さらに先へ
—リウマチの苦痛を除くために—

名古屋大学医学部附属病院
整形外科 リウマチ科

リウマチ治療はおもしろい！

名古屋大学整形外科には，リウマチ，股関節，脊椎・脊髄，腫瘍，小児，膝肩の専門診療グループがあり，石黒教授以下教員8名，医員15名，大学院生21名が所属している．

リウマチ診療スタッフは，石黒直樹（教授），小嶋俊久（講師），金山康秀（医員），塩浦朋根（医員），林 真利（医員），舟橋康治（医員）の6名で，薬物療法と手術療法とをあわせて，積極的にリウマチ治療をおこなっている．診療実績は，登録リウマチ患者約1,000名，生物学的製剤使用患者はこの1年でも20%から30%ほどへ増加し，リウマチ患者さんに対する手術件数は数年前の週1～2件から現在週2～3件と増加し，年間約100件となっている．また，全身合併症，積極的薬物療法に伴う有害事象に対応するための呼吸器内科，腎臓内科，消化器内科，血液内科などと良好な連携，集学的な診療環境がある．そして若い人から，リウマチ治療をより深く学びたいという声が多く届くようになった．

さらに先へ進むために

1）多施設大規模臨床研究

名古屋大学整形外科には，約75あまりの関連病院があり，リウマチ専門外来をもつ病院も15ほどある．このチームワークを生かし，"Tsurumai Biologics Communication（TBC）"と名づけた生物学的製剤使用患者データベース構築を開始し，現在1,059名の登録を得た．登録数を増やしていくとともに，参加施設からの疑問，アイデアを検討し，整形外科の視点をもった臨床研究をおこなっていきたいと考えている．またリウマチの肺病変，消化器病変については，呼吸器内科，消化器内科との共同臨床研究も進めている．

2）新しい治療に向けての基礎的研究

関節リウマチ，変形性関節症における細胞外マトリックスの分解，再生のメカニズムの探究が大きなテーマであり，グループに所属する5名の大学院生を中心におこなっている．今後も分子標的治療薬はつぎつぎと開発され，それぞれの薬剤を理解し，治療を有効かつ効率的に進めるためには，基礎的研究により得られる知識は不可欠と思われる．

3）地域基幹病院としての社会的活動

名古屋リウマチネットワーク」という名古屋地区の開業医の先生方との病診連携，患者さんへの情報提供を目的としたグループもつくり，市民公開講座，療養相談，症例検討など情報交換をおこなっている．

めざすべきもの

変わっていく治療環境を積極的に先取りし，これからリウマチで困る患者さんをなくすため，いま困っている患者さんの苦痛を取り除くために，薬物療法，手術療法ともに最高水準の治療をすべて提供できるよう，研究，診療をおこなっていきたいと思っている．

（小嶋俊久）

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Morphological differences during *in vitro* chondrogenesis of bone marrow-, synovium-MSCs, and chondrocytes

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Mesenchymal stem cells (MSCs) from a variety of mesenchymal tissue contain common features, but distinguishing properties dependent on their origin are emerging. We investigated morphological differences of human bone marrow-MSCs, synovium-MSCs, and chondrocytes during *in vitro* chondrogenesis. Two hundred thousands cells were pelleted after centrifugation and cultured in chondrogenic media that contained BMP-2, TGF-β3, and dexamethasone. The pellets were analyzed histologically, immunohistologically, and electron microscopically. Before chondrogenic induction, trypsinized MSCs and chondrocytes looked similar. At day 1, the structure of the three masses was divided into two layers, and the most obvious differences in the three populations were observed in the deep zone. In bone marrow-MSCs, round cells accumulated without intercellular space, and the cells were mainly connected through intermediate junctions. In synovium-MSCs, elongated cells accumulated with small desmosomes and intercellular spaces could occasionally be seen. In chondrocytes, separated oval and polygonal cells connected only in a narrow spotty area through a small desmosome. At day 7, the structure of the three masses was divided into three layers, and the most obvious differences in the three populations were observed in the middle zone. In bone marrow-MSCs, the middle zone consisted of dense smaller cells and apoptotic cells. In synovium-MSCs, the middle zone consisted of dense arrayed wider cells and apoptotic cells. In chondrocytes, the middle zone was acellular without apoptotic cells. At day 21, the morphology of cells and extracellular space became similar in that each cell was located separately with abundant extracellular matrix. The superficial zone was still obvious in bone marrow-MSCs, but hardly seen both in synovium-MSCs and chondrocytes. In this study, we revealed morphological differences of bone marrow-MSCs, synovium-MSCs, and chondrocytes during *in vitro* chondrogenesis. The most obvious differences in the three populations were observed at day 1 in the deep zone.
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KEYWORDS: mesenchymal stem cells; chondrogenesis; bone marrow; synovium; chondrocytes

Toward the development of cell therapy for cartilage regeneration, mesenchymal stem cells (MSCs) are attractive because of their chondrogenic potential.[1–4] MSCs can be obtained from a variety of mesenchymal tissues including bone marrow,[5] which seems to be the most popular MSC source at present. Synovium, a thin membrane covering the inside of joints, is another promising MSC source due to its high chondrogenic potential.[6–8] MSCs derived from various mesenchymal tissues contain common features, but distinguishing properties due to their origin are emerging.[9–12] However, morphological differences of MSCs dependent on the source, especially during chondrogenesis, remain unknown.

