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Self-assemblies of enzymatically degradable amphiphilic oligopeptides as nonviral gene carrier

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ABSTRACT

Novel biodegradable oligopeptide-type gene carriers composed of cationic residues (KRRRKRKRRRKRKRRC) and oligo leucine segments were developed. The amphiphilic carrier was found to form micelle-like assemblies in aqueous solutions, when the oligo leucine is 12 amino acids length (Pep-L12). NMR, CMC, and GPC analysis revealed their hydrophobic/cationic core/shell morphology. Hydrophobic interaction between leucines is thought to be the major driving force behind formations of assemblies. The transient expression of luciferase introduced to COS-1 cells using Pep-L12 below the CMC is as low as that by the control cationic peptides without leucine residue (Pep-L0), while improved transgene expression was observed in the case of Pep-L12 above CMC. The self-assembly raised the apparent molecular weight and gene transfection ability without loosening their low cytotoxicity. These results indicate that the amphiphilic oligopeptides are very promising materials as highly efficient and less toxic gene carriers.

1. Introduction

Polymeric gene carriers are now extensively studied due to their high abilities to deliver and protect pDNA, but the polyplexes formed between the carriers and pDNAs are sometimes too highly compacted to be recognized by transcription factors in nucleus. Recently, the destabilization of the polyplexes by conjugating hydrophilic or hydrophobic segments to polymeric carriers has been reported [1–3]. However, excess modification of side chains results in the low resistance to DNase at the same time.

Effect of the carrier molecular weights (Mws) has been also being studied [4–8]. Recently, high potential of low Mw polymeric carriers was attracting great attention. Kunath et al. reported that low Mw PEI (5 kDa) was much less toxic than high Mw PEI (48 kDa), and reporter gene expression of 5 kDa PEI was 3.7-fold higher than 48 kDa PEI in various cell lines [6]. Breuning et al. compared PEIs with the Mw of 1–9 kDa and showed that the highest reporter gene expression was obtained at 5.6 kDa, with low cytotoxicity. Schaffer et al. reported higher gene expression for low Mw PLL (19 and 36 residues) than high Mw PLL (180 residues) because of effective *in vitro* transcription and easy pDNA release [4]. Taken together, low cytotoxicity and high DNA releasing ability of low Mw carries were important key features for the high potential gene carriers. On the other hand, low Mw carriers are pointed out to reduce cellular uptake [9] and decrease stability of polyplexes at the same time. Thus, a new type "low Mw carriers", which have low cytotoxicity, high cellular uptake, and adequate polyplex stability, would be more useful gene carriers.

In the present study, oligopeptide-type carriers were selected in order to reduce cytotoxicity and to induce the intracellularly digestible feature. Since the chemical chain elongation of cationic oligopeptide would increase the cytotoxicity, we tried to raise the apparent Mw of oligopeptide-type carriers by their self-assembly. Amphiphilic oligopeptides having cationic and hydrophobic sequences were then designed. Hydrophobic interactions between oligo leucine sequences make carriers form assemblies and increase the apparent Mw. Cationic sequences for interacting with pDNA include cleavable sequences (Arg-X-Lys/Arg-Arg (R-X-K/R-R)) by intracellular proprotein convertase, furin [10,11]. We have previously found that carriers including this cleavable sequences are enough cationic to form polyplexes with pDNA, and these polyplexes became destabilized if carriers were cleaved by furin [12]. Increased apparent Mw is expected to increase cellular uptake of the polyplex and the enhanced stability can be destabilized by furin cleavage resulting in the pDNA release in intracellular environments.

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2. Experimental

2.1. Amphiphilic oligopeptides

We synthesized four oligopeptides by Fmoc-based solid phase method using 9050 plus PepSynthesizer (Applied Biosystems, CA, USA) and purified in the usual way. They are composed of cationic KRRRKRKRRRKRKRRC and hydrophobic oligo leucine segment with different lengths.

Oligopeptide solutions were analyzed by GPC (Shimadzu Corporation, Kyoto, Japan) which fitted with a combination of two columns of TSK gel G6000PWXL (21.5 mm I.D. × 300 mm length, Tosoh Corporation, Tokyo, Japan) and TSK gel G3000PWXL, RID-10A Refractive index detector, and SPD-M10A UV–VIS detector. Elution was carried out with 1/15 M phosphate buffer (pH 7.5) at 0.3 mL/min.

2.2. Critical micelle concentration (CMC) measurements

CMCs of oligopeptides in aqueous solution were measured on a RF5300PC (Shimadzu Corporation, Kyoto, Japan) using pyrene (Nacalai Tesque, Inc., Kyoto, Japan) as a hydrophobic region probe [13]. Five μL of pyrene solution in acetone at a concentration of 6×10^{-5} M was transferred into a vial and evaporated. Five hundred μL of oligopeptide solutions which ranging from 5.0×10^{-4}–1.5 g/L were added dropwise to make the pyrene concentration of 6.0×10^{-7} M, incubated at 65 °C for 3 h, and cooled down to the room temperature. Pyrene excitation spectra were measured with the slit widths of 5 and 1.5 nm for excitation and emission at an emission wavelength of 380 nm.

2.3. Polyplex formation with pDNA

pCMV-Luc and pT7-Luc (Promega corporation, WI, USA) were amplified to sufficient quantities by standard molecular biology techniques, and purified with a QIAGEN-tip 500 (QIAGEN K.K., Tokyo, Japan). Oligopeptide solutions were mixed with pDNA solutions at a given charge ratio which is the ratio of the number of cationic groups of oligopeptide to that of anionic group of pDNA (*C/A* ratio). The solutions were incubated for 30 min at 37 °C to allow the polyplex formation and analyzed on 0.8 wt% agarose gel in Tris–borate EDTA buffer at 100V for 30 min. pDNA was visualized by staining with 0.5 μg/mL ethidium bromide (EtBr, Sigma chemicals, St Louis, MO, USA).

2.4. In vitro *transfection*

COS-1 cells were grown in DMEM (Nissui, Tokyo, Japan) containing 10% fetal bovine serum (FBS) (Sigma chemicals, USA) at 37 °C under a 5% CO_2 atmosphere. COS-1 cells were seeded in 96 well culture plates at a density of 1×10^4 in 100 μL DMEM containing 10% FBS per well. After 24 h incubation, cells were washed with PBS, and 40 μL DMEM was added. Ten μL of polyplex solutions containing 100 ng pCMV-Luc at the concentration above or below CMC of Pep-L12 were poured gently to the wells. Fifty μL of 200 μM chloroquine solution was added (final concentration is 100 μM) and incubated for 5 h. Cells were washed with PBS and cultured for 43 h with DMEM containing 10% FBS at 37 °C in a 5% humidified CO_2 environment. The cells were washed with PBS, treated with the lysis buffer containing 1% Triton-X100, and incubated for 30 min at 37 °C. Cell lysate was diluted into luciferase assay solution containing 470 μM luciferin. The relative light units (RLU) of expressed luciferase were measured using ATP-300 Lumicounter (Advantec Toyo Kaisya, Ltd., Tokyo, Japan). Luciferase solutions at a known concentration were used for calibration. The protein concentration was determined by DC Protein Assay kit (Bio-Rad Laboratories, Hercules, CA, USA) using bovine serum albumin as a standard. The obtained luciferase expression (ng luciferase) was divided by total protein content of cell lysates and expressed as ng luciferase/mg protein.

Table 1
Sequences of amphiphilic oligopeptides.

Oligopeptide	Sequences and cleavage sites	Amino acid composition (K/R/L/C)
Pep-L0	H_2N-K-R-R-R-K-R*-K-R-R*-R-K-R*-K-R-R*-C-$CONH_2$	10/5/0/1
Pep-L4	H_2N-$(L)_4$-K-R-R-R-K-R*-K-R-R*-R-K-R*-K-R-R*-C-$CONH_2$	10/5/4/1
Pep-L8	H_2N-$(L)_8$-K-R-R-R-K-R*-K-R-R*-R-K-R*-K-R-R*-C-$CONH_2$	10/5/8/1
Pep-L12	H_2N-$(L)_{12}$-K-R-R-R-K-R*-K-R-R*-R-K-R*-K-R-R*-C-$CONH_2$	10/5/12/1

* represents the cleavage site of furin.

2.5. Cell-free assay system for luciferase expression

Fifteen μL of polyplexes ($C/A = 10$) were mixed with 12.8 μL of rabbit reticulocyte lysate mixtures (T_NT Coupled Reticulocyte Lysate Systems; Promega, WI, USA) and incubated with shake at rate of 300 rpm/min for 90 min at 30 °C. After transcription/translation assay according to the manufacture's protocol, luciferase activities were measured by the same method described in the above section.

3. Results and discussion

3.1. Self-assembly of amphiphilic carriers

Sequences and abbreviation of synthesized amphiphilic oligopeptides were shown in Table 1. GPC chart for each amphiphilic oligopeptide in phosphate buffer is shown in Fig. 1. Only Pep-L12 exhibited two peaks, while the other oligopeptides showed peak which is at the similar elution time to the second peak of Pep-L12. The first peak of Pep-L12 is considered to be attributed to the self-assembly of the Pep-L12 with the apparent higher Mw and the second peak corresponds to the unimer as low Mw as the other oligopeptides, Pep-L0, Pep-L4, and Pep-L8. These results indicated that only Pep-L12 forms micelle-like assemblies in aqueous solution.

Micelle-like assemblies can be confirmed by comparing ^{1}H NMR spectra in good solvents and water [14,15]. Protons in the core structure composed of the insoluble fractions do not provide sufficient NMR signals. Thus, self-assembly of oligopeptides was analyzed in DMSO and water. Leucine contents (X_{Leu}) in water and in DMSO were measured using the signal intensity at 0.8 ppm (CH_3 in leucine) and at 1.6 ppm (β-CH_2 and γ-CH in leucine, β, γ, and δ-CH_2 in lysine, β and γ-CH_2 in arginine, and SH in cysteine). The

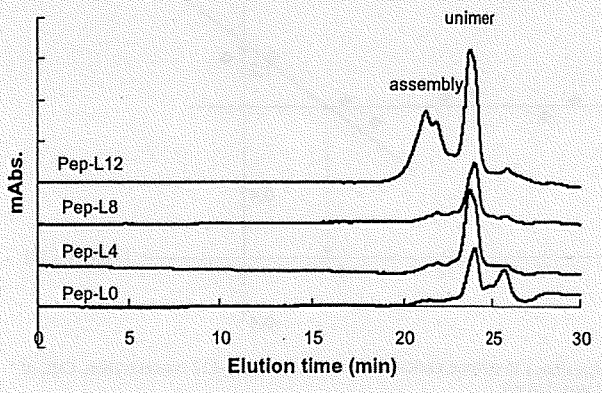

Fig. 1. GPC charts of Pep-LX ($X = 0$, 4, 8 and 12).

relative value of [X_{Leu} in water]/[X_{Leu} in DMSO] for Pep-L4 and Pep-L8 were 1.00 and 1.08, respectively, indicating that these oligopeptides has a same structure in both of medium. On the other hand, [X_{Leu} in water]/[X_{Leu} in DMSO] for Pep-L12 was 0.69, which strongly supports the oligo leucine/oligo cation core/shell structure of Pep-L12 in water.

