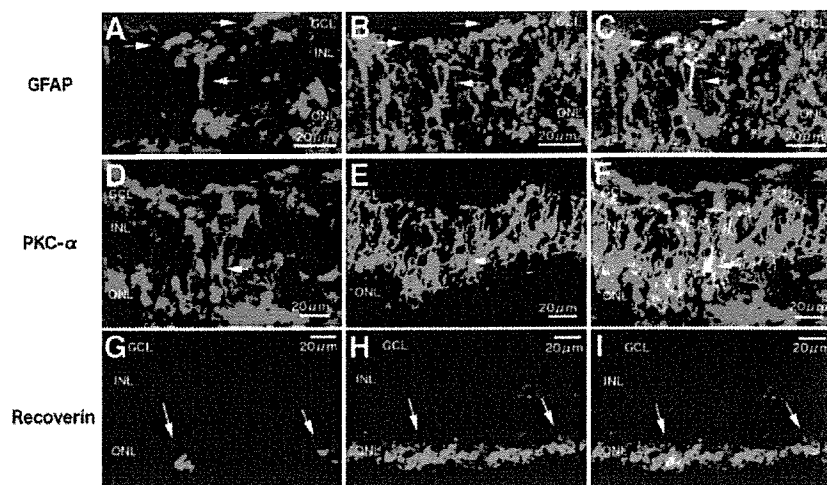


Figure 6. Migration and differentiation of pretreated retinal progenitor cells (RPCs) into explanted retinas of $\rho^{-/-}$ mice. Confocal images of the expression of neural and photoreceptor markers by RPCs grafting to explanted retinas of $\rho^{-/-}$ mice, seen at 1 week after grafting; constitutive green fluorescent protein expression (A, D, G), antibody/cytokeratin-3 immunoreactivity for GFAP (B), PKC- α (E), recoverin (H), and merged images (C, F, I). Abbreviations: GCL, ganglion cell layer; GFAP, glial fibrillary acidic protein; INL, inner nuclear layer; MSC, marrow stromal cell; ONL, outer nuclear layer; PKC, protein kinase C.

morphological evidence of neuronal differentiation (Fig. 6D–6I). GFP⁺ donor cells coexpressed a number of markers indicative of phenotypic maturation, including GFAP (Fig. 6A–6C), PKC- α (Fig. 6D–6F), and recoverin (Fig. 6G–6I). In the $\rho^{-/-}$ mice, the rod marker rhodopsin was not detected in either grafted RPCs or the host outer nuclear layer.

DISCUSSION

The results presented here demonstrate that MSCs treated with BDNF, NGF, and bFGF can differentiate into retinal cells expressing Map2, BT-III, GFAP, PKC- α , and recoverin by immunocytochemistry and RT-PCR. In the explanted retina, pretreated MSCs showed differentiation into retinal cells expressing NF200, GFAP, PKC- α , and recoverin, although nonpretreated MSCs did not show any evidence of differentiation into retinal cells. This shows that treatment with growth factors (as in our previous report [17]) is very important for neural induction of MSCs. Moreover, our data show that using growth factors promoted neuronal differentiation over glial differentiation in RPCs (Fig. 3A). In the present study, RPCs clearly showed a higher level of differentiation into retinal cells compared with MSCs. Induced MSCs expressed neuronal and glial markers and morphologically differentiated into neuron- and glia-like cells; however, RPCs showed better morphological differentiation and also expressed rhodopsin (Figs. 1, 2). Although a subpopulation of MSCs differentiated morphologically into neuronal-like cells and expressed neuronal markers, the majority remained undifferentiated both in terms of morphology and marker expression during the time course examined. The lack of rhodopsin expression *in vivo* and *in vitro* by MSCs may be an impediment to their use in photoreceptor replacement. One must be cognizant of the fact that the absence of evidence is not evidence of absence. The lack of differentiation *in vitro* indicates that the optimal conditions have yet to be determined. This is especially true in the case of RPC photoreceptor differentiation, which we have shown to be dependent upon specific conditions *in vivo*. The fact that RPCs failed to express rhodopsin after migration into explants is not surprising, considering that our previous studies found no evidence for rhodopsin among RPCs transplanted to $\rho^{-/-}$

mice *in vivo* [32]. The same study showed that RPCs expressed rhodopsin in another mouse strain with RD, the C3H mouse [32].

As with previous studies in the brain [34, 35], our results showed that macrophages migrated into explanted retina and appeared to differentiate into microglia. Although a previous report showed that microglia have potential for neuronal differentiation [33], we did not find evidence of differentiation into neuronal or glial cells in our explant study. Further studies will be needed to determine the neuronal potential of macrophages and microglia.

From a clinical perspective, MSCs are a good source for stem cell transplantation. Bone marrow cell transplantation is already an approved therapy for some kinds of hematological diseases and has the advantage of the possibility of autologous cell transplantation. Moreover, because recent reports have shown that MSCs have the capacity to modulate allogeneic cellular immunity [40, 41], MSCs may be useful for allogeneic transplantation.

Cell fusion has recently been proposed as the underlying explanation for the apparent plasticity and “transdifferentiation” of stem cells, including MSCs. This raises questions about the mechanisms of transdifferentiation *in vitro* and *in vivo* [42, 43]. Evidence against cell fusion has begun to mount; recent studies reported that MSCs can undergo transdifferentiation into various organ cell types, including neurons, without fusion [10, 44, 45]. We believe that our results cannot be attributed to cell fusion; this study shows that MSC differentiation into post-mitotic neuronal and retinal cells occurred in a controlled culture environment. Recent studies have shown that MSCs have a potential of transdifferentiation as cultured MSCs express mesodermal, endodermal, ectodermal, and germline genes, suggesting the potential to differentiate into all these cell types [46–48]. Moreover, our previous study [17], using the same methods for neuronal induction as this study, showed neuroectodermal induction, neural differentiation, and calcium uptake in response to a depolarizing stimulus from human MSCs. It has also been reported that neuroectodermal induction and electrophysiological characteristics of midbrain dopaminergic, serotonergic, and GABA-ergic neurons arise from treated MSCs [16].

CONCLUSION

The present study shows that RPCs have clear advantages over MSCs in potential retinal transplantation applications. First, no evidence was found for MSC differentiation into rod photoreceptors. Second, RPCs showed more complete differentiation into retinal cell subtypes than did MSCs, and this occurred at a significantly higher rate. Finally, we have previously reported that neuronal progenitor cells (NPCs) have inherent immune privilege, suggesting increased resistance of allogeneic NPC grafts to host rejection [49, 50]. Such findings suggest the possibility that RPCs possess immune privilege properties as well. MSCs also have significant therapeutic potential in transplantation medicine because they can be readily obtained through a well-established clinical procedure. They are relatively easy to isolate and expand

for autologous transplantation without the need for immunosuppression or the risk of rejection. In this comparison study, we submit that RPCs possess significant advantages for differentiation into retinal cells compared with MSCs.

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DISCLOSURES

The authors indicate no potential conflicts of interest.

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Increased Mobilization of c-kit⁺ Sca-1⁺ Lin⁻ (KSL) Cells and Colony-Forming Units in Spleen (CFU-S) Following De Novo Formation of a Stem Cell Niche Depends on Dynamic, But Not Stable, Membranous Ossification

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Stem cells are thought to inhabit in a unique microenvironment, known as “niche,” in which they undergo asymmetric cell divisions that results in reproducing both stem cells and progenies to maintain various tissues throughout life. The cells of osteoblastic lineage have been identified as a key participant in regulating the number of hematopoietic stem cells (HSCs). HSCs receive their regulatory messages from the microenvironment in the bone marrow. This would account for a reason why the localization of hematopoiesis is usually restricted in the bone marrow. To clarify the above possibility we employed a cell implantation-based strategy with a unique osteoblast cell line (KUSA-A1) derived from a C3H/He mouse. The implantation of KUSA-A 1 cells resulted in the generation of ectopic bones in the subcutaneous tissues of the athymic BALB/c nu/nu mice. Subsequently the mice obtained a greater amount of the bone marrow than normal mice, and they showed an increased number of HSCs. These results indicate that the newly generated osteoblasts-derived ectopic bones are responsible for the increase in the number of the HSC population. Furthermore, the increased number of HSCs directly correlates with both the magnitude of dynamic osteogenic process and the size of the newly generated bone or “niche.” *J. Cell. Physiol.* 208: 188–194, 2006. © 2006 Wiley-Liss, Inc.