Chondrocyte transplantation is currently one of the prevailing methods for cartilage regeneration therapy.[13] The digested and expanded chondrocytes produce cartilage

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matrix again when cultured in a proper condition. This process seems to contain some similarities to that in MSCs, and it would be intriguing to compare the morphology of MSCs and chondrocytes during their chondrogenesis.

Ectopic cartilage formations such as chondrophyte, free body, and metaplasia are one of the pathological conditions in articular joints.[14] Cell sources and the pathophysiology of ectopic cartilage formations are poorly understood. We speculate that cell sources for the ectopic cartilage formations are stem cells in bone marrow and synovium, in addition to chondrocytes.

In this study, we compared the morphology of bone marrow-, synovium-MSCs, and chondrocytes during *in vitro* chondrogenesis. Our results shed light on some aspects of both the mesenchymal stem biology and pathophysiology of ectopic cartilage formations.

MATERIALS AND METHODS

Isolation of Bone Marrow-, Synovium-MSCs, and Chondrocytes

The study was approved by an institutional review board, and informed consent was obtained from all study subjects. Human bone marrow, synovium, and cartilage were harvested from three patients during total knee arthroplasty with medial compartment osteoarthritis. The patients were all females, 68, 70, and 73 years old. Bone marrow was aspirated from the tibia with an 18-gauge needle during the operation. Synovial tissue was harvested from the suprapatellar pouch. Cartilage was obtained from resected lateral femoral condyle. Nucleated cells from bone marrow were isolated with Ficoll density gradient (Ficoll-Paque, Pharmacia Biosystems, Uppsala, Sweden). Synovium and cartilage were minced into small pieces, digested in a collagenase solution, and filtered. Nucleated cells from synovium and cartilage were plated at 10^3, 10^4, or 10^5 cells/60-cm^2 dish (Nalge Nunc International, Rochester, NY, USA), and those from bone marrow at 10^4, 10^5, or 10^6 cells/60-cm^2 dish. The cells were plated in six dishes and cultured in 10 ml complete culture medium: αMEM containing 10% fetal bovine serum (Invitrogen, Carlsbad, CA, USA), 100 units/ml penicillin (Invitrogen), 100 mg/ml streptomycin (Invitrogen), and 250 ng/ml amphotericin B (Invitrogen) for 14 days as passage 0. Three dishes for each cell concentration were stained with 0.5% crystal violet. The optimal initial cell density was determined based on the following criteria: (1) the colony size was not affected by contact inhibition, and (2) the greatest number of colonies was obtained. We then harvested the cells plated at optimal densities from the three remaining dishes. Passage 0 cells were replated at 50 cells/cm^2 in a 145-cm^2 dish and cultured for 14 days for the analyses.[11]

Surface Epitopes

One million cells were suspended in 200 ml PBS containing 20 mg/ml of antibody, incubated for 30 min at 48°C, and resuspended in 1 ml of PBS. Fluorescein isothiocyanate (FITC)- or phycoerythrin (PE)-coupled antibodies against CD90 and CD45 were from Becton Dickinson; CD44 was from eBioscience (San Diego, CA, USA); and CD105 was from Ancell Corporation (Bayport, MN, USA). For the isotype control, FITC- or PE-coupled nonspecific mouse IgG (Becton Dickinson) was substituted for the primary antibody. Cell fluorescence was evaluated by FACSCalibur instrument (Becton Dickinson), and data were analyzed using CellQuest software (Becton Dickinson).[11,15]

Chondrogenesis

Two hundred thousands cells at passage 2 were placed in a 15-ml polypropylene tube (Becton Dickinson) and centrifuged at 450 *g* for 10 min. The pellets were cultured at 37°C with 5% CO_2 in 400 μl chondrogenic media that contained 500 ng/ml bone morphogenetic protein 2 (Astellas Pharm, Tokyo, Japan), 10 ng/ml transforming growth factor-β3 (R&D Systems, Minneapolis, MN, USA), 100 nM dexamethasone, 50 μg/ml ascorbate-2-phosphate, 40 μg/ml proline, 100 μg/ml pyruvate (Sigma-Aldrich), and 50 mg/ml ITS + Premix in high-glucose Dulbecco modified Eagle medium (Invitrogen). The medium was replaced every 3–4 days for 21 days.[15–18]

Histology

The cultures were ended by fixing the pellets with 2.5% glutaraldehyde in 0.1 M PBS for 2 h. The cells were washed overnight at 4°C in the same buffer and post-fixed with 1% OsO4 buffered with 0.1 M PBS for 2 h. The pellets were dehydrated in a graded series of ethanol and embedded in Epon 812. Semi-thin (1 μm) sections for light microscopy were collected on glass slides and stained for 30 s with toluidine blue.[19]