3.2. CMC measurements

The excitation spectra of pyrene in oligopeptides solutions at various concentrations were measured. Fig. 2 demonstrates the intensity ratios ($I_{338.6}/I_{330.4}$) as a function of the logarithm of Pep-L12 concentration. As Pep-L12 concentration increased, the intensity ratio start increasing at a certain concentration, suggesting that pyrene molecules were incorporated into hydrophobic region upon assembly formation. CMC of Pep-L12 is determined from the crossover point was 0.16 g/L. This CMC is very high compared with reported CMC of other amphiphilic polymers [13,16]. This result suggested that Pep-L12 forms unstable assemblies resulting from weak hydrophobic interaction between leucine residues. In case of Pep-L8, a crossover point was not obtained. Hydrophobic interactions of Pep-L8 seem to be not strong enough to form assemblies in aqueous solution, which is in agreed with the GPC chart in Fig. 1. In addition, Pep-L12 assemblies were observed in AFM images above CMC (data not shown). While there were no assemblies at the lower concentration than CMC.

3.3. Polyplex formation

Fig. 3 shows the polyplex formation of the Pep-L12 at various *C/A* ratios. When Pep-L12 was mixed with pDNA, bands for free pDNA disappeared at the *C/A* ratio of 5, indicating that all pDNA form polyplexes with carriers. Concentrations of polyplex formation above and below CMC were same, indicating the polyplex forming ability of the micelle-like self-assembly of the Pep-L12 is same to that for Pep-L12 unimer. This phenomenon can be elucidated by the micelle-like architecture, which cationic residues are covering the hydrophobic core. The net amount of the cationic groups was then not significantly changed upon the self-assembly. Pep-L0 also formed polyplexes completely from *C/A* ratio of 5 similar to Pep-L12 (data not shown).

3.4. In vitro gene transfection

COS-1 cells were transfected with pCMV-Luc using Pep-L12 and Pep-L0 at various *C/A* ratio, and the transient expressions of

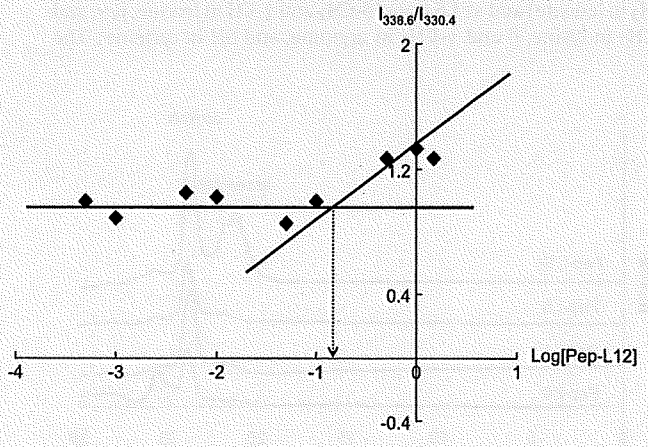

Fig. 2. $I_{338.6}/I_{330.4}$ in pyrene excitation spectra versus Pep-L12 concentration. CMC of Pep-L12 was 0.16 g/L.

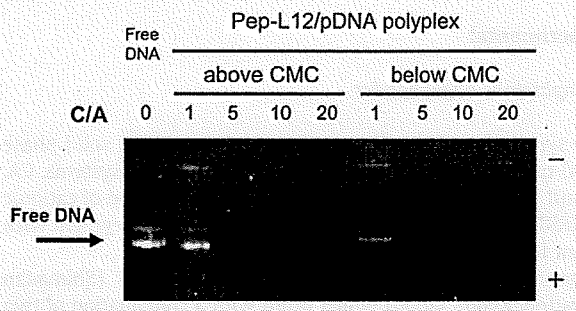

Fig. 3. Comparison of electrophoretic mobility profiles of Pep-L12 polyplexes. Polyplexes were analyzed at various *C/A* ratios on an agarose gel (0.8 wt%). Left five lanes represent polyplexes containing 200 ng pDNA above CMC and right four lanes are those containing 100 ng pDNA below CMC.

luciferase gene were evaluated. Cell viabilities for Pep-L12 and Pep-L0 by after transfection procedure were higher than 80% (data not shown). In general, high Mw polycations have profound cell damages, but the cytotoxicity of Pep-L12 above CMC is low. As is shown in Fig. 4(b), both Pep-L0 and Pep-L12 oligopeptides did not work as gene carriers in the unimer forms. However, only Pep-L12 did lead to improved transgene expression as increasing *C/A* ratio when used as the micelle-like architecture above the CMC (Fig. 4(a)). Luciferase expression for Pep-L12 and Pep-L0 was 220.0 ± 68.0 and 19.3 ± 0.2 ng luciferase/mg protein at *C/A* ratio of 10, respectively. Under the same condition, we confirmed that the luciferase expression for oligoarginine (16 mer) was 2.4 ± 0.7 ng luciferase/mg protein at *C/A* ratio of 8 (data not shown). Luciferase expression for Pep-L12 was 100-fold higher than that for widely studied oligoarginine [17], indicating that Pep-L12 is a useful gene carrier.

Possible reasons for improved transfection efficiency by Pep-L12 micell-like carrier is discussed below. First, pDNA uptake was improved because of the high apparent Mw. It was reported that cellular uptakes were increased as increasing in carrier Mw [9,18]. The second reason is the resistance of pDNA to DNase. We have studied the DNase I resistance of polyplexes for poly-L-lysine (from 15 to 1170 mer) or poly-L-arginine (from 70 to 650 mer) by incubating polyplexes with DNase I *in vitro*. As results, higher Mw polypeptide leads to the larger DNase resistance may be because of the large compaction of the polyplexes (data not shown).

Enhanced transcription is the third possible reason for the improved luciferase expression. We previously reported that a micelle-type polycation is superior to the linear-type polycation in gene transfer due to the enhanced transcription [2]. In addition, we found the enhanced gene expression of the linear-type oligopeptide composed of furin cleavage sequences in comparison to control sequences without cleavage sites [12]. These results indicated that the intracellular cleavage of the cationic residues in Pep-L12 self-assembly by intracellular furin enzyme might play a role in weakening the polyplex compaction by decreasing the charge density of the cationic micelle-like architecture.

3.5. Transcription/translation efficiency in cell-free system

To elucidate the reason for enhanced transgene expression, cell-free transcription/translation assay was performed using Pep-L0 and Pep-L12. The transcription efficiency of Pep-L12 was suppressed completely in comparison with free pT7-Luc, but Pep-L0 showed slightly residual transcription (Fig. 5). In general, polyplexes composed of high Mw polycation are strongly compacted and then hard to be transcribed. As is similarly, Pep-L12 forming micelle-like structure seems to suppress transcription in cell-free system. However, Pep-L12 successfully led to the transgene

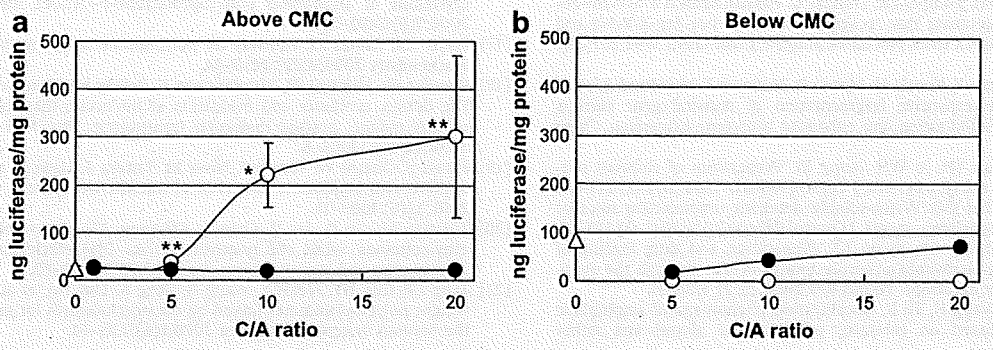

Fig. 4. Transient luciferase expression in COS-1 cells transfected using Pep-L0 (●) and Pep-L12 (○) in the presence of 100 μM chloroquine. (△) represents results for naked pCMV-Luc. Transfection assays were perfumed at above (a) or below (b) CMC of Pep-L12. (*$P < 0.01$, **$P < 0.05$.)

expression above CMC when evaluated in COS-1 system (Fig. 4), which indicates that the intracellular furin is able to associate with Pep-L12 somehow in cells.

In the present study, hydrophobic modification of the cationic gene carriers was proved to be effective. Pep-L12 formed hydrophobic/cationic core/shell morphology in aqueous solutions and lead to the enhanced gene expression *in vitro*. This type of core-shell structure should be energetically stable but the inverse structure has been also proposed. Futaki et al. reported that stearylated octaarginine forms polyplexes with the hydrophobic stearyl moieties at the outer surface and induces enhanced transgene expressions due to earlier endosomal escape. They expected that hydrophobic moieties contributed to interactions between polyplexes and cell membranes [19]. In our system, the leucine residues form core structure covered by the charged group and then it worked in the different mechanism.

In order to improve gene delivery efficiency with minimum cytotoxicity, several groups have reported the cross-linking of small PEIs with biodegradable linkage. Linked PEIs presented effective transgene expressions close to or higher than that offered by high Mw PEI (25 kDa) with reduced cytotoxicity [20,21]. Although low Mw PEI is much less cytotoxic than high Mw PEI, undegradable PEI remaining inside cells for a long period of time might interact with cell organelles and affect on cell functions [21]. On the other hand, oligopeptides would be understandably degraded if they remain inside cells after transfection. In this work, we designed novel oligopeptide-type carriers which showed high apparent Mw in aqueous solutions. Synthetic nonviral gene carriers composed of oligopeptides are thought to have potential of low cytotoxicity, enhanced cellular uptake and resistance to DNase. Further researches are necessary to clarify the intracellular behavior, physicochemical properties of polyplexes, such as degree of compaction and surface charge density.

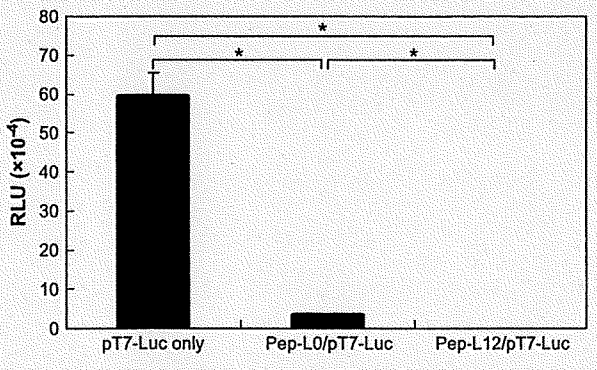

Fig. 5. Transcription efficiency determined by luciferase activity in *in vitro* transcription/translation system at C/A of 10. Polyplex formation was perfumed at a higher concentration than CMC of Pep-L12. (*$P < 0.0001$.)

4. Conclusions

A novel amphiphilic carrier Pep-L12 was synthesized by conjugating cationic sequences and hydrophobic sequences. Pep-L12 formed assemblies in aqueous solution at concentration above 0.16 g/L. Formations of assemblies brought about a dramatic increasing apparent Mw of carriers. Assemblies led enhanced transgene expression than linear carriers. Further analysis has to be done to design more effective self-assembly type gene carrier with low cytotoxicity.