Stem cell with potential for self-renewal and multi-lineage differentiation can be identified in various self-renewing tissues, including epidermis, intestinal epithelium, and testis, and hematopoietic stem cells (HSCs) are also capable of both self-renewal and multipotency (Ikehara, 2000; Weissman, 2000). The most important experimental evidence for the existence of such cells is the ability of a single bone-marrow-derived cell to reconstitute long-term hematopoiesis in lethally irradiated recipients (Till and McCulloch, 1961; Siminovitch et al., 1963; Till et al., 1964; Matsuzaki et al., 2004). Molecular markers that characterize transplantable cells with stem cell potential and allow their selective purification have been identified, and this achievement has been important to progress both applied and basic science (Spangrude et al., 1988; Goodell et al., 1996). As an example, CD34⁻, c-kit⁺, Sca-1⁺, and Lin⁻ cells have been identified as the most primitive HSCs (Osawa et al., 1996).

Stem-cell fate decisions in the developing embryo are governed by complex interplays between cell-autonomous signals and stimuli from the surrounding tissues. Stem cells are thought to inhabit in a unique microenvironment, known as “niche,” in which they undergo asymmetric divisions that generate both stem cells and progenies to maintain the tissue throughout life (Dzierzak et al., 1998; Matsuzaki et al., 2004). HSCs migrate from the yolk sac to the liver during early development, and they ultimately settle in the bone marrow and spleen of the adult. The bone marrow and spleen serve as the microenvironment that supports the

HSCs via cytokines, membrane-bound molecules, and gap junctions. And the classical experiment on HSC-colony formation by Till and McCulloch (1961) showed that reconstitution of hematopoiesis takes place only in hematopoietic organs. The niche hypothesis was first proposed by Schöfield, 1978, and it is supported by the evidence that HSCs have been successfully maintained in co-culture systems with marrow-derived stromal cells in vitro. Steel mice (Sl/Sl^d) have a mutation at the Sl locus, and spleen colonies cannot be produced in the mice when transplanted with normal marrow cells.

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Steel mice have a defect in the hematopoietic micro-environment, or the niche, where marrow stromal cells constitute (Harrison and Russell, 1972).

Bone marrow stromal cells are capable of differentiating into adipocytes, endothelial cells, chondrocytes, and osteoblasts (Pittenger et al., 1999). They are also capable of transdifferentiating into cardiomyocytes, skeletal myocytes, and neurons when exposed to inducers in vitro and in vivo (Umezawa et al., 1992; Makino et al., 1999; Kohyama et al., 2001; Takeda et al., 2004; Mori et al., 2005; Terai et al., 2005). Previous studies on the role of stromal cells in supporting HSCs have mainly been based on in vitro culture. The trabecular area of cancellous bone is the primary site of HSCs. They arise next to the inner surface of bone, and then migrate towards the blood vessels at the center of the bone marrow cavity as they mature. Since the 1970s, efforts to characterize the HSC niche have been focusing on developing systems in vitro that mimic some of the features of stem cell–niche interactions in vivo, and single clones of stromal cells have been found to be capable of supporting HSC self-renewal and differentiation in vivo (Okada et al., 1991, 1992). Osteoblastic marrow stromal cells are a regulatory component of the HSC niche in vivo that influences stem cell function, and some stromal cell clones are part of the bone-forming ‘osteoblastic’ lineage, which is consistent with a notion that osteoblasts may be a component of the HSC niche in vivo (Lord, 1990; Yoshimoto et al., 2003).

In the present study, we demonstrate that KUSA-A1 osteoblasts, whose number has been increased by local injection into the tissues, support an increase in the number of HSCs in both bone marrow and peripheral blood as a result of an increase in size of the microenvironment or niche in vivo. We provide in vivo evidence that shows an extra osteogenic process independent from that in the normal bone affects the reproduction of stem cells.

MATERIALS AND METHODS

Mice and their major histocompatibility complex (MHC) Class I

BALB/c nu/nu (H-2d), BALB/c (H-2d), C57BL/6N (H-2b), and C3H/He (H-2k) mice were obtained from Clea Japan Inc (Tokyo, Japan).

Cell lines and cell culture

KUSA-A1 cells, that was derived from a C3H/He mouse, were maintained in the M061101 medium (okada@med-shirotoiri.co.jp, MED SHIROTORI Co., Ltd., Tokyo) on 100 mm culture dishes (Falcon 3003; Becton Dickinson Labware, Bedford, MA) at 37°C under a humidified atmosphere of 5% CO₂. ST-2 cells were obtained from the RIKEN cell bank, Japan, and were maintained in RPMI 1640 (Invitrogen Corporation, Auckland, New Zealand) supplemented with 10% FCS and 10⁻⁵M of 2-ME (GIBCO BRL) at 37°C under a humidified atmosphere of 5% CO₂ in air.

Cell transplantation

Freshly scraped confluent cells (5 × 10⁶) were subcutaneously implanted into BALB/c nu/nu mice (Clea). These animals were sacrificed by cervical dislocation between 3 and 10 weeks after implantation.

Antibodies

Phycoerythrin (PE)-conjugated antibodies to CD4, CD8, CD3, B220, Mac-1, Gr-1, and Tre119 (Pharmingen, San Diego, CA), fluorescein isothiocyanate (FITC)-conjugated antibody to CD34, H-2k (Pharmingen), allophycocyanin (APC)-conju-

gated antibody to c-kit (Pharmingen), Sca-1 biotinylated antibody (Pharmingen), and antibody to CD16/32 (Fc III/II receptor; 1: 100; Fcblock; Pharmingen) were used for flow cytometric analysis.

Flow cytometric analysis

The monoclonal antibodies (mAbs) were either biotinylated or fluoresceinated. Biotinylated mAbs were detected with streptavidin-conjugated Red 613 (Invitrogen Corporation). Cells were incubated for 30 min on ice with CD16/32 (Fc III/II receptor; 1: 100; Fcblock) before staining with the first antibody. Cells were stained with the first antibody, incubated for 30 min on ice, and then washed twice with washing buffer. The secondary antibody was added, and after incubating the cells for 30 min on ice, they were washed twice with washing buffer and suspended in washing buffer. KUSA-A1 cell suspensions were prepared from monolayer cultures by exposure to trypsin (0.02% for 3 min at 37°C), followed by two washes in cold PBS plus 2% FCS and 0.01% sodium azide. After staining with a series of monoclonal antibodies according to manufacturer's protocol, cells were analyzed by fluorescence-activated cell sorter (FACS) with the FACS vantage system (Becton Dickinson, San Jose, CA).

Colony-forming unit in spleen (CFU-S) assay of hematopoietic cells obtained from ectopic bone

Freshly scraped confluent KUSA-A1 cells (5 × 10⁶) were subcutaneously implanted into BALB/c nu/nu mice (Clea). Hematopoietic cells were obtained from ectopic bone marrow generated by KUSA-A1 cells, and were assayed for CFU-S. Bone marrow cells (5 × 10⁵) were implanted into lethally irradiated BALB/c mice, and the number of colonies (Day 12 CFU-S) was counted 12 days after transplantation. Day 12 CFU-S including erythrocytic, granulocytic, megakaryocytic, and lymphocytic lineages are derived from multipotent HSCs and are more potent in terms of repopulating ability than day 8 CFU-S.

Soft X ray system

BALB nu/nu mice were examined by whole body soft X-ray radiography at 25.0 kV and 3.0 mA for 10 sec (SRO-IM50, Sofron, Tokyo) with X-ray RX film (Fuji Photofilm GmbH, Düsseldorf, Germany).

RESULTS

Induction of hematopoiesis by KUSA-A1 cells

When KUSA-A1 cells were implanted into the subcutaneous tissue, solid hard masses (Fig. 1A) were detected 5 weeks later as electron-dense nodules by soft X-ray analysis (Fig. 1B) at all implantation sites, that is, in the dermal tissue right beneath the cutaneous muscle. Histological examination revealed that the implanted cells survived, and some of them showed mitotic figures (Fig. 1C(a)). At 2 weeks following implantation, an osteogenic matrix was formed in the interstitium, but its matrix formation was still scanty (Fig. 1C(b)). And marked formation of capillary vessels containing erythrocytes in their lumen was observed. At 3 weeks, dense immature bone trabeculae with prominent vascular formation and osteoclast induction were seen (Fig. 1C(c)). By 4 weeks, mature bone trabeculae and sinusoids formed (Fig. 1C(d)), and there were mature granulocytic cells in the marrow space. Hematopoiesis began by 3–5 weeks after implantation.