Transmission Electron Microscopy

Ultrathin (90 nm) sections were collected on copper grids, double-stained with uranyl acetate and lead citrate, and then examined by transmission electron microscopy (H-7100, Hitachi, Hitachinaka, Japan).[19]

Immunohistochemistry

The micromasses were fixed in 4% paraformaldehyde, dehydrated, and embedded in paraffin. Sections were cut at a thickness of 5 μm and deparaffinized in xylene, dehydrated through graded alcohol, and pretreated with 0.4 mg/ml proteinase K (DAKO, Carpinteria, CA, USA) in Tris-HCl for 15 min for optimal antigen retrieval. Residual enzymatic activity was removed by washing in PBS, and nonspecific staining was blocked with PBS containing 10% normal horse serum for 20 min. Mouse monoclonal antibodies against human type I and type II collagen (Daiichi Fine Chemical, Toyama, Japan; 1:100 dilution with PBS containing 1% BSA) were applied for 1 h. After extensive washing with PBS, a secondary antibody of biotinylated horse anti-mouse (1:200;

Vector Laboratories, MA, USA) was applied for 30 min. Immunostaining was detected by Vectastain ABC reagent (Vector Laboratories, Burlingame, CA, USA), followed by diaminobenzidine staining.[19]

TUNEL and Ki67 Staining

Immediately after fixation in 4% paraformaldehyde in 0.1 M PBS for 1 h, the micromasses were immersed in 1.8 M sucrose containing 20% polyvinylpyrrolidone in 0.1 M PBS for 24 h at 4°C, mounted on a holder, and quickly frozen in liquid nitrogen. Frozen sections were cut on an ultracut S microtome (Reichert, Wien, Austria) equipped with a low-temperature sectioning system (Reichert) at a thickness of 1 μm at −80°C.

For TUNEL staining, an apoptosis *in situ* detection kit (Wako Pure Chemical Industries, Ltd, Osaka, Japan) was used. The frozen semi-thin sections were incubated with terminal deoxynucleotidyl transferase for 10 min at 37°C in a moist chamber. The sections were washed with 0.1 M PBS for 15 min. Peroxidase-conjugated antibody was then applied to the specimens at 37°C for 10 min in a moist chamber. The sections were developed with 3,3-diaminobenizidine, and counterstained with methyl green.

For Ki67 staining, the frozen semi-thin sections were blocked with 1% BSA in 0.1 M PBS for 1 h at 4°C. Mouse monoclonal anti-Ki67 antibody (Zymed, South San Francisco, CA, USA; 1:100 dilution with PBS containing 1% BSA) was then incubated with the sections for 24 h at 4°C. After extensive washing with 0.1 M PBS, the sections were incubated for 10 min with biotinylated secondary antibodies. Immunostaining was detected with a Zymed Histostain kit (Zymed). Counterstaining was performed with methyl green.

Immunocryo-ultramicrotomy

The frozen ultrathin (90 nm) sections were collected on formvar-coated nickel grids and then placed on droplets of 1% BSA in 0.1 M PBS. The sections were subsequently transferred to droplets of mouse antibody against collagen type I, II, X (Cosmo Bio, Japan), and chondroitin sulfate proteoglycan (Seikagaku Kogyo, Japan) for 12 h at 4°C. The dilution of antibody against collagen type I, II, X, and chondroitin sulfate proteoglycan was 1:20, 1:20, 1:20, and 1:50 with 1% BSA in 0.1 M PBS, respectively. Each section was then washed with 0.1 M PBS and incubated with goat anti-rabbit IgG or goat anti-mouse IgG + IgM conjugated with 10 nmΦ gold colloidal particles (diluted 1:20, 1:20, 1:20, and 1:50 with 1% BSA in 0.1 M PBS, respectively; British Bio Cell International, UK) for 12 h at 4°C. The sections were stained with 1% uranyl acetate, washed with distilled water, and then embedded with a mixture of 3% polyvinylalchol and 0.3% uranyl acetate. The sections were examined by transmission electron microscopy (H-7100, Hitachi).[19]

RESULTS

Characterization of Bone Marrow-, Synovium-MSCs, and Chondrocytes

We first analyzed the colony-forming capacity. When nucleated cells were plated at the same density, the number of developed colonies was highest in synovium-MSCs, was second highest in chondrocytes, and was the least highest in bone marrow-MSCs (Figure 1). To prepare colony-forming cells unaffected by colony-to-colony contact inhibition, we harvested bone marrow-MSCs plated at 10^6/dish, synovium-MSCs plated at 10^4/dish, and chondrocytes plated at 10^5/dish for further analyses.

Flow cytometric analysis showed that each population of cells was negative for CD45 and positive for CD44, CD90, and CD105 (Figure 2). Bone marrow- and synovium-MSCs were calcified when cultured in medium containing β-glycerophosphate[20] and differentiated into adipocytes when cultured in medium containing isobutylmethylxanthine (data not shown).[21]

In Vitro Chondrogenesis

MSCs were pelleted into micromasses and then cultured in chondrogenic medium. Immediately after centrifugation, they appeared to be fragile and flat at the bottom of the tube (data not shown). One day later, they became substantial masses (Figure 3a). At day 7 and thereafter, they became round or elongated spheres, and their size and weight increased along with the culture period in the three populations (Figure 3b).