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AIChE

Antibody-Immobilized Column for Quick Cell Separation Based on Cell Rolling

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Cell separation using methodological standards that ensure high purity is a very important step in cell transplantation for regenerative medicine and for stem cell research. A separation protocol using magnetic beads has been widely used for cell separation to isolate negative and positive cells. However, not only the surface marker pattern, e.g., negative or positive, but also the density of a cell depends on its developmental stage and differentiation ability. Rapid and label-free separation procedures based on surface marker density are the focus of our interest. In this study, we have successfully developed an antiCD34 antibody-immobilized cell-rolling column, that can separate cells depending on the CD34 density of the cell surfaces. Various conditions for the cell-rolling column were optimized including graft copolymerization, and adjustment of the column tilt angle, and medium flow rate. Using CD34-positive and -negative cell lines, the cell separation potential of the column was established. We observed a difference in the rolling velocities between CD34-positive and CD34-negative cells on antibody-immobilized microfluidic device. Cell separation was achieved by tilting the surface 20 degrees and the increasing medium flow. Surface marker characteristics of the isolated cells in each fraction were analyzed using a cell-sorting system, and it was found that populations containing high density of CD34 were eluted in the delayed fractions. These results demonstrate that cells with a given surface marker density can be continuously separated using the cell rolling column. © 2009 American Institute of Chemical Engineers *Biotechnol. Prog.*, 26: 441–447, 2010
Keywords: cell separation, cell rolling, surface marker, antibody, CD34

Introduction

Because they do not lead to immunoreactions, tissue-derived stem cells have been the subject of much interest as an autologous source of stem cells.[1,2] The first important step in regenerative medicine using stem cells is to isolate a sufficient quantity of high purity stem cells in the clinically permitted period.[3,4] However, the isolation of homogeneous stem cells harvested from the body along with other mature cells is complicated procedure. Generally, stem cells are purified on the basis of their density,[5] size,[6] adhesion properties,[7] or surface maker patterns.[8–12] Although density gradient centrifugation and separation by size-sieving are relatively simple and easy to perform, they are not specific for stem cells. The most popular method for isolating mesenchymal stem cells (MSCs) is separation of the adherent cells on a plastic culture dish.[7] However, this method of cell isolation is also unsatisfactory for obtaining highly homogeneous stem cell populations.[2,13]

In contrast, an antibody-based strategy is much more effective and specific. Various cell surface markers have been found to be useful in identifying every type of stem cell. Once identified, stem cells can be isolated using fluorescence-activated cell sorting (FACS) or magnetic-activated cell sorting (MACS) systems. These strategies have been useful for separating target cells with an identified cell surface marker from unpurified cell populations.[14] For clinical stem cell therapy in cardiac revascularization, unpurified bone marrow cells or purified bone marrow CD133+ cells were injected into the infarct area; in these treatments, improvement in both blood flow and left ventricular function were observed.[13] However, contamination with other cell populations has also been described as a potential hurdles for clinical cell-therapy.

The types of surface markers expressed, as well as the level of marker expression, depend on the differentiation or developmental stage.[15,16] For example, the CD34 expression level of hematopoietic stem cells continuously decreases with developmental stage.[17] In myogenic progenitor cells, the expression level of CD34 changes during its differentiation into a myotube.[16] Marker density is a critical factor for stem cell separation; however, the widely used MACS system is not sensitive to marker density. One effective approach to this problem is to use a gate to set fluorescence intensity in FACS. The FACS system requires a rapid flow for cell sorting, and this affects the viability of sorting cells. Moreover, the cells thus obtained are contaminated with fluorescence- or magnetic bead-modified antibodies, which must be subsequently removed for safety.

Additional Supporting Information may be found in the online version of this article

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As a solution to these problems, a novel cell separation system was designed based on the cell-rolling process that can separate cells with a given surface marker density. First reported by Andrian in 1991, the leukocyte-rolling mechanism has been defined as the temporal interaction between a leukocyte surface marker and endothelial cells on the blood vessel luminal surfaces.[18] Hammer et al. described the temporal interaction between the cell surface markers and the immobilized ligand in the flow media.[19] Detailed mechanisms of the rolling adhesion properties of cells have been reported by other groups.[20–25] This unique concept has also been applied in drug screening,[26] local delivery of therapeutics,[27] and studies of cell regulation.[22,28,29] Antibody-immobilized microfluidic devices and microfabricated-cell sorters have been developed for isolating target cells with an adequate surface marker using the positive/negative selection method.[30,31] Patterning surface of receptors has been used as a means of continuous separation of cells by cell rolling.[32] This mechanism effectively isolates large quantities of cells. However, the cells in this system are intermittently rolled on the surface, and cell rolling as well as tethering between the receptor-coated region and the unmodified region are induced by the pattern and its edge. This surface approach is also an effective method of cell separation by cell rolling.

In this study, we focused on whether CD34-positive cells could be finely separated based on the CD34 densities on their surface. The KG-1a cell line, which is CD34-positive, was used as the model, while the CD34-negative HL-60 cell line was used as the control. We developed a tubular column with a continuous surface for cell separation such that the anti-CD34 antibody was immobilized at a high density on the surface. Chemical immobilization of the antibody through poly(acrylic acid) graft polymerization prevents antibody contamination of the purified cells. The injected cells are rolled on the inner surface of the column due to the medium flow shear force, in a manner similar to that of the rolling adhesion process of a leukocyte in a blood vessel.[18] The cell suspensions of KG-1a or HL-60 were passed through the column, and the cell numbers and the surface marker pattern on the cells were evaluated in each elution fraction.

Materials and Methods

Culturing of KG-1a and HL-60 cells

CD34-positive KG-1a cells were grown in IMEM culture medium (Invitrogen, Carlsbad, CA) supplemented with 10% fetal bovine serum (FBS) (Sigma, St. Luis, MO), penicillin (100 U/mL), and streptomycin (100 μg/mL). CD34-negative HL-60 cells were grown in RPMI medium (Invitrogen, Carlsbad, CA) containing 20% FBS with antibiotics. The cell lines were cultured in a humidified atmosphere containing 5% CO_2 at 37°C.

Antibody-immobilized column

Polyethylene tubes with a 1-mm inner diameter were selected as the substrate for the cell-separation column. Graft polymerization of acrylic acid onto the column was conducted as follows. The tube was treated with ozone gas (ON-3-2, Nippon Ozone Co.Ltd., Tokyo, Japan) for 4 h, dipped in 0–30% acrylic acid/methanol solution, and incubated at 60°C. After 4 h, the tube was washed with water.[33,34] The graft polymerization was confirmed by toluidine blue staining. To immobilize the anti-CD34 antibody on the tube surface, the poly(acrylic acid)-grafted tube was activated using 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride (WSC) under various conditions. Thereafter, the activated tube was filled with a 0.1 mg/mL solution of the monoclonal mouse anti-human CD34 class II antibody (Dako Ltd., Carpenteria, CA), and incubated at 37°C for 15 h. The tube was washed with PBS, treated with 1 mM 2-aminoethanol solution for 1 h and preserved at 4°C until experimental use. The antibody density on the luminal surface was evaluated using peroxidase conjugated anti-mouse IgG (whole molecule) antibody (Sigma, St. Luis, MO). Peroxidase activity was measured using the SMILON Peroxidase Detection Kit (Sumitomo Bakelite Co.,Ltd., Tokyo, Japan).

Separation of cells on the antibody-immobilized column

The antibody-immobilized column was connected using a syringe pump (Model:780120J; KD Scientific Inc., Hollistone, MA) through the unmodified tube. The length of the antibody-immobilized column and the unmodified tube was 100 mm, and the cell suspension was directly injected into the unmodified tube using a disposable syringe with a 27 G needle. The column was inclined against the ground, and the tilt angle was fixed by clamping. Cell separation was performed as follows. The KG-1a or HL-60 cell suspension (2×10^4 cells/50 μL) was injected into the column. After injection, PBS buffer was flushed into the column to promote cell rolling on the surface. The flow rate of PBS was optimized by experimentation. The eluted cell suspension was then collected from the end of the column; collected volume of each fraction was 50 μL. The numbers and surface marker profiles of the eluted cells were analyzed using FACS.

Rolling velocity of the KG-1a cells

The microfluidic device was purchased from ibidi GmbH (Model ib80501; ibidi GmbH, Martinsired, Germany). The dimensions of the microfluidic channel were 24 mm (length) × 500 μm (width) × 300 μm (height), with one inlet and one outlet. Anti-CD34 antibody was immobilized on the channel surface, and the modification method used was the same as that used for the tubular column. The cell suspension (2×10^6 cells/mL) was injected into the inlet at a rate of 50 μL/min, and cell rolling was recorded using a high-speed CCD camera (EM-CCD digital camera; Hamamatsu,

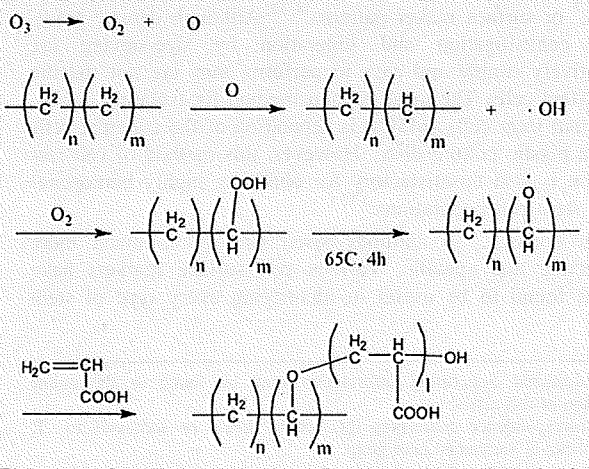


Figure 1. Graft polymerization of acrylic acid on the polyethylene tube.

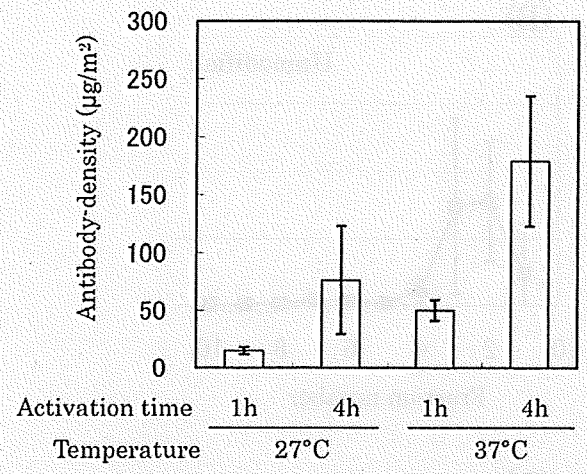
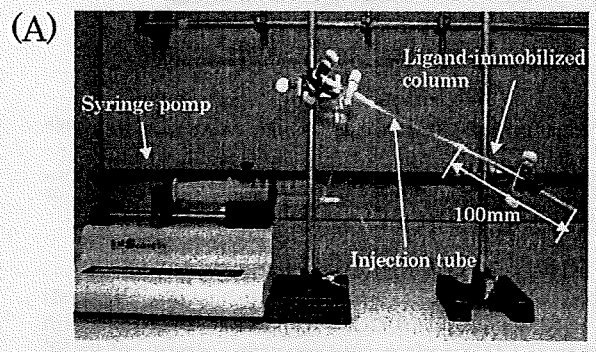


Figure 2. Effects of reaction conditions on immobilized antibody density.

The degree of immobilization is substantially affected by the duration and temperature of the WSC activation reaction. Each data point represents the results of three independent experiments. Data are presented as means ± standard error on the mean.