To determine whether the size of the bone generated by KUSA-A1 cells depends on the implanted cell number, we implanted different numbers of KUSA-A1 cells into subcutaneous tissue (Fig. 1D). The results showed that bone size was clearly depending on the number of cells implanted. Nevertheless, hematopoiesis occurred regardless of the number of cells implanted and bone size.

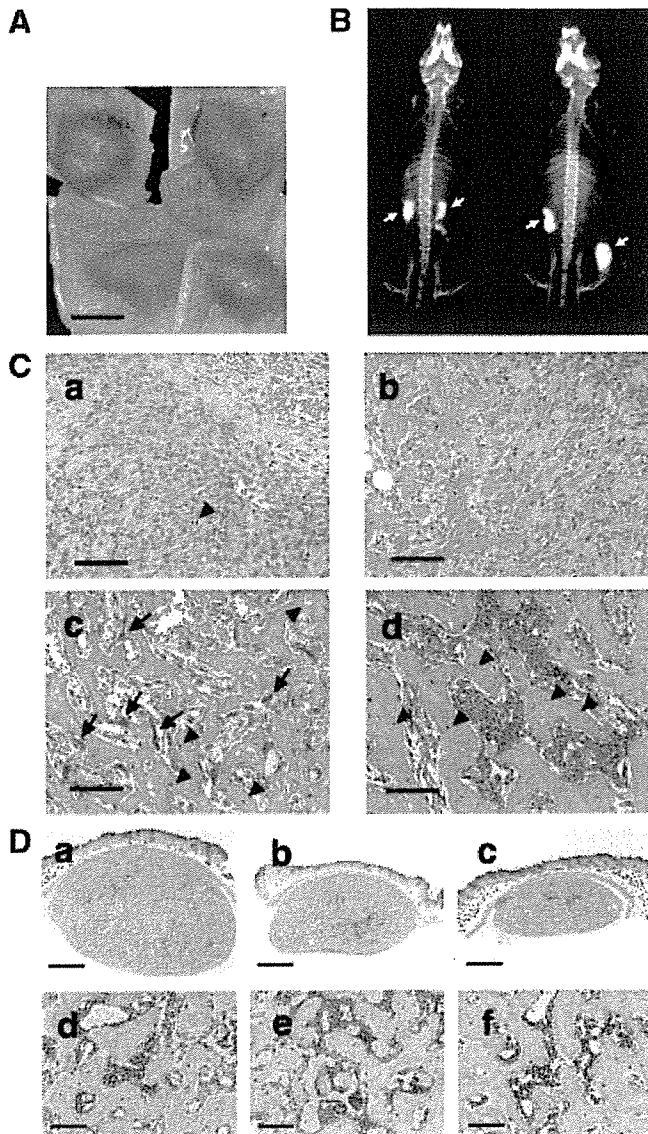


Fig. 1. Time course analysis of hematopoietic induction by KUSA-A1-induced membranous osteogenesis. KUSA-A1 cells were implanted into the subcutaneous tissue of BALB/c nu/nu mice at a density of 2×10^7 cells/200 μ l. A: Macroscopic view of bone formation at 5 weeks after KUSA-A1 cell injection. B: Soft X-ray image of a bone nodule formed by KUSA-A1 cells 5 weeks after implantation. C: Histopathological examination of induction of hematopoiesis and bone formation at 1 (a), 2 (b), 3 (c), and 4 (d) weeks after KUSA-A1 cell implantation. The mitotic figure of the implanted cell is indicated by an arrowhead (a). Note that numerous osteoclasts (c, arrows) as well as osteoblasts and osteocytes (c, arrowheads) were detected at 3 weeks after implantation. Mature osteocytes were observed at 4 weeks (d, arrowheads). Hematoxylin and eosin stain. Scale bars: 10 mm (A), 230 μ m (C–F). D: Correlation between the number of cells implanted and the size of the bone nodules. Microscopic view of the KUSA-A1 bone 5 weeks after implantation of 2×10^7 (a, d), 1×10^7 (b, e), or 5×10^6 (c, f) KUSA-A1 cells into subcutaneous tissue. Hematoxylin and eosin stain. Scale bars: 2 mm (a–c), 250 μ m (d), 300 μ m (e), 250 μ m (f).

Expression of major histocompatibility antigen (MHC) after implantation

Marrow stromal cells have been reported to be immunologically tolerant, probably due to lack of transplantation antigen expression. To determine whether KUSA-A1 cells are tolerant when implanted into an allogeneic host, KUSA-A1 cells, which are C3H/He mouse origin, were implanted into BALB/c mice (Fig. 2). Time-course analysis clearly revealed that all of

the cells were rejected and formed no bone, but numerous foreign body giant cells were observed (Fig. 2C,D), suggesting that KUSA-A1 cells are immunogenic in our experimental setting.

To determine alterations in MHC antigens after implantation, flow cytometric analysis was performed on KUSA-A1 cells (Fig. 2E, open peaks) and cultured mesenchymal cells obtained from KUSA-A1-induced ectopic bone (Fig. 2E, closed peaks) in BALB/c nu/nu mice. The KUSA-A1 cells started to express one of the MHC antigens, H-2k, after implantation into BALB/c nu/nu mice, but expression of Sca-1 was downregulated. Expression of Lin (CD3, CD4, CD8, B220, Gr-1, Mac-1, and Ter119), c-kit, and CD34 remained unchanged after implantation.

MHC expression of the hematopoietic cells in the KUSA-A1 cell-induced bone

Morphological analysis showed that hematopoiesis took place in the KUSA-A1-induced ectopic bone (Fig. 3A–E). Megakaryocytes (arrows in Fig. 3D), erythrocytes (Fig. 3D,E), and granulocytes (Fig. 3D,E) were detected as well as osteoblasts (arrows in Fig. 3E) and mature osteocytes (arrowheads in Fig. 4E). The hematopoietic cells isolated from the KUSA-A1 cell-induced ectopic bone expressed the H-2d antigen, implying that they were derived from the host cells and had not differentiated from the implanted KUSA-A1 cells.

Cytokine production by the implanted KUSA-A1 cells may not be attributable to the migration of hematopoietic cells

To determine whether cytokines, that is, interleukin-6, macrophage-colony stimulating factor, stem cell factor, fms-like tyrosine kinase-3 ligand, and thrombopoietin, were produced by the implanted cells and contributed to the hematopoiesis, ELISA analysis was performed on the serum from mice with cell implantation as well as conditioned medium of the KUSA-A1 cultures (Fig. 3F). RT-PCR analysis of cytokine gene expression revealed that the KUSA-A1 cells express CSF-1, thrombopoietin, angiotensinogen, c-kit ligand, leptin, lymphotoxin A and B, IL4, IL5, IL6, IL10, IL12B, IL16, IL17B, IL19, and angiopoietin1 genes (Supplementary Figure 1S) and transcriptome analysis revealed that KUSA-A1 cells express the SDF-1 gene at a high level (a frequency of 1.1×10^{-3}) (Sharov et al., 2003). However, none of the cytokine levels increased in the serum.

Analysis of KSL cells in the femur and the ectopic bone, and CFU-S in the peripheral blood and the ectopic bone

To investigate whether HSCs as well as mature hematopoietic cells migrates into the ectopic bone, the proportion of KSL cells was examined. The proportion was found to be the same, that is, 0.08%, in both the host femur (Fig. 4A) and the KUSA-A1 ectopic bone (Fig. 4B), suggesting that the ectopic bone as well as native bone serves microenvironment for HSCs.