Morphology of Cells Before Chondrogenic Induction

Microscopically, the cells were dissociated and round in the three populations (Figure 4a). Transmission electron microscopy demonstrated a large number of elongated thin processes at the cell surface. The cells contained well-developed cell organelles, including mitochondria, endoplasmic reticulum, Golgi apparatus, lysosomes, and large quantities of free ribosomes. Their nuclei were euchromatic and notched (Figure 4b). The bone marrow-, synovium-MSCs, and chondrocytes looked similar before chondrogenic induction.

Aggregation

One day later, the cells aggregated into a firm pellet. Histological sections embedded in Epon showed that the structure of the three masses was divided into two layers: the superficial zone and the deep zone (Figure 5a). The superficial zone consisted of spindle cells parallel to the surface. In the deep zone, obvious morphological differences were observed in the three populations. In bone marrow-MSCs, pale-stained round cells accumulated without intercellular space. In the synovium-MSCs, the deep zone consisted of elongated cells, and intercellular spaces could occasionally be seen. In chondrocytes, oval and polygonal cells with abundant intercellular spaces comprised the deep zone. At this stage, type I

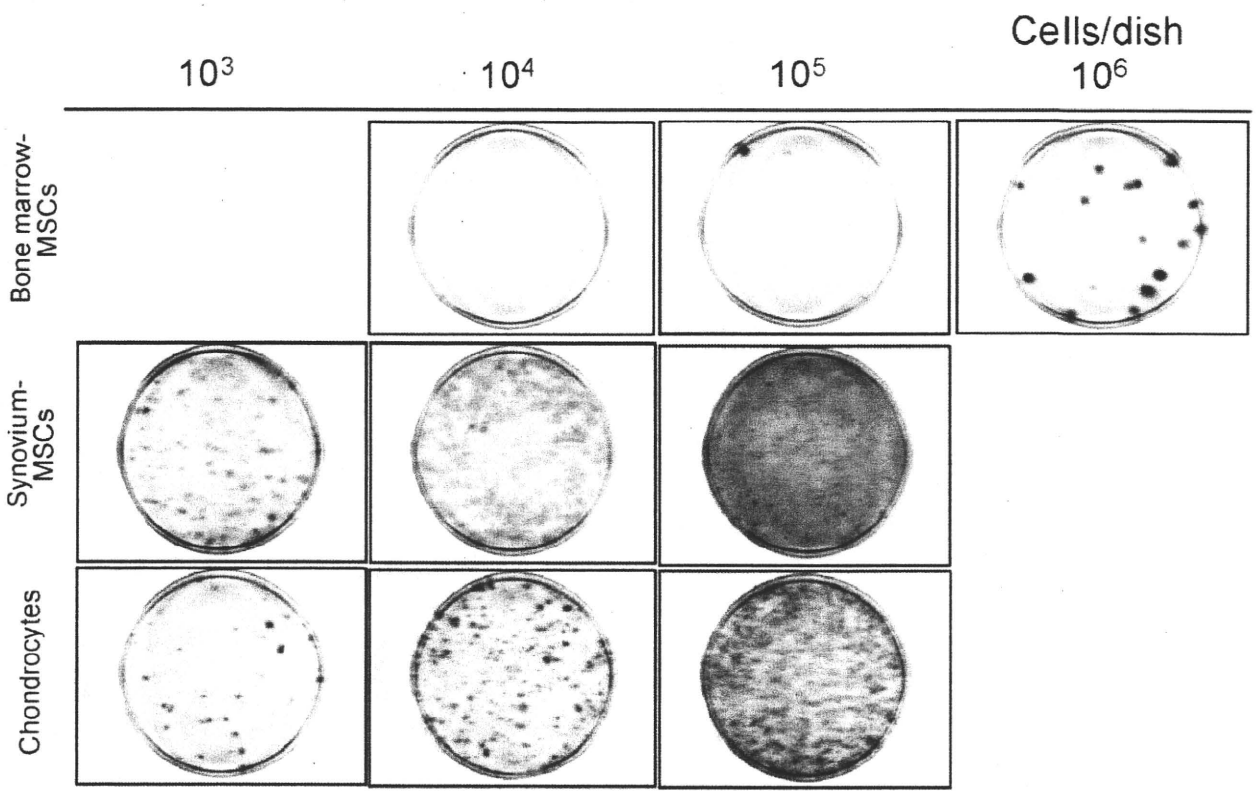

Figure 1 Colony formation of bone marrow-, synovium-MSCs, and chondrocytes. Nucleated cells were plated at indicated cell number per 60-cm^2 dish and cultured for 14 days. Culture dishes were stained with crystal violet.

collagen was detected in the intercellular spaces, whereas type II collagen was absent in the three populations (Figure 5b).