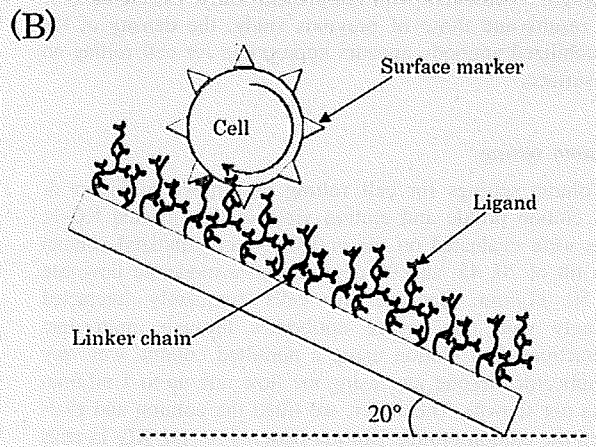
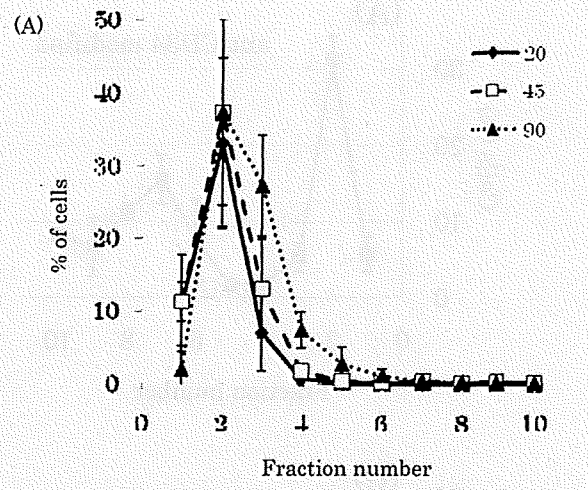


Figure 3. (A) Photograph of the cell separation column system. The antibody-immobilized column was connected to the injection tube and syringe pump. Cells were injected into the injection tube and PBS continuously flowed into the column. The eluted fraction was collected at the end of the column. (B) Schematic diagram of cell rolling on the antibody-immobilized column.



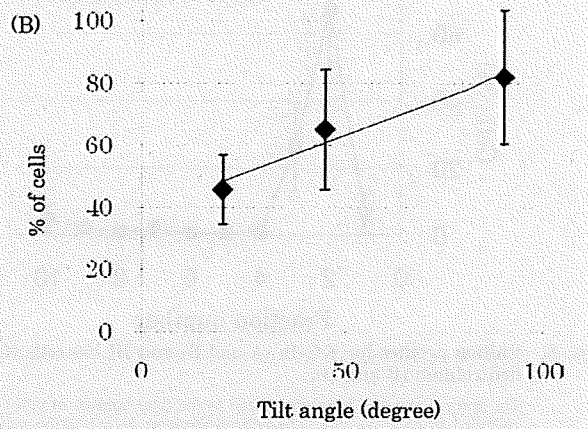


Figure 4. (A) Elution pattern for KG-1a cells at different tilt angles of the antibody-immobilized column, and (B) elution yield of injected KG-1a cells. The vertical axis has been normalized to the total number of injected KG-1a cells. Each data point represents the results of three independent experiments.

Hamamatsu city, Japan). The motion and velocity were analyzed using a personal computer.

FACS analysis

Isolated cells were incubated with FITC-conjugated anti-human CD34 monoclonal antibody (BD Bioscience, San Diego, CA) in PBS for 30 min at 4°C and analyzed using a FACS-Calibur Flow Cytometer (BD Bioscience, San Jose, CA).

Results and Discussion

Fabrication of the antibody-immobilized column

Ozone-induced graft polymerization is effective for polyethylene matrices with a fine structure because ozone gas can be charged into the inner surface and peroxides can be uniformly introduced. The reaction mechanism is shown in Figure 1. The surface concentration of peroxide and its reaction mechanism with vinyl monomer have been previously reported.[33,34] The introduction of the graft polymer chain was confirmed by toluidine blue staining. When the polymer

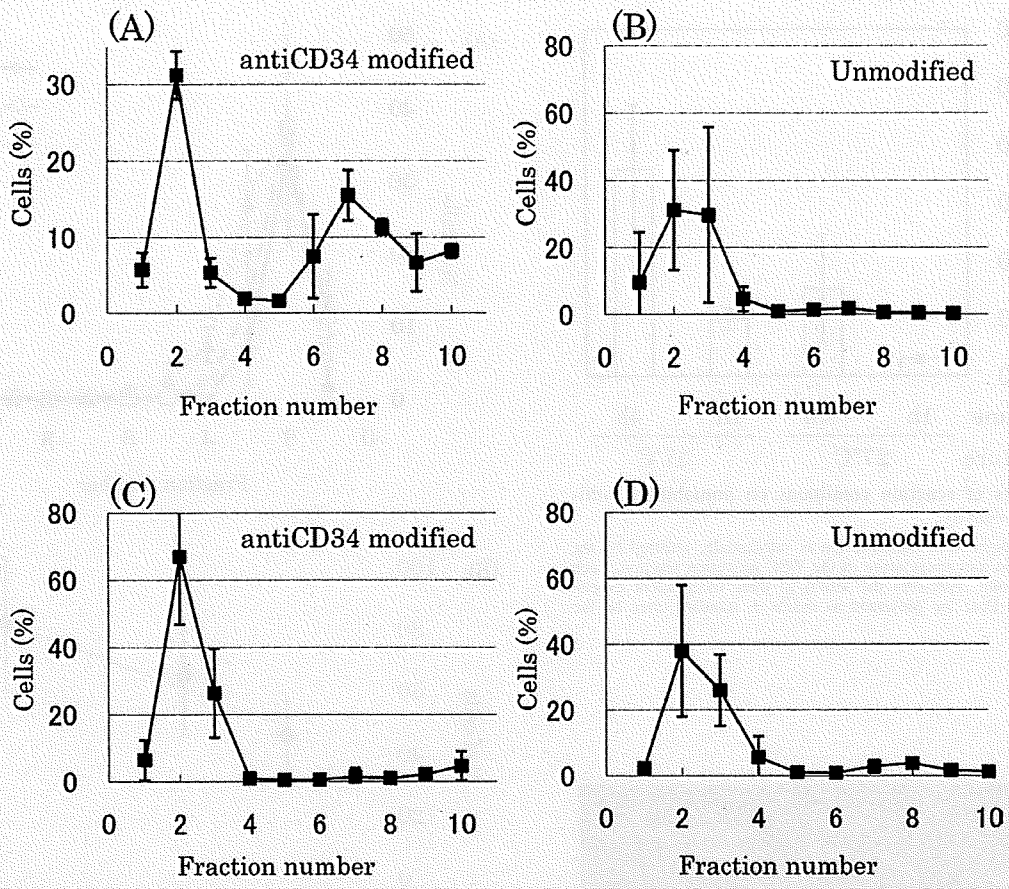


Figure 5. Elution profiles for KG-1a (A and B) and HL-60 cells (C and D) on the anti-CD34 modified column (A and C) and unmodified column (B and D).

The vertical axis has been normalized to the total number of cells. Fifty microliters of the cell suspension was applied and 50 μL of the eluant was collected in each fraction. The cell numbers in each fraction were analyzed using FACSCalibur flow cytometry. Each data point represents the results of 3 independent experiments; the data are presented as means ± standard error on the mean.

concentration was 30%, it was more difficult to flash medium inside the column compared with the lower concentrations. Therefore, a column reacted with 20% acrylic acid solution was selected for the subsequent experiments.

To develop a high-performance column for separating cells with various surface marker densities, the density of the immobilized anti-CD34 antibody should be well controlled. To optimize conditions for antibody immobilization on the inner surface of the tube, we measured the density of the immobilized antibody using HRP-labeled anti-mouse IgG goat antibody. Figure 2 shows the effects of temperature and the WSC activation period on the immobilized density of the anti-CD34 antibody. At an activation temperature of 27°C, the antibody could not be immobilized to the graft chain. On the other hand, when the reaction mixture was incubated at 37°C, the density of the immobilized antibody was approximately 180 $\mu g/m^2$ or about 1.2×10^9 mol/m^2. Cell rolling adhesion is defined as the continuous interaction between a ligand and the cell surface.[18] Rolling velocity is largely restricted by the ligand density and the interaction with the surface marker. Greenberg reported that 10^9 mol/m^2 (800 sites/μm^2) was suitable for cell rolling on a ligand-modified substrate in an experimental as well as theoretical study.[22] In our experiments, the anti-CD34 antibody density in the area occupied by a single cell was 6.3×10^4 sites/cell, and the antibody density was nearly the same as that in Greenberg's report. On the basis of QuantiBrite PE analysis, Zborowski and coworkers reported that Jurkat cells expressed a high number of CD45 surface antigens with a density of 9×10^4 sites/cell,[35] consistent with the present study. On the basis of our results and those of previous study, the density of the immobilized antibody appears appropriate for cell rolling on the surface.

Column setting

Column settings for cell rolling are shown in Figure 3. The elution profile and elution yield of the injected KG-1a cells were evaluated on the anti-CD34 immobilized column at a tilt of 20, 45, and 90 degrees and a moderate flow rate of 50 μL/min. Because the cells frequently interacted strongly with the surface antibodies through multivalent interactions, cell elution using a nontilted column was very complicated, despite increasing the flow rate up to 1 mL/min (data not shown). Thereafter, we tilted the column and evaluated the elution profile. Elution patterns for the KG-1a cells at various tilt angles of the column were almost the same, with a single elution peak observed at Fraction 2 (Figure 4A). The injected cells were almost completely eluted without any surface interactions at an angle of 90 degrees. However, the total recovery ratio of the injected cells decreased with decrease in tilt angle (Figure 4B). When the column

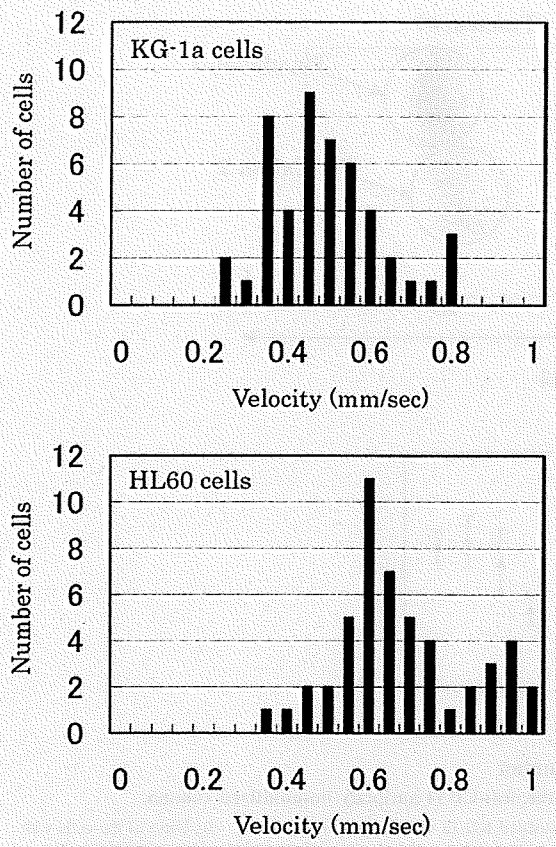


Figure 6. Distributions of the rolling velocities of KG-1a and HL-60 cells on the anti-CD34 antibody immobilized surface. Rolling cells were monitored using a high-speed CCD camera.

angle was 20 degrees, half of the injected cells remained in the column. It is likely that these cells interacted with the surface antibodies, thereby greatly reducing the rolling velocity. After flushing at 50 μL/min, the flow rate was changed to 600 μL/min and most of the injected cells were eluted. We tilted the column angle to 20 degrees, and thus, the cells that interacted with the antibody-immobilized surface rolled on the surface with higher velocity because of the increase in the flow rate. The initial flow rate was maintained at 50 μL/min through Fraction 5, and the rate was changed to 600 μL/min thereafter.