The number of CFU-S were also counted in the host femur, peripheral blood, and KUSA-A1-induced bone marrow (Fig. 4C–E), and were found to account for $11.2 \pm 0.8/1.0 \times 10^5$ the cells in the KUSA-A1-induced ectopic bone (Fig. 4E, right). By day 12 the CFU-S of the host femur had increased from 28.3 ± 6.0 to $35.0 \pm 3.4/10^5$ cells (Fig. 4E, left). At day 12 CFU-S were also detected in the peripheral blood from the mice and

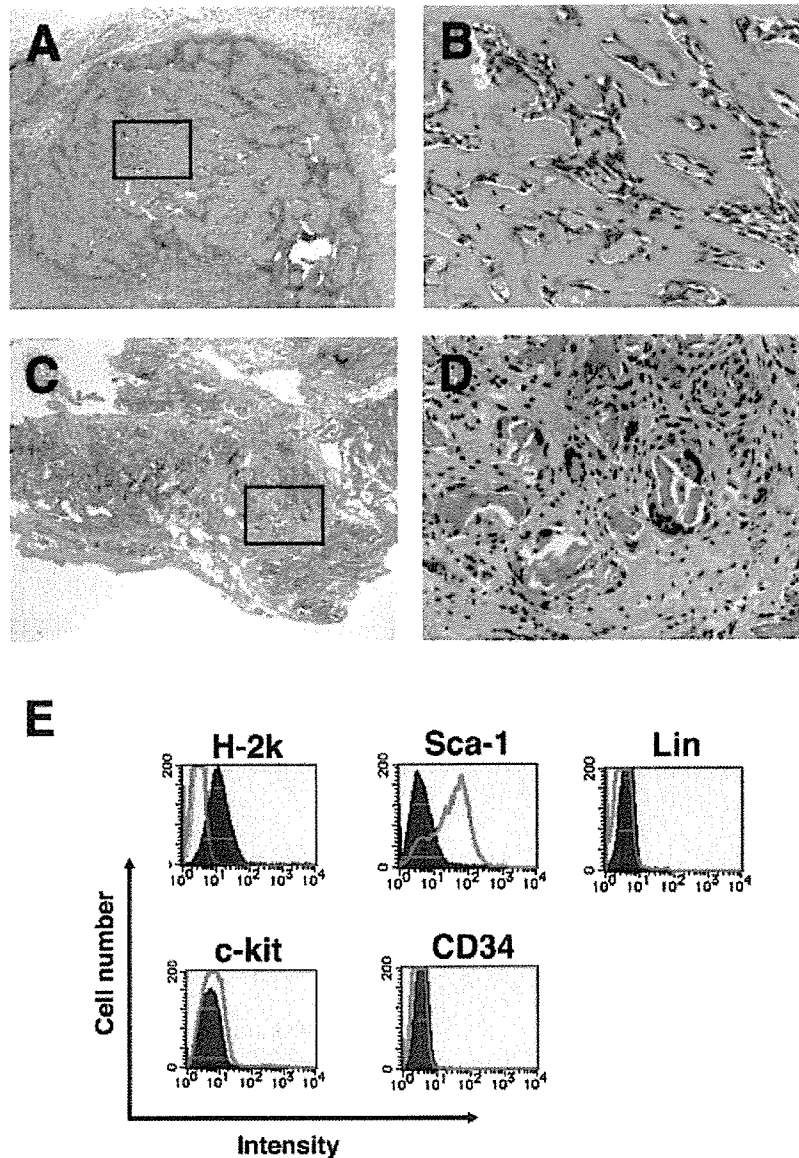


Fig. 2. Rejection of the implanted KUSA-A1 cells in an allogeneic combination. Microscopic view of the generated bone 18 days after the implantation of 5×10^6 KUSA-A1 cells, which were derived from C3H/He mice, into the subcutaneous tissue of syngeneic C3H/He mice (A, B) or allogeneic BALB/c mice (C, D). Hematoxylin and eosin stain. Parts B and D are higher magnifications of A and C, respectively. E: Alterations in cell surface antigens after implantation. Flow

cytometric analysis was performed on KUSA-A1 cells (open peaks) and cultured mesenchymal cells obtained from KUSA-A1 ectopic bone (closed peaks) in BALB/c nu/nu mice. The mesenchymal cells were obtained from the KUSA-A1 ectopic bone, and analyzed by flow cytometry. One of major histocompatibility antigens, H-2k, was upregulated, and Sca-1 antigen was downregulated.

accounted for $7.0 \pm 1.7/10^6$ cells (Fig. 4E, middle). In contrast, no CFU-S was detected in the peripheral blood from the mice without KUSA-A1 cell implantation.

Since the upregulation of HSCs in the femurs from the KUSA-A1 cell-implanted mice was rather surprising to us, the time-course of the KSL cell numbers in the femurs from the mice with KUSA-A1 ectopic bone was investigated (Fig. 4F). The number of KSL cells started to increase at 3 weeks, continued to increase to 0.47% by 5 weeks, returned to the basal level, that is, 0.08% at 6 weeks, and then fell down to 0.07% at 7 weeks, implying that the HSC number is strongly correlated with the process of dynamic membranous osteogenesis at the implanted site.

DISCUSSION

Bone remodeling occurs continuously throughout life, and HSCs may mobilize during this remodeling process.

The finding in this study support such hypothesis that a very specific niche may be functionally enhanced by bone remodeling (Watt and Hogan, 2000), while a stable or static microenvironment does not support hematopoietic mobilization. For example, accelerated bone remodeling by physical exercise and Vitamin D intake trigger increasing mobilization of HSCs. On the other hand, lack of dynamic bone remodeling in bedridden elderly, astronauts, dieters, postmenopausal women, and patients immobilized for long periods results in downregulation of HSCs in bone marrow.

Upregulation of HSCs by "dynamic" membranous ossification of implanted KUSA-A1 osteoblasts

The cell implantation-based strategy employed in this study revealed that increased niche size following subcutaneous implantation of an osteoblast cell line in syngeneic or immunodeficient mice resulted in

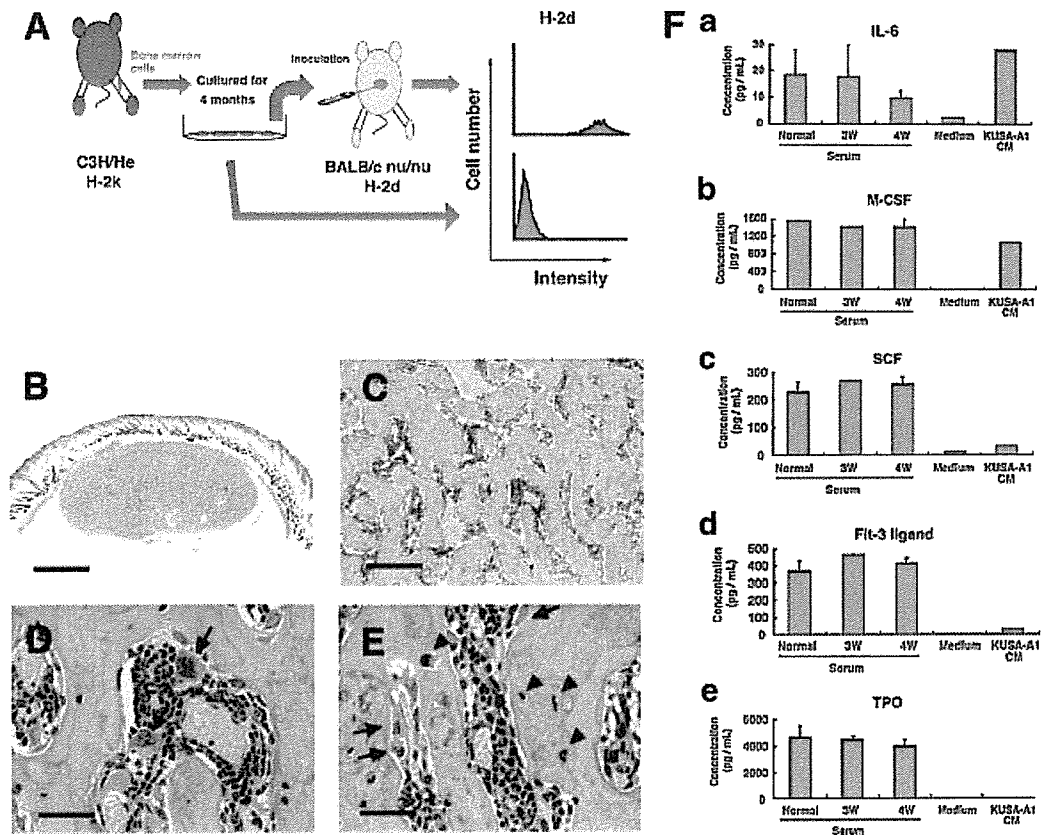


Fig. 3. Hematopoietic cells of host origin in the ectopic bone and serum levels of cytokines after subcutaneous implantation of KUSA-A1 cells. **A**: Flow cytometric analysis of the H-2d antigen in the hematopoietic cells of ectopic bone and KUSA-A1 cells in vitro. The hematopoietic cells in KUSA-A1 bone were examined for expression of the H-2d antigen of the host mice. **B–E**: Histopathological appearance of the hematopoietic cells used for flow cytometric analysis. Tri-lineage cells, that is, megakaryocytes (**D**, arrows), erythroblasts (**D**, **E**),

and granulocytes (**E**), were observed. Osteoblasts and mature osteocytes are indicated by arrows and arrowheads, respectively (**E**). Scale bars: 2 mm (**B**), 400 μ m (**C**), 100 μ m (**D**, **E**). **F**: Serum levels of interleukin-6 (IL-6) (**a**), macrophage-colony stimulating factor (M-CSF) (**b**), stem cell factor (SCF) (**c**), fms-like tyrosine kinase-3 (Flt-3) ligand (**d**), and thrombopoietin (TPO) (**e**), measured by the ELISA method. The blood samples were obtained at 5 weeks after implantation.