Morphological differences in the deep zone were analyzed by transmission electron microscopy (Figure 5c). In bone marrow-MSCs, round clear cells were attached to each other in a wide area. Cell–cell junctions mainly consisted of intermediate junctions (arrow heads), and desmosome (arrow) also existed. Extracellular matrix could not be seen. In synovium-MSCs, a small desmosome (arrow) was observed between oval cells. The contact area between each cell was smaller than that in bone marrow-MSCs. Collagen fibers (asterisk) existed in extracellular space. In chondrocytes, spindled cells appeared to be separated from each other or connected only in a narrow spotty area through a small desmosome (arrow). Extracellular space was larger than that in others. Collagen fibers (asterisk) could be seen.

Early Phase of Differentiation

At day 7, the structure of the three masses appeared to be divided into three layers: the superficial zone, the middle zone, and the deep zone (Figure 6a). The superficial zone consisted of spindle-shaped cells organized along the surface of the pellet. The deep zone was composed of unorganized polygonal cells with intercellular space, which was narrow in synovium-MSCs, large in chondrocytes, and intermediate in bone marrow-MSCs. The middle zone could be distinguished between the superficial and the deep zone. In bone marrow-MSCs, the middle zone consisted of smaller cells, and cell density was higher than in other zones. In synovium-MSCs, the middle zone appeared to be more obscure, but it consisted of more arrayed wider cells than superficial cells. In chondrocytes, the middle zone appeared to be almost acellular. Immunostaining demonstrated that bone marrow- and synovium-MSCs expressed type I collagen in the periphery. The three populations of MSCs expressed type II collagen diffusely (Figure 6b). TUNEL positive cells (Figure 6c) and apoptotic cell death (Figure 6d) were observed sporadically in the middle zone of bone marrow- and synovium-MSCs, but could hardly be seen in chondrocytes. Ki67 expressions were also examined for proliferation but not observed in bone marrow- and synovium-MSCs (Figure 6e), and chondrocytes (data not shown).

Late Phase of Differentiation

At day 21, the intercellular spaces and their metachromasia became more prominent in the deep zone (Figure 7a). The superficial zone was still obvious in bone marrow-MSCs, but hardly seen both in synovium-MSCs and chondrocytes. The three populations increased both type I and type II collagen expression (Figure 7b). Mature chondrocyte-like cells were