Specificity of the separation profile

KG-1a cells could be separated using the antiCD34 antibody-immobilized column with the settings described earlier. A bimodal elution pattern was observed (Figure 5A). The first elution peak corresponded to the single peak in Figure 4A, suggesting that the cells in the first peak did not interact with the immobilized antibody. In contrast, the delayed fraction was not observed when the KG-1a cells were injected into the unmodified column (Figure 5B). Elution profiles for HL-60 cells (CD34-negative) were compared with those for the CD34-positive cells. All injected HL-60 cells were eluted from the anti-CD34 antibody-immobilized and unmodified column in Fractions 1–3 (Figure 5C,D). This elution profile was the same as the pattern resulting from the column angle fixed at 90 degrees (Figure 4A); that is, HL60 cells injected into the column did not interact with the immobilized antibody. This indicates that the retention time of the cells in the delayed fraction depends on the specific interaction between the surface marker and the immobilized antibody (Supporting Information).

Additional evidence of successful cell separation using the cell rolling mechanism on the column was provided by observation of the rolling velocities on the antibody-immobilized surface. We used a microfluidic channel to measure the distribution of rolling velocities. The microfluidic channel, which was modified with anti-CD34 antibody in the same manner as the column, was set on a microscopy stage, and cell rolling was monitored using a high-speed CCD camera at a moderate flow rate of 50 μL/min. Some cells adhered onto the antibody-immobilized surface and were not able to flow again after adhesion due to multivalent interaction between the cell surface and immobilized antibody. The velocities of the KG-1a and HL-60 rolling cells on the anti-CD34 antibody-immobilized microchannel were 0.45 mm/s and 0.6 mm/s, respectively (Figure 6). Conditions for measurement of the cell rolling velocity on the microscope were different from the cell separation experiments, because the microfluidic device was placed on the flat stage of the microscope without a tilt angle. Under these conditions, large differences in rolling velocity between KG-1a and HL-60 cells were not observed (Figure 6). However, the distributions of the velocities were distinctly different between the KG-1a and HL-60 cells. The difference in the interactions is likely reflected in the velocity distributions. Thus, the velocity of cells rolling was largely dependent on the cell surface marker.

Hammer et al. reported that the rolling velocity of saturated sLe^x-modified polystyrene microspheres was 20 times slower than that of microspheres with a low surface density of sLe^x on an L-selectin coated surface; this difference could be successfully exploited for separation.[8,9] However, it was also reported that CD34-positive bone marrow cells rolled only twice as slowly as CD34-negative cells on an L-selectin modified surface. We observed similar differences in rolling velocities between CD34-positive and -negative cells on the antibody-immobilized surfaces. This small difference in the rolling velocity on a flat microfluidic device prevented cell separation, as shown in Figure 5. We optimized a variety of separation conditions such as consideration of the surface modification tendency, changes in the medium flow rate, and modifying the column setting conditions; this resulted in the bimodal pattern shown in Figure 5A. In our system, separation of rolling cells was most effective after optimization of the column tilt angle and flow rate.

Surface marker characteristics of the isolated cells

To confirm whether our column could be used to separate cells based on CD34 surface density, the CD34 expression level of the KG-1a cells in each fraction was investigated by dual dimensional FACS analysis. Forward-light scatter characteristics (FSC) depend on cell size, which is related to cell cycle or cell proliferation. Fluorescence intensity, indicating the CD34 expression level of each cell line for fractions 2 and 7, is shown in Figure 7A. Two populations of KG-1a were identified by the FACS analysis of CD34 expression versus FSC signal. Although a single population was indicated by the FACS data for Fraction 2, two cell populations (Populations 1 and 2) were observed in Fraction 7. The CD34 expression level of Population 1 was nearly the same as for Population 2, but the cell size of Population 2 was

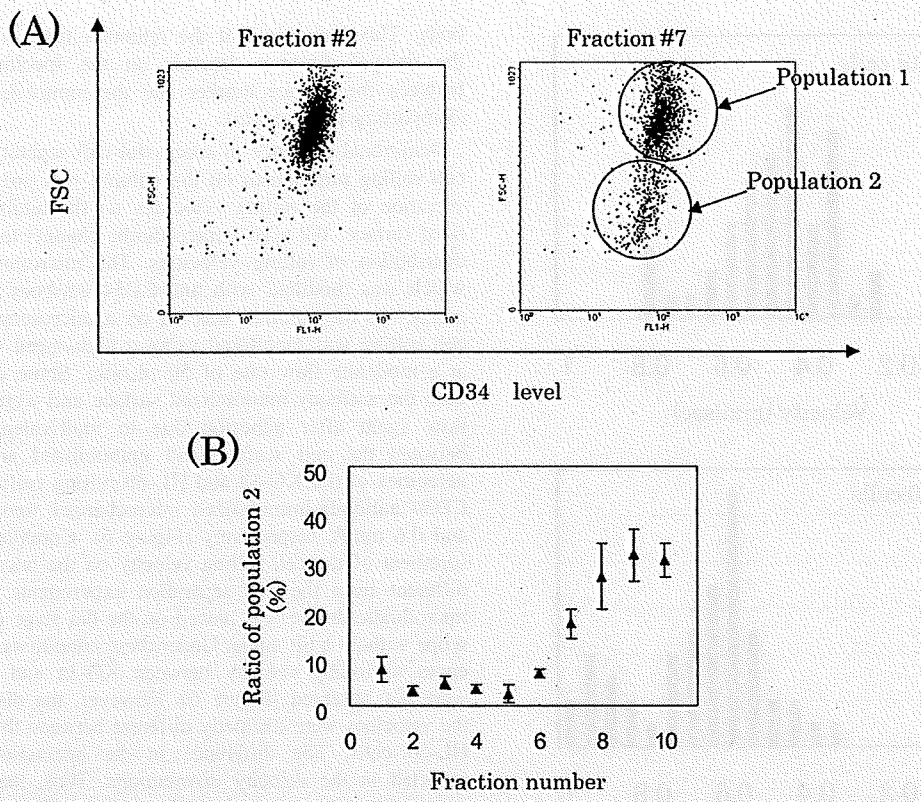


Figure 7. Analysis of the surface marker density of isolated KG-1a cells on the anti-CD34 antibody immobilized column.

(A) Dual dimensional analysis of the CD34 expression level and FSC of the isolated KG-1a cells in Fractions 2 and 7. (B) Ratio of the cells with population producing a high concentration of CD34 in each fraction. Each data point represents the results of three independent experiments.

about half of Population 1. Therefore, the density of CD34 in Population 2 was about 4 times higher than that of Population 1. In Fraction 2, a majority of the cells were of Population 1 as the cell rolling velocity was much larger than for Population 2. The population of the CD34-dense populations was plotted against the fraction number (Figure 7B), and gradually increased with elution time. If the cells in the delayed fraction were separated by static adhesion onto the surface, the high CD34-expression population could not have been isolated from the CD34-positive cell population, because all of the injected cells would have adhered to the resulting surface (Figure 4A). These findings suggest that the cells in the delayed fraction rolled more slowly on the surface than the cells in the previous fractions in a marker-specific manner under shear flow conditions. Thus, this separation procedure is able to isolate cell populations with different marker densities in a continuous manner.

Conclusions

Development of an effective cell separation system is crucial for cell transplantation and for the fundamental study of cell biology. In many cases, negative or positive selection has been used as an effective strategy for cell separation, and the MACS system is a suitable technology for conducting the selection. However, this system cannot separate cells with different densities of surface markers. On the other hand, FACS system can separate cells based on the marker expression level, cellular density, and cell size. For these reasons, FACS was effective in separating the cells in Population 1 and 2 of the KG-1a cells. In this study, we demonstrated the feasibility of a novel cell-separation column that isolates cells through the cell rolling process based on surface marker density under labeling-free conditions. In the standard FACS system, the cells would be exposed to strong media flow, and its velocity and antibody labeling would reduce its viability. To improve the purity of the cells isolated by the column, it is necessary to optimize the surface antibody modification and column structure.

Our system offers several advantages over conventional methods. We would expect cell separation to be more rapid than with conventional methods; moreover, an antibody-immobilized column would likely reduce the degree of cellular damage because cell modification using fluorescence- or magnetic beads-labeled antibodies is unnecessary. For the same reason, the cells thus purified are free of contamination. A highly purified cell population without such impurities or additives will provide an important tool for both transplantation therapy and fundamental study.

Acknowledgments

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Continuous separation of cells of high osteoblastic differentiation potential from mesenchymal stem cells on an antibody-immobilized column

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ABSTRACT

Here, we report that two distinctive cell populations with osteoblastic differentiation ability were found in adherent cell populations from bone marrow. Mesenchymal stem cells (MSCs) were conventionally isolated by using adherent property of bone marrow cells onto a plastic culture dish. MSCs enriched on the basis of their adherent property were considered phenotypically and functionally heterogeneous. We developed a ligand-immobilized surface for separating subpopulation of adherent cells derived from bone marrow by the cell rolling process. We successfully isolate two cell populations with high differentiation ability for osteoblasts in adherent bone marrow cells by using the anti-CD34 antibody-immobilized column. The antibody was covalently conjugated with polyacrylic acid and introduced onto the inner surface of a silicone tube. When cell suspension of MSCs was injected into the antibody-immobilized column, different cell populations were isolated. After the cultivation of isolated cells in the osteoblastic differentiation medium for 1 week, few sub-populations were strongly induced to form osteoblastic cells. This study revealed that the ligand-immobilized surface can be used to continually separate cell populations under a labeling-free condition.

1. Introduction

It is widely known that adherent cells found in bone marrow have an ability to differentiate into osteoblasts, adipocytes and chondrocytes. That stem cell is generally named as marrow stromal cells or mesenchymal stem cells (MSCs). Cell differentiation property and its mechanisms have been widely studied in clinical and biological fields. In particular, the field of regenerative medicine focuses on tissue derived stem cells for autologous cell transplantation [1,2]. One important finding is that MSCs, which exist in not only bone marrow but also cord blood and adipose tissue, have therapeutic potential for heart, neural, and brain diseases [3–5]. A standard procedure for isolation of MSCs was reported by Pittenger et al. [6]. MSCs are easily separated by using the adherent property of bone marrow cells onto plastic culture dishes. Ficoll-Hypaque density gradient centrifugation is also used for separating mononuclear cells containing MSCs [7,8]. Other isolation methods based on selection of non-adherent cell population [9], STRO-1 antibody-recognized antigen level [10], and size-sieved cell population [11] have been reported. Isolation methods based on various combinations of cell surface markers have been reported by many groups [12–16].