increases in the HSC population. In the HSC population, both the CFU-S and KSL cells increased. The niche that regulates the generation and differentiation of the HSCs was formed following KUSA-A1 cell implantation, and subsequent membranous ossification in vivo. The enlarged area of niche, that is, the inner surface of bone during the dynamic process of membranous osteogenesis may account for the dramatic upregulation of HSCs in the host bone marrow. Once the osteogenic process is terminated, the number of osteoclasts decreases and no bone is remodeled. Furthermore, the number of the KSL cells returns to the basal level in host bone marrow. These facts suggest a correlation between the osteogenic process (Fig. 1C) and increasing number of KSL cells (Fig. 4F).

The source of the CFU-S in the peripheral blood of the mice implanted with KUSA-A1 osteoblasts may be the bone marrow of (a) the ectopic bone; (b) the host femur; (c) both the ectopic bone and the host femur (Fig. 4C). Mobilization of CFU-S from ectopic bone into the peripheral blood is the most likely cause since the induction of HSCs was accompanied by dynamic osteogenesis. The increased HSC number in the host bone marrow can be explained by HSC mobilization from ectopic bone into the peripheral blood. In the normal mice, such migration or mobilization of hematopoietic cells occurs during development. Hematopoietic events in the mouse begin in the yolk sac and aortogonad-mesonephros region at day 7 of gestation, and

they shift the site to the fetal liver at mid-gestation followed by the bone marrow shortly before birth. The prevailing notion has been that this sequence reflects the migration of HSCs from the yolk sac to the definitive hematopoietic sites. Observation in this study, that is, the generation of ectopic bone in the subcutaneous tissues and the resultant migration of HSCs via the peripheral blood, seems to mimic above process during developments (Dzierzak et al., 1998).

Unexpected upregulation of MHC antigen after implantation of donor cells

Although most HSCs have been reported to express MHCs, that is, HLA in humans, and H-2 antigens in mice, no mesenchymal stem cells have been reported to express MHC antigens at least in vitro (Jiang et al., 2002). Since lack of these antigens on the cell surface may contribute to the induction of tolerance in these cells when transplanted in allogeneic combination, the complete rejection of the transplanted mesenchymal cells and de novo expression of the H-2 antigen after in vivo implantation was contrary to our expectation. We do not know the molecular mechanisms responsible for upregulated expression of H-2 and downregulated expression of Sca-1 after cell implantation, but care should be exercised when mesenchymal cells are implanted for therapeutic purposes, because membrane-bound molecules, including functionally essential molecules, might be modulated after implantation.

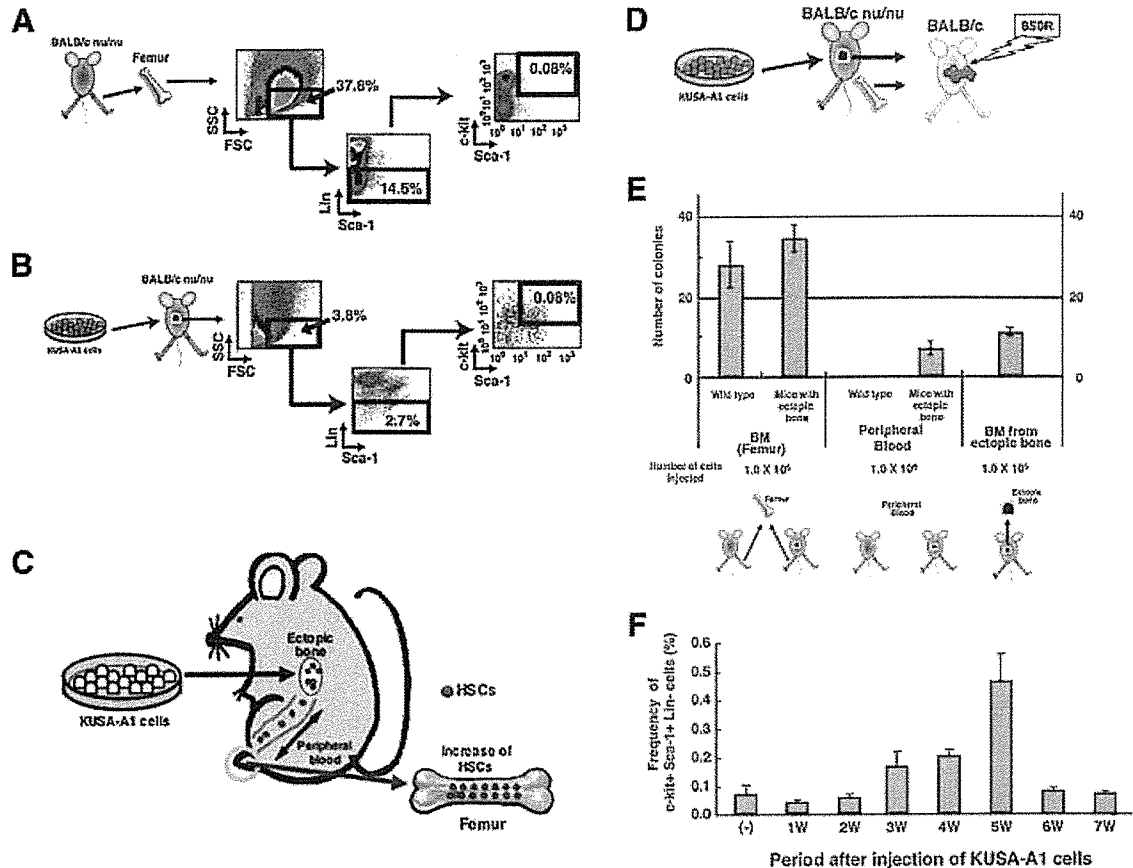


Fig. 4. Mobilization of $c\text{-kit}^+ \text{Sca-1}^+ \text{Lin}^-$ (KSL) cells in the ectopic bones generated by KUSA-A1 cells. **A** and **B**: Flow cytometric analysis of hematopoietic stem cell markers was performed on hematopoietic cells in the femur of BALB/c nu/nu mice (A) and the ectopic bone generated in BALB/c nu/nu mice (B). KSL cells accounted for 0.08% of the hematopoietic cells in KUSA-A1 bone. **C**: Proposed mechanism of HSC mobilization in the peripheral blood of mice with the ectopic bone, and the increased HSCs in the femur of mice implanted with osteoblasts. Osteoblastic cells whose number has been increased by local injection into the tissues support an increase in number of HSCs in both bone marrow and peripheral blood, as a result of an increase in size of the microenvironment or niche in vivo. The niche size defined by dynamic osteogenic process affects the number of stem cells. **D**: Experimental design to investigate mobilization of CFU-S in the peripheral blood of mice with the ectopic bone, and the proportion of KSL cells in the femur of mice implanted with KUSA-A1 cells.

Crucial role of marrow stromal subsets in HSC regulation

HSCs are a subset of bone marrow cells that are capable of self-renewal and of forming all types of blood cells. The increases in bone size generated by the spindle-shaped KUSA-A1 osteoblasts correlated with the increase in the number of HSCs. The osteoblasts and a subpopulation of the HSCs expressed N-cadherin, a cell-surface molecule that helps cells adhere to one another, and N-cadherin and -catenin may form important components of the interaction between HSCs and their niche (Zhang et al., 2003). The Notch signaling pathway is also known to regulate cell-fate decisions in many organisms (Calvi et al., 2003). Involvement of cytokine signaling in HSC regulation has been reported to be crucial to the development of blood-forming tissue in embryos. The doubling of bone size mirrored the increase in the HSC population in the mice implanted with KUSA-A1 cells.