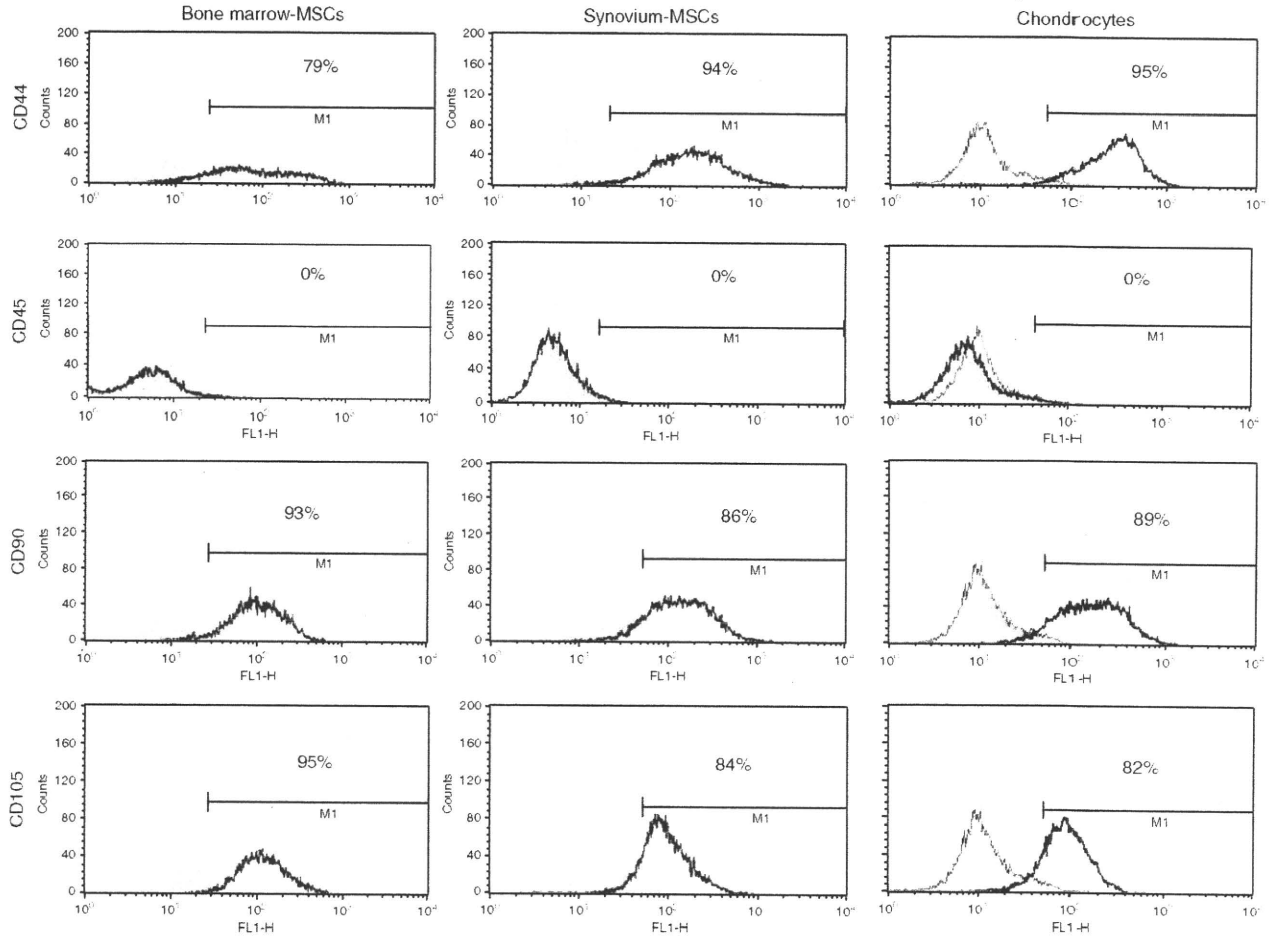

Figure 2 Surface epitopes of bone marrow-, synovium-MSCs, and chondrocytes. Representative histograms are shown as an open plot, and isotype controls are shown as gray.

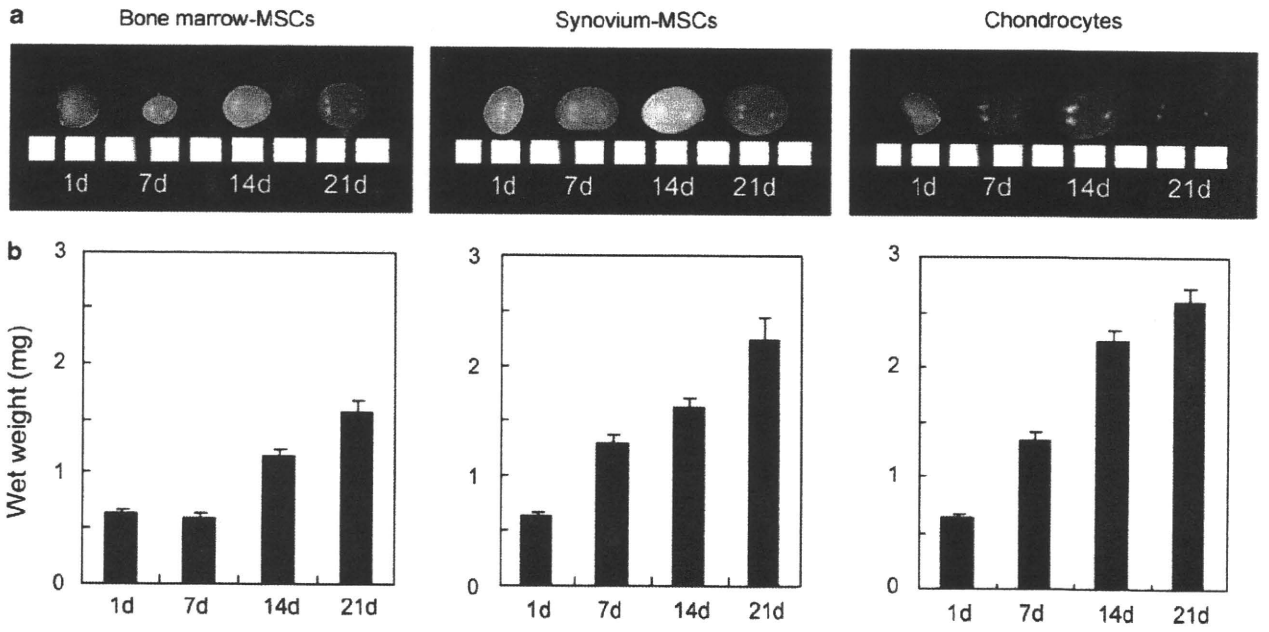

Figure 3 Time course of *in vitro* chondrogenesis of bone marrow-, synovium-MSCs, and chondrocytes. (**a**) Macro pictures of pellets with a 1-mm scale. (**b**) Wet weight of pellets. The data are expressed as mean ± s.d. ($n = 3$).