Although the adherent property of MSCs has been widely used for their isolation, MSCs enriched on the basis of their adherent property are considered as phenotypically and functionally heterogeneous [17]. Surface marker characteristics such as marker density and its variation change with the differentiation process and development of MSCs. Surface marker profile of murine MSCs significantly differ with the passage levels [18,19]. CD34 expression of hematopoietic stem cells continuously decreases with the developmental stage [20]. Consequently, the development of a new approach to isolate MSCs population is important for homogeneous separation.

We have recently developed an antibody-immobilized column which can separate CD34-positive KG-1a cells from CD34 negative HL60 cell [21]. The separation mechanism seems to be based on dynamic interaction between cell surface marker (CD34) and immobilized antibody, known as the cell rolling. In nature, cell rolling is mainly observed in blood vessels as an inflammatory response of leukocytes [22], and its mechanism is derived from temporary interaction between cell surface and ligands. Rolling velocity is regulated by the ligand or cell surface receptor density [23–27]. Thus, cells with different rolling velocities are separated on the surface constantly modified with the ligand against a specific cell surface marker. This separation technique would

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principally enable a labeling-free process, and the isolated cells are not contaminated with fluorescent or magnetic-labeled antibody. This procedure would be effective in separating sub-populations of MSCs with different density of surface marker.

In the present study, we applied the antibody-immobilized column to heterogeneous which acquired from murine bone marrow by conventional isolation procedures, and successfully found two different populations in the crude MSCs. The fractions of MSCs were cultured under an osteoblastic differentiation condition for 1 week, and gene expression of specific markers was analyzed by real-time polymerase chain reaction (PCR). To evaluate calcium deposition on the cells, staining with alizarine red S solution was carried out.

2. Materials and methods

2.1. Isolation and culture of mouse MSCs

MSCs were collected according to a protocol modified from Tropel et al. [16]. Mouse bone marrow cells (BMCs) were isolated by flushing the marrow cavities of 8–10-weeks-old C57Bl/6 mice (Japan SLC, Inc., Shizuoka, Japan). BMCs were cultured on a polystyrene cell culture dish (Iwaki Glass, Chiba, Japan) with alpha-MEM (Gibco-Invitrogen, Carlsbad, CA) containing 15% fetal bovine serum (FBS; MB Biomedicals, Inc., Eschwege, Germany), 25 U/ml penicillin, and 25 μg/ml streptomycin (Wako Pure Chemical Industries, Ltd., Osaka, Japan). Non-adherent cells were removed by replacing the culture medium after 3 days. The cells were grown to confluency, washed with the medium, and subcultured by using the Trypsin/EDTA kit (Lonza, Walkersville, MD). Confluent cells were plated at 1:2 to 1:3 dilutions. The adherent cells enriched into plastic culture dish with early passage (passage 3 or 4) were subjected to all experiment as crude MSCs.

2.2. Surface marker analysis and cell sorting by fluorescence activated cell sorting

To evaluate the expression of surface markers by fluorescence-activated cell sorting (FACS), cells were suspended in PBS buffer for 30 min at 4 °C with fluorescein- or phenylephrine-conjugated antibodies against the surface markers CD29, CD31, CD34, CD44, CD45, CD81, CD11b and Sca-1. Antibody labeling was performed using the standard protocol. CD29 and CD31 antibodies were purchased from AbD Serotec (Oxford, UK) and Immunotech (Marseille, France), respectively. CD34, CD11b and Sca-1 antibodies were purchased from eBiocience (San Diego, CA). CD44, CD45 and CD81 antibodies were purchased from Pharmingen (San Diego, CA). After labeling with antibodies, 10^4 cells were analyzed with a FACScalibur flow cytometer (BD Biosciences, San Jose, CA). Conventional sorting of cells with different CD34 expression levels was conducted by FACSAria (BD Biosciences), as control experiment.

2.3. Preparation of the anti-CD34 antibody-immobilized column

Silicone tubes with 0.5 mm inner diameter were used as a substrate for the antibody-immobilized column. Graft polymerization of acrylic acid onto the silicone tube surface was conducted as follows. The tube was treated with ozone gas (ON-3-2, Nippon Ozone Co., LTD., Tokyo, Japan) for 4 h, dipped in 10% acrylic acid/methanol solution, and incubated at 60 °C. After 4 h, the tube was washed with water [28,29]. Graft polymerization was confirmed by toluidine blue staining. To immobilize anti-CD34 antibody on the tube surface, the poly(-acrylic acid)-grafted tube was pre-activated with 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide hydrochloride (WSC), filled with the anti-mouse CD34 rat IgG antibody (AbD Serotec) solution at concentration of 10 μg/ml, and incubated at 37 °C for 15 h. The tube was washed with PBS, treated with 1 mM 2-aminoethanol solution for 1 h, and preserved at 4 °C until experimental use. The column length was 10 cm, and the tilt angle was 20°.

2.4. Separation of crude MSCs on the antibody-immobilized column

A total of 2×10^4 cells of crude MSCs in 10 μL PBS were injected into the column. The column was flushed with PBS buffer at the flow rate of 50 μL/min until the flow

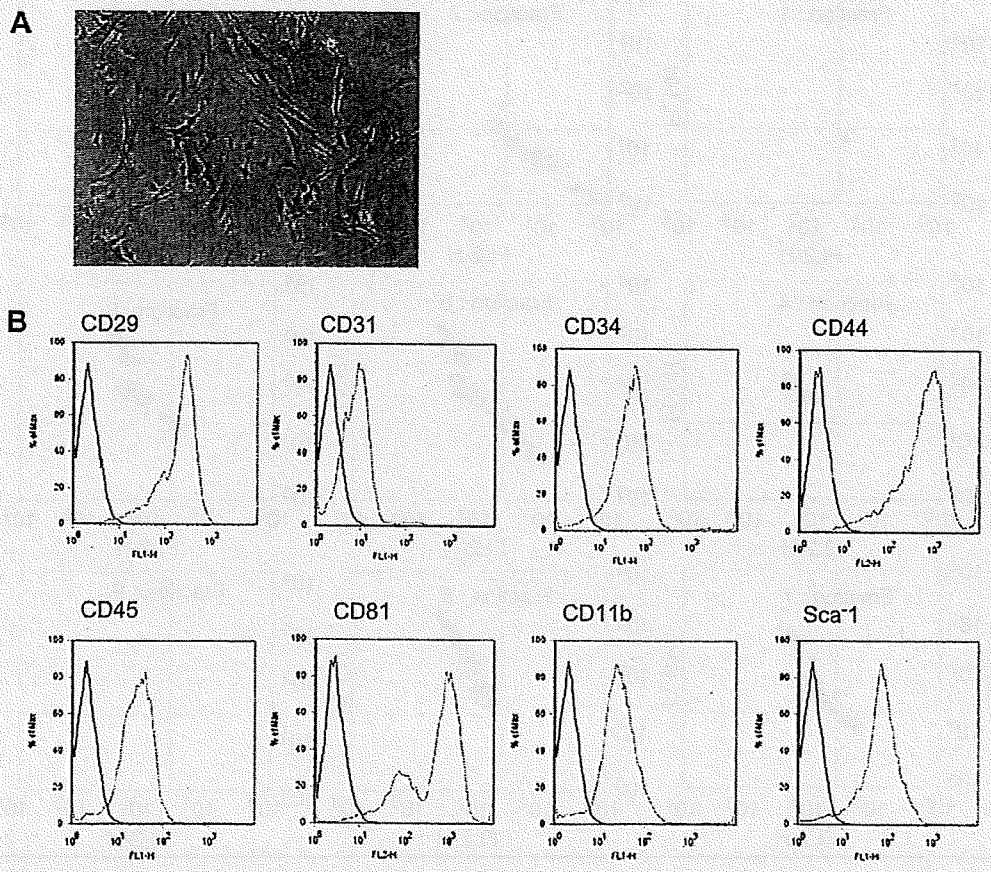

Fig. 1. (A) Morphology of murine MSCs culture. Cultured cells contained some type of cells like small round cells and fibroblast-like cells. (B) Surface marker expression of murine MSCs at passage 2. MSCs were stained with an FITC or PE-labeled antibody. Staining cells were shown in red histogram, and the black is unstained cells as control. These data were confirmed by 3 independent experiments.

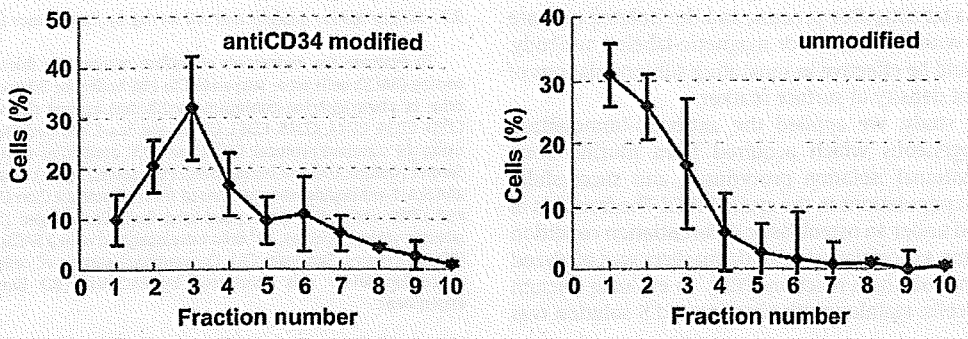

Fig. 2. Elution profiles of murine MSCs on the anti-CD34 antibody-immobilized column or unmodified column. Cell number ratio normalized by the total cell number was plotted against the fraction number. Each data point represents results from 3 independent experiment and the data are presented as mean ± standard error of the means.

volume of 250 μL, and at 600 μL/min thereafter. Eluted cell suspension was collected from top of the column, and cell suspensions were fractionated by elution volume (12.5 μL per fraction). Number and surface marker profile of cells in each fraction was analyzed by the FACS system.

2.5. Differentiation of isolated MSCs into osteoblasts

Purified MSC fractions were acquired from 2×10^4 crude MSCs. MSCs separated on the antibody-immobilized column were cultured on fibronectin-coated 24-well plates (FALCON, Oxnard, CA) with the osteoblastic differentiation medium containing 10^{-8} M dexamethasone, 10 mM β-glycerophosphate, and 0.3 mM ascorbic acid (all three reagents from Sigma–Aldrich, St. Louis, MO). The medium was changed 3 times per week. The cells were fixed with 10% formalin for 20 min at room temperature (RT) and stained with alizarin red S solution.