The strategy to increase the size of the HSC population by implanting osteoblasts into the subcutaneous

Hematopoiesis was induced in the ectopic bone by KUSA-A1 cell implantation (See Fig. 3). The hematopoietic cells in the ectopic bone and the host femur were analyzed for further CFU-S analysis in mice exposed to 850 cGy irradiation. **E**: CFU-S assay in the marrow cells of the femur of mice not implanted with any cells; the femoral marrow cells of mice with ectopic bone; peripheral blood cells of mice not implanted with cells; peripheral blood cells of mice with ectopic bone; marrow cells in ectopic bone. The blood samples were obtained at 5 weeks after implantation. The number of HSC or CFU-s increased to $11.2 \pm 0.8/1.0 \times 10^5$ cells in the KUSA-A1-induced ectopic bone. CFU-s in the peripheral blood increased to $7.0 \pm 1.7/10^6$ cells at day 12 after implantation of the KUSA-A1 cells while no CFU-s were detected in the peripheral blood from mice without cell implantation. **F**: Time course of the proportion of KLS cells in the femur of mice implanted with KUSA-A1 cells.

tissue to increase the osteoblast cell population may be proven to be of certain clinical value in the future. The concept that a microenvironment or niche controls HSCs may be useful for HSC expansion in vivo, and has potential implications for HSC harvesting and recovery after transplantation (Fig. 4C). Direct implantation of KUSA-A1 cells into syngeneic or immunodeficient mice, in order to better understand the interactions between HSCs and bone marrow, may therefore lead to the development of practical methods of manipulating stem cells and define a model for investigating the impact of the microenvironment on cell physiology (Li et al., 2000). Cellular and molecular identification using the strategy of niche-constituent cells or signaling pathways will provide pharmacological targets with therapeutic potential for stem-cell-based therapies.

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Differentiation of Adult Stem Cells Derived from Bone Marrow Stroma into Leydig or Adrenocortical Cells

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Adult stem cells from bone marrow, referred to as mesenchymal stem cells or marrow stromal cells (MSCs), are defined as pluripotent cells and have the ability to differentiate into multiple mesodermal cells. In this study, we investigated whether MSCs from rat, mouse, and human are able to differentiate into steroidogenic cells. When transplanted into immature rat testes, adherent marrow-derived cells (including MSCs) were found to be engrafted and differentiate into steroidogenic cells that were indistinguishable from Leydig cells. Isolated murine MSCs transfected with green fluorescence protein driven by the promoter of P450 side-chain cleaving enzyme gene (CYP11A), a steroidogenic cell-specific gene, were used to detect steroidogenic cell production *in vitro*.

During *in vitro* differentiation, green fluorescence protein-positive cells, which had characteristics similar to those of Leydig cells, were found. Stable transfection of murine MSCs with a transcription factor, steroidogenic factor-1, followed by treatment with cAMP almost recapitulated the properties of Leydig cells, including the production of testosterone. Transfection of human MSCs with steroidogenic factor-1 also led to their conversion to steroidogenic cells, but they appeared to be glucocorticoid- rather than testosterone-producing cells. These results indicate that MSCs represent a useful source of stem cells for producing steroidogenic cells that may provide basis for their use in cell and gene therapy. (*Endocrinology* 147: 4104–4111, 2006)

STEM CELLS ARE self-renewing elements with the capacity to generate multiple distinct cell lineages. They exist in various tissues, even in adults, and have been isolated from a variety of differentiated tissues, including bone marrow, umbilical blood, brain, and fat (1–6). Among these, bone marrow-derived mesenchymal stem cells (MSCs), also known as marrow stromal cells, are defined as pluripotent cells and have been shown to differentiate into adipocytes, chondrocytes, osteoblasts, and hematopoietic-supporting stroma both *in vivo* and *ex vivo* (1–3). Furthermore, they are able to generate cells of all three germ layers (7, 8). In addition to their multipotency for differentiation, MSCs have attracted considerable interest for use in cell and gene therapy because these cells can easily be obtained from adult marrow tissue (8–10).

The gonad and adrenal gland are the primary steroidogenic organs in mammals. In the gonad, male Leydig cells or female granulosa and theca cells are responsible for the production of androgens and estrogens. The adrenal cortex produces glucocorticoids and mineralocorticoids, although

some androgens are also produced in many species, except rodents. These steroidogenic organs develop from the common adrenogenital primodium, which originates from the intermediate mesoderm (11). Fetal-type steroidogenic cells appear when the adrenogenital primodium differentiates into the adrenal cortex and the gonads of the two sexes. These are replaced by adult-type steroidogenic cells during the period between birth and puberty (12, 13), but these processes are poorly understood.

One approach to resolving the complexities of organogenesis is to use stem cells as a model system for differentiation. In this study, the differentiation of MSCs into steroidogenic cells was examined *in vivo* and *in vitro* by several methods. A number of studies have reported that the injection of MSCs into some tissues leads to the differentiation of the injected cells into tissue-specific cells, probably due to the microenvironment near the injection sites. To determine whether MSCs are able to differentiate into steroidogenic cells, we injected a purified population of rat MSCs into the prepubertal rat testis and examined the fate of these cells by immunohistochemistry. In addition, the spontaneous differentiation of MSCs to specific cells can be monitored by the expression of specific genes in the differentiated cells. One such experimental approach, known as a promoter-sorting method, is to use fluorescence-activated cell sorting (FACS) to select green fluorescence protein (GFP)-positive MSCs in which the expression of GFP is under the control of the promoter of a gene that is expressed in a cell type-specific fashion. In this study, to demonstrate the emergence of steroidogenic cells from isolated MSCs *in vitro*, a GFP expression vector driven by the CYP11A promoter (CYP11A is a

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Abbreviations: ES, Embryonic stem; FACS, fluorescence activated cell sorting; GFP, green fluorescence protein; hMSC, human MSC; 3 β -HSD I, 3 β -hydroxysteroid dehydrogenase I; 17 β -HSD III, 17 β -hydroxysteroid dehydrogenase III; mMSC, murine MSC; MSC, mesenchymal stem cell; P450arom, cytochrome P450 aromatase; P450c17, cytochrome P450 17 α -hydroxylase; P450c21, cytochrome P450 steroid 21-hydroxylase; P450sc, P450 side-chain cleaving enzyme; SF, steroidogenic factor; StAR, steroidogenic acute regulatory protein.

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gene encoding the cholesterol side-chain cleavage enzyme, an essential enzyme for steroidogenesis) was integrated into the MSCs, and GFP-positive MSCs were then separated by fluorocytometry. Finally, to achieve the efficient differentiation of the isolated MSCs *in vitro*, the orphan nuclear receptor, steroidogenic factor (SF)-1 was ectopically expressed in MSCs. MSCs successfully differentiated into steroidogenic cells using any of these procedures. These results indicate that MSCs represent a useful source of stem cells for producing steroidogenic cells that may provide basis for their use in cell and gene therapy.

Materials and Methods

Animals

GFP transgenic rats [SD TgN(act-EGFP)OsbCZ-004] were kindly provided by Dr. M. Okabe (Osaka University, Osaka, Japan). Sprague Dawley rats were purchased from Sankyo (Shizuoka, Japan). At all times, the animals were treated according to National Institutes of Health guidelines. The donor animals used in this study were generally 4–5 wk old, and the recipient animals were 3 wk old.

Histology and immunofluorescence analysis

Immunohisto- and cytochemical staining with antirat P450 side-chain cleaving enzyme (P450scc) (C-16; Santa Cruz Biotechnology, Santa Cruz, CA), antimouse β -hydroxysteroid dehydrogenase I (β -HSD I) (kindly provided by Dr. A. Payne, Stanford University Medical Center, Stanford, CA), antipig cytochrome P450 17 α -hydroxylase (P450c17) (kindly provided by Dr. D. Hales, University of Illinois at Chicago, Chicago, IL) or anti-GFP (Medical & Biological Laboratories Co., Ltd.) were performed on 10- μ m frozen sections or cultured cells on glass slides using standard protocols. Appropriate Cy3- or fluorescein isothiocyanate-conjugated secondary antibodies (Sigma, St. Louis, MO) were used for detection.

Cell culture, stable transfection, and hormone assay

MSCs from GFP transgenic rats were collected and cultured as described by Pochampally *et al.* (14). Mouse (KUM9) (15) or human (hMSC-hTERT-E6/E7) (16) bone marrow-derived MSCs were maintained in Iscova's MEM or DMEM with 10% fetal calf serum. Plasmid DNA was transfected using the LipofectAmine PLUS reagent (Invitrogen, Carlsbad, CA) or calcium phosphate coprecipitation. Cells were used for the experiments after 10–12 passages, and steroid hormone production was sustained for at least 4 months. The levels of each steroid hormone in the media were measured by RIA.