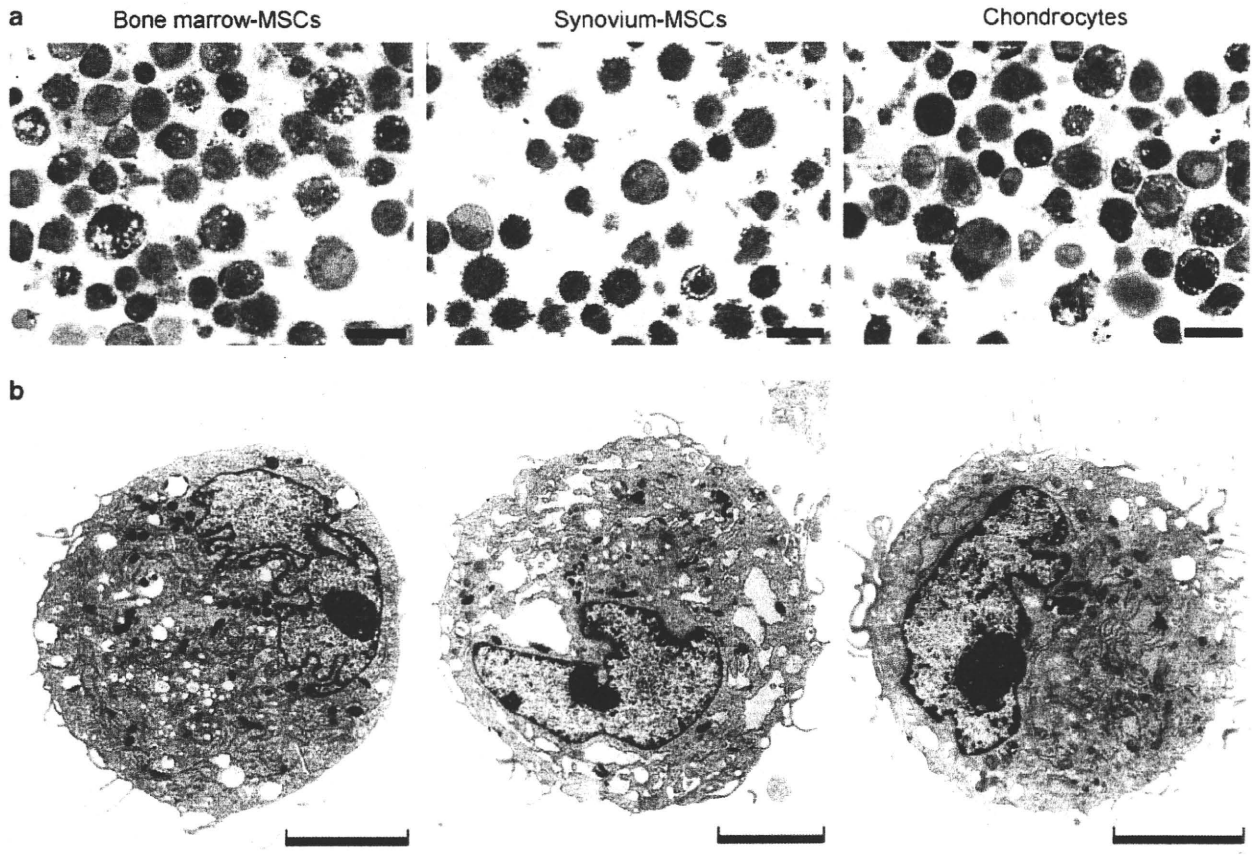

Figure 4 Morphology of bone marrow-, synovium-MSCs, and chondrocytes before induction of chondrogenesis. (**a**) Optical micrographs of the cells stained with toluidine blue. Scale bar = 20 μm. (**b**) TEM images. Scale bar = 5 μm.

observed by transmission electron microscopy images in the deep zone in the three populations. The cells with irregular contours were surrounded by well-developed matrix fibers (Figure 7c). Neither TUNEL positive nor Ki67 positive cells were observed. Immunoelectron microscopy at day 21 demonstrated only slight expression of type I collagen, and higher expression of type II, X collagen, and chondroitin sulfate in the deep zone in the three populations (Figure 8).

DISCUSSION

In this study, we compared the morphology of bone marrow-MSCs, synovium-MSCs, and chondrocytes during their *in vitro* chondrogenesis (Table 1; Figure 9). Before induction for chondrogenesis, trypsinized cells looked similar among the three populations.

At day 1 (aggregation phase), the structure of the three masses was divided into two layers, and the most obvious differences in the three populations were observed at the deep zone. In bone marrow-MSCs, round cells accumulated without intercellular space, and the cells were mainly connected through intermediate junctions. In synovium-MSCs, elongated cells accumulated with small desmosomes, and intercellular spaces could occasionally be seen. In chondrocytes, separated oval and polygonal cells were connected only in a narrow spotty area through a small desmosome.

At day 7 (early phase of differentiation), the structure of the three masses was divided into three layers, and the most obvious differences in the three populations were observed at the middle zone. In bone marrow-MSCs, the middle zone consisted of dense smaller cells and apoptotic cells. In synovium-MSCs, the middle zone consisted of dense arrayed wider cells and apoptotic cells. In chondrocytes, the middle zone was acellular without apoptotic cells.

At day 21 (late phase of differentiation), the morphology of cells and extracellular space became similar in that each cell was located separately with abundant extracellular matrix. The superficial zone was still obvious in bone marrow-MSCs, but hardly seen both in synovium-MSCs and chondrocytes.