2.6. Gene expression analysis by real-time PCR

After culturing in differentiation medium for 1 week, total cellular RNA was isolated using Quickgene Mini80 with Quickgene RNA cultured cell kit S (FUJIFILM, Tokyo, Japan). Reverse transcription (ReverTra Ace, TOYOBO Co., LTD., Osaka, Japan) using oligo dT_{18} primer was performed on aliquots (200 ng) of total RNA as a template. The resultant cDNA was used for PCR amplification, and PCR analysis was

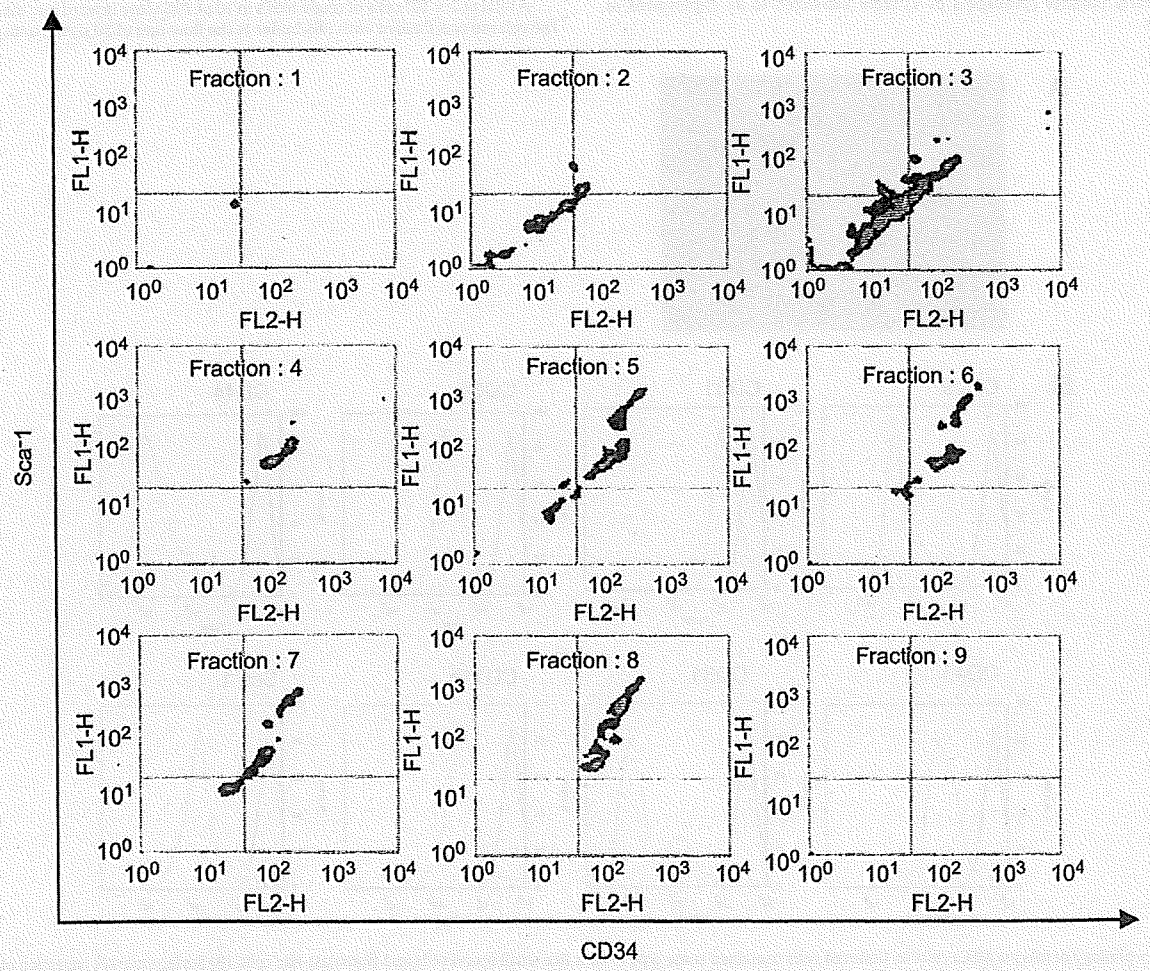

Fig. 3. Surface maker expression of isolated MSCs. Two-dimensional expression analysis of CD34 or Sca-1 was carried out in isolated cells fractions.

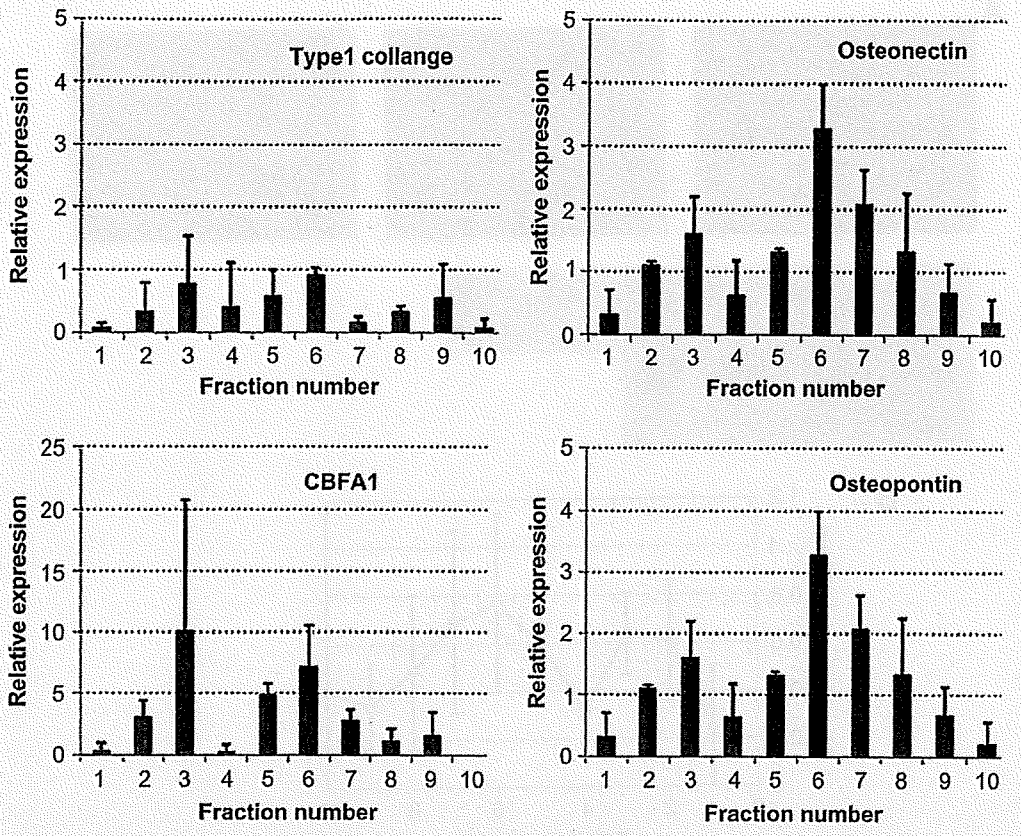

Fig. 4. Gene expression analyses of isolated MSCs on the anti-CD34 antibody-immobilized column for osteoblastic differentiation after 1 week. Relative expression is normalized by the expression of crude MSCs. GAPDH expression level was used as the internal standard control. Each data point represents results from 3 independent experiment and the data are presented as mean ± standard error of the means.

carried out by the GeneAmp 5700 Sequence Detection System (Applied Biosystems, Foster City, CA). PCR primers were designed by Primer Express software (Applied Biosystems). Type 1 collagen, CBFA1, osteopontin and osteonectin were selected as specific marker genes for differentiation. PCR reaction mixture contained 0.52 μL cDNA, 5 pmol of each primer, 25 μL SYBR Green Real-time PCR Master Mix (TOYOBO Co., LTD., Osaka, Japan). Amplification conditions were as follows: 40 cycles of 95 °C for 1 min; 60 °C for 15 s; 74 °C for 1 min. Primers used were (5′ to 3′) CBFA1: CCGCACGACAACCGCACCAT (forward), CGCTCCGGCCCACAAATCTC (reverse); Type 1 collagen: GAAGTCAGCTGCATACAC (forward), AGGAAGTCCAGGCTGTCC (reverse); Osteopontin: TCACCATTCGGATGAGTCTG (forward), ACTTGTGGCTCTGATGTTCC (reverse); Osteonectin: AGCGCCTGGAGGCTGGAGAC (forward), CTTGATGCCAAAG-CAGCCGG (reverse); GAPDH: CAAAATGGTGAAGGTCGGTGTG (forward), ATTT-GATGTTAGTGGGGTCTCG (reverse).

3. Results and discussion

3.1. Surface marker analysis of adherent cell population

MSCs are isolated by the bases of adherent property of bone marrow in some species, such as human [6] and rat [30]. However, it is difficult to isolate homogeneous MSCs by adhesion separation because of unwanted contamination. The crude MSCs displayed a fibroblast-like morphology shown in Fig. 1(A). To eliminate the monocytic cell fraction in adhesion cell population, magnetic beads conjugated with anti-CD11b or anti-CD45 antibodies were used for negative selection [14,16]. Although some surface markers for MSCs were reported in a recent study, homogeneous MSCs could not be identified by such kinds of markers [17,31]. Surface marker expression level of adherent population of murine MSCs are shown in Fig. 1(B). A strong expression of the surface markers CD29, CD44, CD81, and Sca-1, and a weak expression of the surface markers CD34, CD45, and CD11b were observed. No expression of CD31 was observed. Some studies have reported that murine MSCs were positive for the surface markers CD29, CD44 and Sca-1 [14,15,32], and this finding was confirmed in our experimental data. Sca-1 expression level changed with the culture period (data not shown). This phenomenon was already reported in other studies [32]. The MSCs showed a weak and broad expression of CD34, a hematopoietic lineage marker. Umezawa et al. reported that murine MSCs with a low expression of CD34 have a high potential for the regenerative effect in cardiopulmonary disease. CD34 is the progenitor or stem cell marker, and the expression continuously decreased with the culture period. That is, the CD34 expression would be closely related with the differentiation stage. Hence, we chose the anti-CD34 antibody as the immobilized ligand and evaluated the differentiation ability of MSCs isolated on the anti-CD34 antibody-immobilized column.

3.2. Separation profile of MSCs on the anti-CD34 antibody-immobilized column

We have developed a separation column in previous work [21]. Details about the separation column were shown in Materials and methods. The antibody-immobilized column was connected with an injection tube. The length of the column and injection tube was 100 mm. Medium flow into the column was accomplished with a syringe pump. Elution profile of crude MSCs on the anti-CD34 antibody-immobilized column was evaluated by counting the number of eluted cells in each fraction. When the crude MSCs were injected into an unmodified column, almost all the cells were eluted in early fractions. On the other hand, when the crude MSCs were injected into the anti-CD34 antibody-immobilized column,

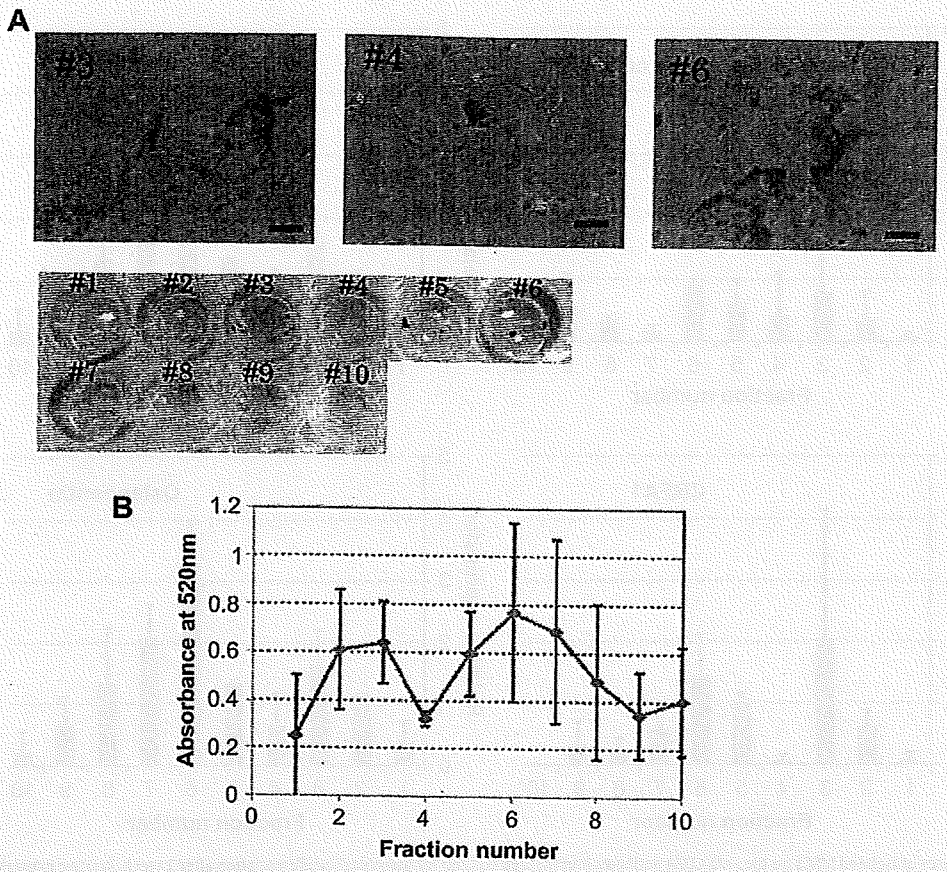

Fig. 5. (A) Photograph of alizarin red S staining MSCs after differentiation for 1 week. Cells were cultured on fibronectin-coated 24-well plate. (B) Quantification of alizarin red S staining in each fraction by absorbance spectrum. Absorption at 540 nm was plotted against the fraction number. Each data point represents results from 3 independent experiment and the data are presented as mean ± standard error of the means.