Transplantation

Bone marrow cells from TgN(ActbEGFP) transgenic rats (1×10^6) were injected into the testes of 3-wk-old SD rats. Two to three weeks after transplantation, testes were removed to examine histochemically survival and differentiation of transplanted cells.

Plasmid construction

A 2.3-kb fragment of the human CYP11A (P450scc gene) promoter that functions specifically in steroidogenic organs (17) was obtained by PCR using pSCC2300-LacZ (kindly provided by Dr. B. C. Chung, Institute of Molecular Biology, Taipei, Taiwan) as a template and integrated into a promoter-less pEGFP-1 vector (CLONTECH, Palo Alto, CA). The *EcoRI*-*StuI* restriction fragment, containing the CYP11A promoter-GFP, was then excised and inserted into *EcoRI* and *SwaI* site of pPUR (CLONTECH). The expression vector for rat SF-1 cDNA containing the entire coding region was generated by RT-PCR and subcloned into pIRES-puro2 vector (CLONTECH).

FACS analysis and cell purification

Cells were harvested by treatment with 0.25% trypsin/EDTA, after which they were neutralized with DMEM with 10% fetal calf serum,

washed twice with PBS, and filtered through a 35-mm pore size nylon screen. FACS analysis was performed on a flow cytometer with a 488-nm argon laser and GFP-positive cells were isolated.

RT-PCR and real-time PCR

Total RNA from the cultured cells was extracted using the Trizol reagent (Invitrogen). RT-PCR was performed as described previously (18). The reaction mixture was subjected to electrophoresis in a 1.5% agarose gel, and the resulting bands were visualized by staining with ethidium bromide. Real-time PCR was performed as described by Rutledge and Cote (19). Reagents for real-time PCR were purchased from Applied Biosystems (Warrington, UK), except for SYBER green PCR master mix (QIAGEN, Valencia, CA). Reactions were carried out and fluorescence was detected on a GeneAmp 7700 system (Applied Biosystems). The primers used are shown in Table 1.

Western blot analysis

The extraction of protein from the cultured cells and subsequent quantification was performed as described previously (20). Equal amounts of protein (50 μ g) were resolved by 12.5% SDS-PAGE and transferred to polyvinylidene difluoride membranes. Western blot analyses of SF-1, steroidogenic acute regulatory protein (StAR), P450scc, β -HSD I, P450c17, and β -tubulin were carried out with antisera directed against SF-1 (Ad4BP, kindly provided by Dr. K. Morohashi, National Institute of Basic Biology, Okazaki, Japan), StAR (kindly provided by Dr. W. Miller, University of California, San Francisco, CA) (21), P450scc (kindly provided by Dr. B. C. Chung) (22), β -HSD I (kindly provided by Dr. A. Payne), P450c17 (kindly provided by Dr. D. Hales) (23), and β -tubulin (D-10, Santa Cruz). ECL Western blot reagents (Amersham Pharmacia Biotech, Piscataway, NJ) were used for detection.

Results

Transplantation of rat bone marrow mesenchymal stem cells

In the prepubertal testis, fetal-type Leydig cells are replaced by adult-type Leydig cells, which originate from mesenchymal precursor cells that are present in the testicular interstitium (12). To determine whether MSCs can be engrafted into the testis and converted into steroidogenic cells we took 1×10^6 bone marrow cells from TgN(ActbEGFP) transgenic rats that had been maintained in culture (Fig. 1A) and injected them into the testes of 3-wk-old SD rats. As shown in Fig. 1C, donor engraftment was confirmed (100%) at various periods after transplantation (1–4 wk). A histochemical examination revealed that the GFP-positive cells present in the testes were located in the interstitium and were not observed within the seminiferous tubules (Fig. 1D). An immunohistochemical study showed that most of the GFP-positive cells in the interstitium were also positive for three Leydig cell markers, P450scc (Fig. 1E), β -HSD I, and P450c17 (data not shown). These results indicate that donor derived-plastic adhered marrow cells had in fact differentiated into steroidogenic Leydig-like cells *in vivo*.

Gene promoter sorting

Although these data suggest that the injected stem cells differentiated into Leydig cells, the apparent stem cell plasticity may also be explained by possible cell-nuclear fusion between donor and recipient cells, as has been recently suggested (24). Therefore, we next performed *in vitro* experiments to determine whether purified murine MSCs (mMSCs), KUM9 (15), have the capacity to differentiate into steroidogenic cells. To detect a cell population committed to

TABLE 1. Primers for RT-PCR and real-time PCR

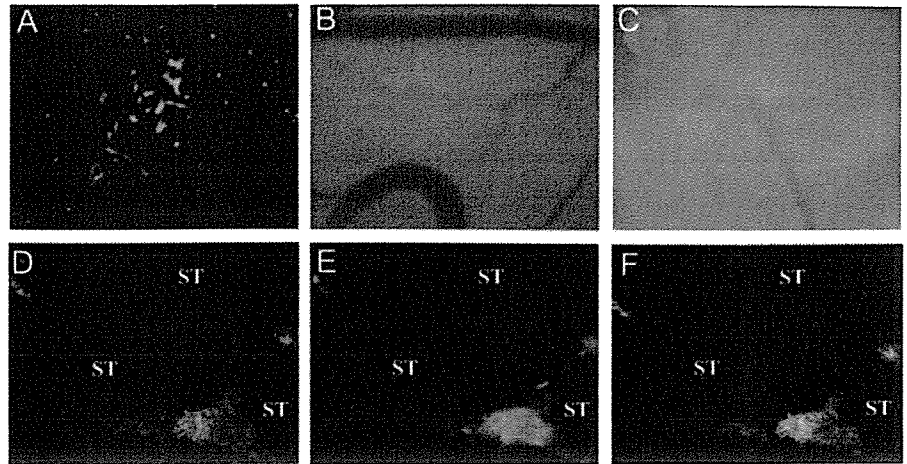
Gene	Sequence	Gene	Sequence
RT-PCR SF-1	F-CGCACAGTCCAGAACAACAAGCA R-CGGTTAGAGAAGGCAGGATAGAG	RT-PCR hHSD3b2	F-CAGTGTGCCAGTCTTCATCT R-AGCAGGAAGCCAATCCAGTA
mStAR	F-GAAGGAAAGCCAGCAGGAGAACG R-CTCTGATGACACCACTCTGCTCC	hP450c17	F-CATGCTGGACACACTGATGC R-GGTTGTATCTCTAAAATCTGT
mP450scc	F-TTCCGCTTTTCCTTTGAGTCCAT R-GTGTCTCCTTGATGCTGGCTTTC	hHSD17b3	F-GCAGATTTTACAAAAGATGACAT R-TCATGGCAAGGCAGCCACAGGT
mHSD3b1	F-ACTGCAGGAGTCCAGAGCT R-GCCAGTAACACAGAATACC	hP450c21	F-TGCCTGCCTATTACAAAATGT R-GGTGAAGCAAAAAACCACG
mHSD3b6	F-TCTGGAGGAGATCAGGGTC R-GCCCGTACAACCGAGAATATT	hP45011 b1	F-ACATTGGTGC GCGTGTTCCTC R-GAGACGTGATTAGTTGATGGC
mP450c17	F-AAATAATAACTGCGGAAGGC R-TGGGTGTGGGTGTAATGAGATGG	hP450 11b2	F-TACAGGTTTTCTCTACTCG R-AGATGCAAGACTAGTTAATC
mP450c21	F-AGAGGATCCGCTTGGGGCTGC R-GGAGGAATTCCTTATGGATGGC	hP450aro	F-CTGGAAGAATGTATGGACTT R-GATCATTTCAGCATGTTTT
mP450 11b1	F-TCACCAATGTATCAAGAATGTGT R-CCATCTGCACATCCTCTTCTCTTT	β -Actin	F-GGGAAATCGTGCCTGACATTAAG R-TGTGTTGGCGTACAGGTCTTTG
mP450 11b2	F-CCAACAGATGTATCTGGAAGGTGC R-CCATCTGCACATCCTCTTGCCTCA	hIGF-2	F-AGTCGATGCTGGTGCTTCTACCTCTT R-TGCGGCAGTTTTGCTCACTTCCGATT
mLHR	F-CTCCACCTATCTCCCTGTC R-TCTTTCTTCGGCAAAATCCTG	Real-time PCR	
mACTHR	F-GCTCCAAGGATCATTTACTTGC R-CGCCAGGAGGCTTAACATAAC	mP450scc	F-CCAGTGTCCCCATGCTCAAC R-TGCATGGTCCTTCCAGGTCT
GAPDH	F-ACCACAGTCCATGCCATCAC R-TCCACCACCCTGTTGCTGA	mHSD3b1	F-TAACAATTTAACAGCCCCCTCCTAAGG R-ATCCAGCCATGGTCAACACA
GFP	F-TGACCACCCTGACCTACGGCGT R-GGTAGTGGTTGTCGGGCAGCA	mHSD3b6	F-AAACCATCTCCACTGTTCTAGCT R-TGGAGATGGTCAGCCACAAG
mHSD17b3	F-ATTTTACCAGACAAGACATCT R-GGGGTCAGCACCTGAATAATG	mP450c17	F-AGTTTGCCATCCCGAAGGA R-CTGGCTGGTCCATTCATTT
mP450aro	F-TCAATACCAGGTCCTGGCTA R-GTATGCACTGATTCACGTTT	mHSD17b3	F-TGGACAATGGGCAGTGAT R-GCCAACCTCAAATGAATAGGCTTTC
hStAR	F-GAGAGTCAGCAGGACAATGG R-CTGGTTGATGATGCTCTTGG	β -Actin	F-CAACCGTAAAAGATGACCCAGATC R-AGTCCATCACAATGCCTGTGGTAC
hP450scc	F-TAGTGTCTCCTTGATGCTGG R-GAAAGGAAGTGTTCACCACG		