two peaks were observed (Fig. 2). That is, the delay of cell elution observed in the case of the anti-CD34 antibody-immobilized column probably resulted from the continuous interaction between the surface marker and the immobilized antibody. In our previous work, KG-1a (CD34+) and HL60 (CD34-) cells know as cell line were separated on antibody-immobilized column [21]. In the results, cells were separated by a marker specific manner, and the elution pattern was distinctly depended on the marker expression level. In the case of MSC separation, elution patterns were comparatively broad because of heterogeneity of crude MSCs. Then, surface marker expression of the isolated MSCs on the anti-CD34 antibody-immobilized column was evaluated by FACS. Two-dimensional FACS analysis of CD34 expression against Sca-1 expression is shown in Fig. 3. MSCs with a high expression of CD34 and Sca-1 were presented in later fractions, and a continuous change in the marker expression level was observed with increasing fraction number. These data indicated that the crude MSCs were separated on the column on the basis of the surface marker density. From the above results, we suggest that the antibody-immobilized column could be used to isolate murine MSCs on the basis of their surface marker density.

3.3. Differentiation of isolated MSCs on the anti-CD34 antibody-immobilized column

Osteoblastic differentiation was evaluated by gene expression analysis and alizarin red S staining. Type 1 collagen, osteonectin, CBFA1, and osteopontin were selected as specific markers for osteoblastic differentiation. The gene expression level was analyzed in separated MSCs obtained from the column. Type 1 collagen and osteonectin are constantly expressed during osteoblastic differentiation [33–35], while CBFA1 is expressed during the process of maturation. CBFA1 is a transcriptional factor, and the osteopontin expression was promoted by the CBFA1. Fig. 4 shows the expression levels of specific marker genes analyzed by real-time PCR. Type 1 collagen was expressed in almost all fractions, and the expression level was the same as that of crude MSCs. In the case of CBFA1, the expression level in fractions 3, 5, and 6 was higher than that in other fractions. This tendency was the same as that observed for the expression pattern of osteopontin.

CBFA1 is a key factor for mature osteoblastic differentiation. The suppression of CBFA1 expression by mutation of CBFA1 completely restricted bone formation of murine neonatal or newborn [33]. That is, the expression of CBFA1 is necessary for calcium deposition on the cells. The isolated MSCs after differentiation were stained with alizarin red S solution. Fig. 5 shows the picture of stained cells. Isolated MSCs in early fractions (fractions #2- and #3) or later fraction (fractions #5–7) were strongly positive. This staining pattern in terms of the fraction number was similar to that of CBFA1 expression pattern.

These results suggest that separated MSCs in early fraction or later fraction had a high potential for osteoblastic differentiation. It has been reported that osteoblastic progenitor cells were enriched in the CD34-positive population from bone marrow [36]. That is, the cells with high expression of CD34 in later fractions are mainly osteoblastic progenitor cells. It is difficult to determine the origin of these progenitor cells. However, there are two possibilities with

regard to their origin. First, the osteoblastic progenitor cells in bone marrow were contaminated in TCPS-adherent cells. Second, a fraction of MSCs differentiated into progenitor cells during cultivation. Stem cells are difficult to be cultured on a TCPS dish keeping with differentiation properties. Because the environment of MSCs on a culture dish is largely different from that *in vivo*, cultured MSCs have heterogeneous characteristics in terms of surface marker [17] and differentiation property. The purification process of stem cells is important for experimental or clinical use. From these results, we suggested that the ligand-immobilized column could be used to isolate MSCs from the heterogeneous cell populations consisting of progenitor or differentiated cells.

3.4. Differentiation of sorted MSCs by FACS

To verify the effect of surface marker density on the differentiation ability of MSCs, crude MSCs were sorted by FACS as a conventional method for cell separation. Four cell populations were sorted for the evaluation of osteoblastic differentiation (Fig. 6). The CD34 expression level in each population was different, and MSCs with a high density of CD34 were contained in $CD34^{High}FSC^{Low}$ population. In contrast, the low density of CD34 was collected in $CD34^{Low}FSC^{High}$ population. The surface marker density of the cells in $CD34^{High}FSC^{High}$ or $CD34^{low}FSC^{Low}$ population was almost the same. Fig. 6(B) shows the relative expression of specific marker genes for osteoblastic differentiation. In case of MSCs sorted by FACS, cell population with high and low marker density of CD34 has shown high expression of differentiation markers. This tendency was the same as that observed for separated MSCs on the antibody-immobilized column. This result supported that the two cell populations with high ability for osteoblastic differentiation were present in crude MSCs, and the populations were separated using a CD34 antibody-immobilized column.

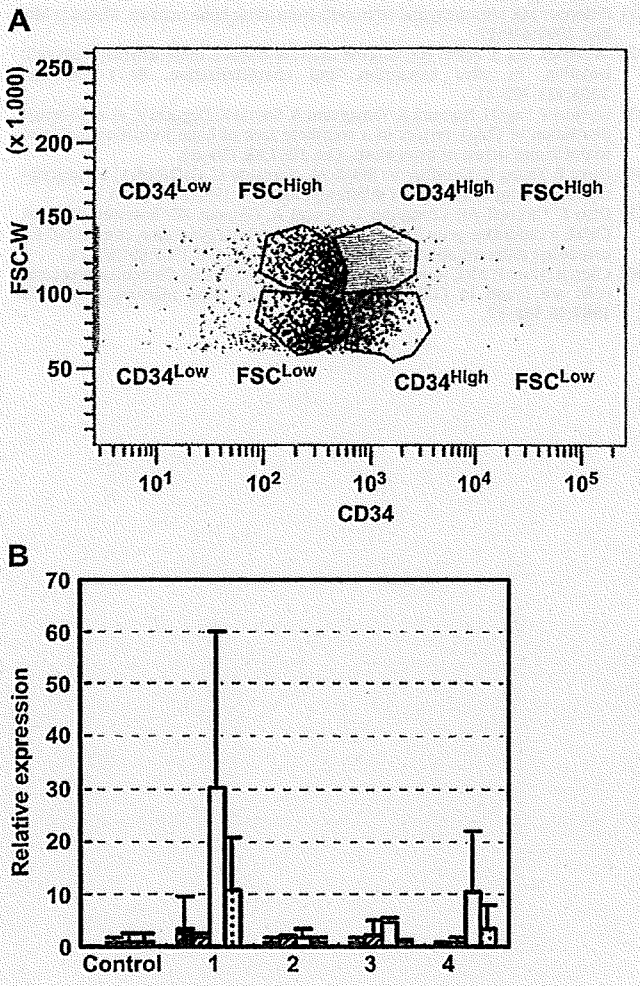

Fig. 6. (A) Sorting regions of isolated cell populations with distinct expression density. Crude MSC populations were divided into four cell populations. Cells with highest CD34 expression density were in the $CD34^{High}FSC^{Low}$ population. On the other hand, cells with lowest expression density were in the $CD34^{Low}FSC^{Hihg}$ population. (B) Gene expression analysis of sorted MSCs by FACS. Sorted MSCs were cultured in the osteoblastic differentiation medium for 8 days. Specific surface markers (bar with lines: type 1 collagen, bar with dots; osteonectin, closed bar; CBFA1, open bar; osteopontin) were analyzed by real-time PCR. Relative expression was normalized by GAPDH. Each data point represents results from 3 independent experiment and the data are presented as mean ± standard error of the means.

4. Conclusion

An anti-CD34 antibody-immobilized column was developed for separating MSCs based on their surface marker density. We selected the anti-CD34 antibody as the immobilized ligand, and crude MSCs were separated on this column. Two cell populations with a high ability for osteoblastic differentiation were purified on this column. MSCs express some surface markers, and their combinations have been explored in many groups in order to specify homogeneous MSCs population. In our approach, marker density is considered as the essential factor for the characterizing MSCs. Two different cell populations could be separated on this column based on their surface marker density. To characterize the cells with a high differentiation ability, it might be effective to use some kinds of ligand-immobilized columns. Further studies on the design of ligand-immobilized surface and construction of the column system are required for effective separation of MSCs.

Acknowledgment

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Appendix

Figures with essential colour discrimination. Most of the figures (Figs. 1, 3, 5 and 6) in this article have parts that may be difficult to interpret in black and white. The full colour images can be found in the on-line version, at doi:10.1016/j.biomaterials.2010.01.126.

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Peripheral Nerve Regeneration and Electrophysiological Recovery with CIP-Treated Allogeneic Acellular Nerves

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Abstract

Acellular nerve grafts are a desirable alternative to autografts, both because the source of acellular nerves is potentially unlimited and because they have the same matrix structure as natural nerves, which would facilitate axon growth from the defective nerve stump. Although some acellular nerves have been developed, most of them were studied in isogenic transplantation models and evaluated only by histological observation. In the present study, novel allogeneic acellular nerves prepared using the cold isostatic pressing (CIP) method were developed and assessed as a potential substitute for autografts. The host immune response to acellular nerves and fresh nerves was analyzed using Lewis rats as donors and SD rats as recipients, which is the allogeneic transplantation model, by subcutaneous implantation for one month. In addition, sciatic nerve transplantation into a 10-mm nerve gap was carried out using the same model, and the axonal growth in acellular nerve transplantation was evaluated histologically and electrophysiologically, and compared with that of axons in the autograft transplant area. The subcutaneously implanted acellular nerves contained more macrophages and less vasculature than the allogeneic fresh nerves. In spite of these results of the subcutaneous implantation, Schwann cell infiltration in the graft transplanted into the sciatic nerve gap was observed after the short-term transplantation. The myogenic potential, which was measured as an index of electrophysiological function in acellular nerve transplantation, was also recovered in the long-term transplantation. Our results indicate that the acellular nerves developed herein have the potential to support nerve regeneration and might be useful as an alternative to autografts.

Keywords

Acellular nerve, allogeneic, electrophysiological study, cold isostatic pressing treatment

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