F, Forward; R, reverse.

the steroidogenic lineage, we first introduced a human CYP11A1 promoter/GFP gene construct into the mMSCs. This was accomplished by using a 2.3-kb fragment of the promoter region of the human CYP11A1 (a gene that encodes cytochrome P450scc, cholesterol side-chain cleavage enzyme), which has been shown to selectively drive transgene expression to adrenal and gonadal steroidogenic cells (17). In some of the transformed cell lines, GFP fluorescence was detected, as shown in Fig. 2, B and C, but the number of GFP-expressing cells was very low. Thus, GFP-positive cells were enriched by sorting with flow cytometry (Fig. 2E, 1–5% of total cells). As shown in Fig. 2, F and G, enriched GFP-

positive cells were also positive for P450scc, indicating that a very small but distinct portion of the mMSCs had spontaneously differentiated into cells that produce the steroid hormone-synthesizing enzyme. Further analysis of the differentiated cells revealed the expression of several genes that are specific to testicular Leydig cells, as shown in Fig. 2H. These include a nuclear orphan receptor SF-1, 3 β -HSD types I and VI, and LH receptor (Fig. 2H, lane SCC+). LH receptor and 3 β -HSD VI are known to be typical markers for androgen producing cells, such as Leydig cells (25). These observations further support the *in vivo* findings that rodent MSCs have the capacity to differentiate into Leydig-like cells in the testis.

FIG. 1. Transplantation of GFP-positive MSCs into the testis. A, Fluorescence view of MSCs from a green rat 3 d after the first passage. Fluorescence microscopic view of testis before (B) or 3 wk after (C) MSC transplantation. Double staining of frozen sections from the testis 5 wk after MSC transplantation with anti-GFP (D) and anti-P450_{scc} (E) antibodies. F, Merged fluorescent image of D and E. ST, Seminiferous tubule.



Stable transfection of SF-1 into mouse MSCs

It is noteworthy that SF-1 expression was induced in the GFP-positive cells (Fig. 2H). SF-1, also known as Ad4BP, regulates the cell-specific expression of a variety of proteins that are involved in steroidogenesis, in addition to its roles in reproduction and gonadal differentiation (26). Therefore,

we next examined the effects of the stable transfection of SF-1 to mMSCs. Various cell lines that stably express SF-1 were isolated. As shown in Fig. 3C, SF-1-induced morphological changes in the cells, such as the accumulation of numerous lipid droplets. However, the transformed cells did not express steroidogenic enzyme genes or produce any steroid

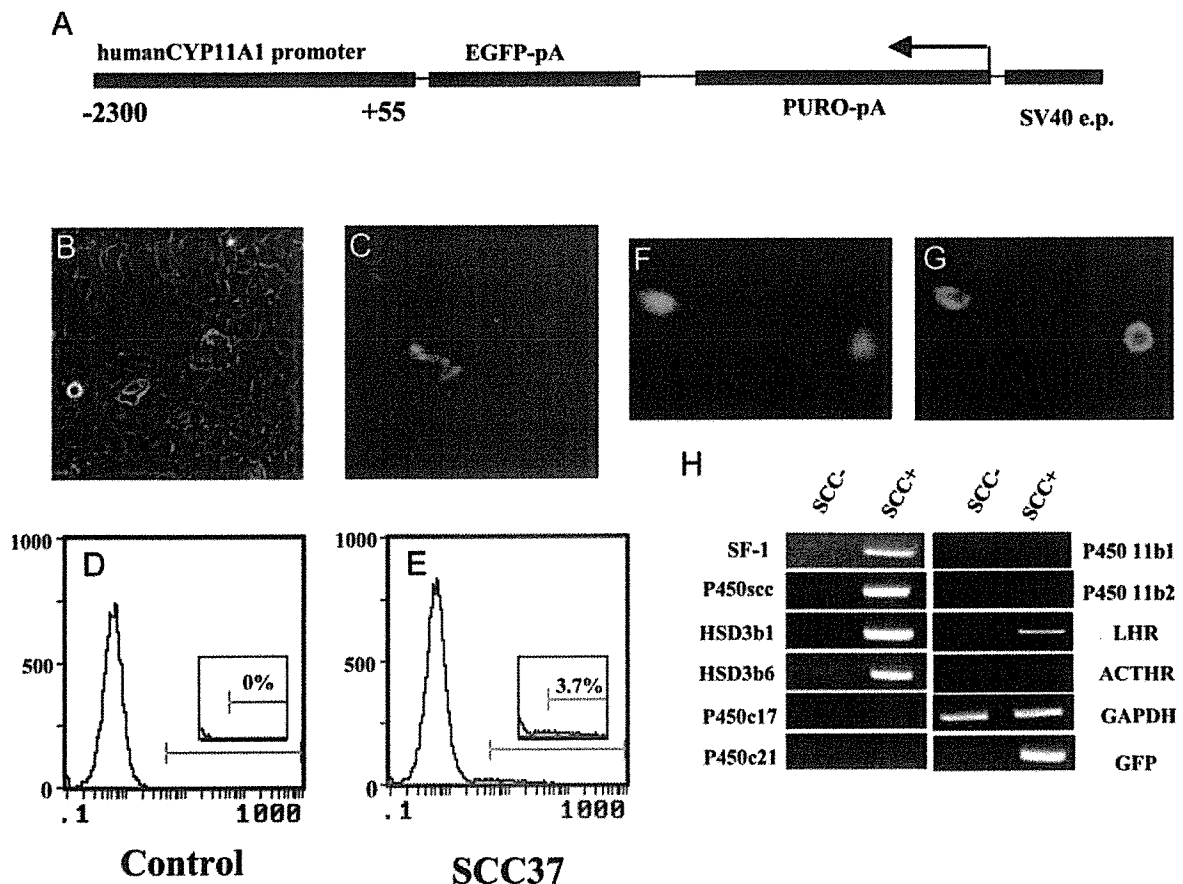


FIG. 2. Spontaneous differentiation of KUM9 into steroidogenic cells. A, Schematic representation of the SCC-reporter gene (SCC-GFP). The SCC-GFP reporter plasmid contains the 2300-bp upstream sequence of the human CYP11A1 gene and the puromycin-*N*-acetyltransferase gene (PURO-pA) driven by the Simian virus 40 early promoter (SV40 e.p.). Phase-contrast (B) and fluorescent (C) images of mMSCs transfected with SCC-GFP and selected by puromycin are shown. Flow cytometric analysis of enhanced GFP (EGFP) expression in KUM9 transfected with control-GFP (D) or SCC-GFP (E) are shown. KUM9-derived cells expressing GFP (F) under the control of the human CYP11A1 promoter were immunocytochemically stained with anti-P450_{scc} antibody (G). H, SCC-GFP-positive (SCC+) and negative (SCC-) populations were sorted and analyzed for various marker genes by RT-PCR.