At the early phase, apoptotic cells were observed in the middle zone. The gradient of oxygen, cytokines, or other nutrients presumably affects the fate of the cells,[19] and the middle zone might be an inappropriate environment for the cells located there. If this is the case, why were there no apoptotic cells of chondrocytes in the middle zone? One

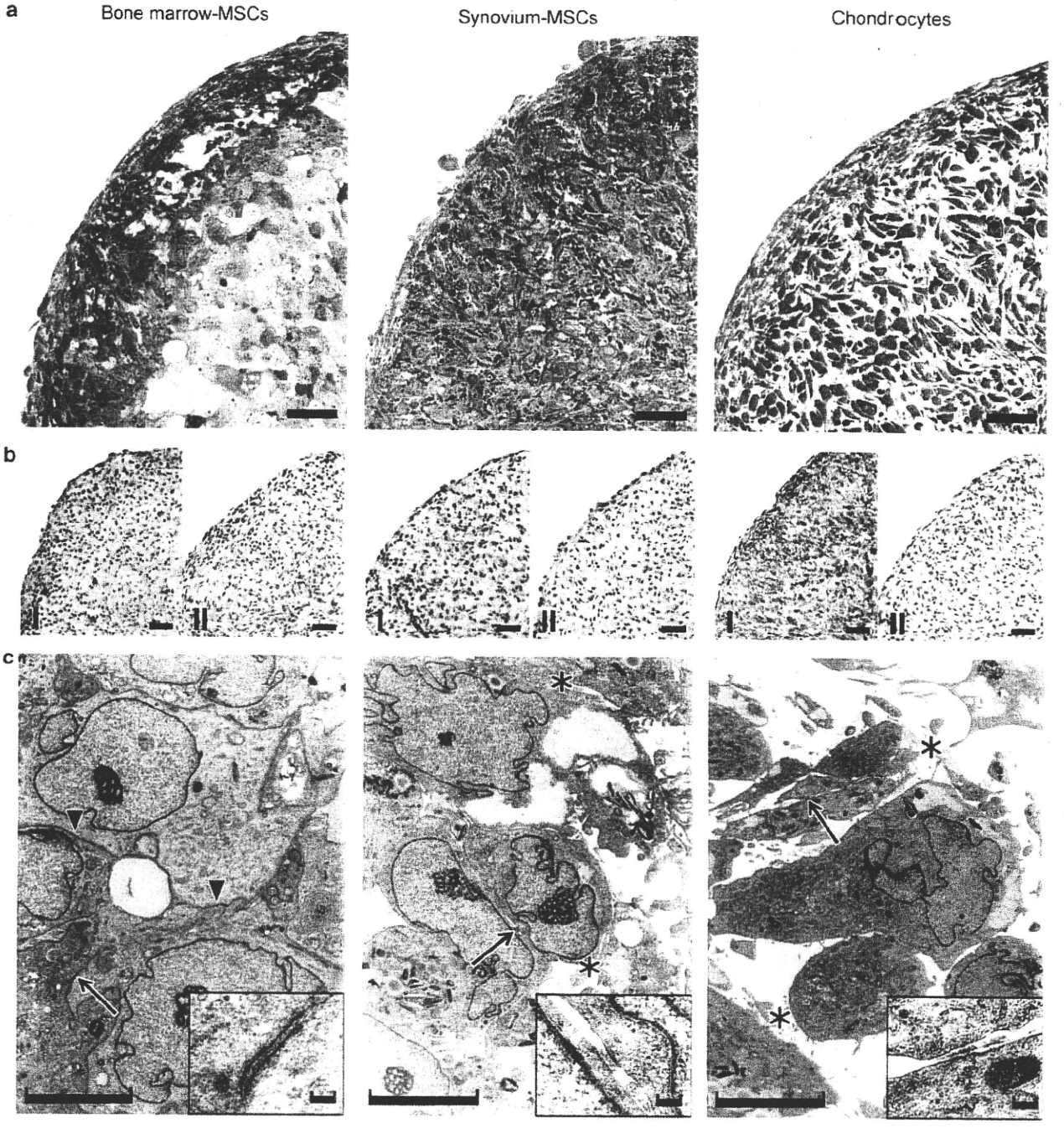

Figure 5 Morphology of pellets 1 day after induction of *in vitro* chondrogenesis. (**a**) Optical micrographs of pellets stained with toluidine blue. Scale bar = 50 μm. (**b**) Immunohistochemical staining for type I and II collagen. Scale bar = 50 μm. (**c**) TEM images of pellets in the deep zone. Scale bar = 5 μm. In bone marrow-MSCs, intermediate junctions are shown as arrow heads, and desmosome as arrow. In synovium-MSCs and chondrocytes, small desmosomes are shown as arrow and type I collagen fibers as asterisks. Desmosome and small desmosomes are magnified. Scale bar = 100 nm.

possibility is that chondrocytes do not die due to apoptosis during *in vitro* chondrogenesis. Tallheden *et al*[22] reported that chondrocytes did not express apoptosis-related genes during *in vitro* chondrognesis.

In bone marrow- and synovium-MSCs, we observed TUNEL positive cells at day 7 and no TUNEL positive cells at day 21. In our earlier reports, DNA content decreased largely within the first week and only slightly between 2 and 3 weeks during *in vitro* chondrogenesis of MSCs derived from bone marrow[17] and synovium.[23] The results of TUNEL assay in this study and the results of DNA content assays in earlier reports indicate one possibility that viable cells decreased

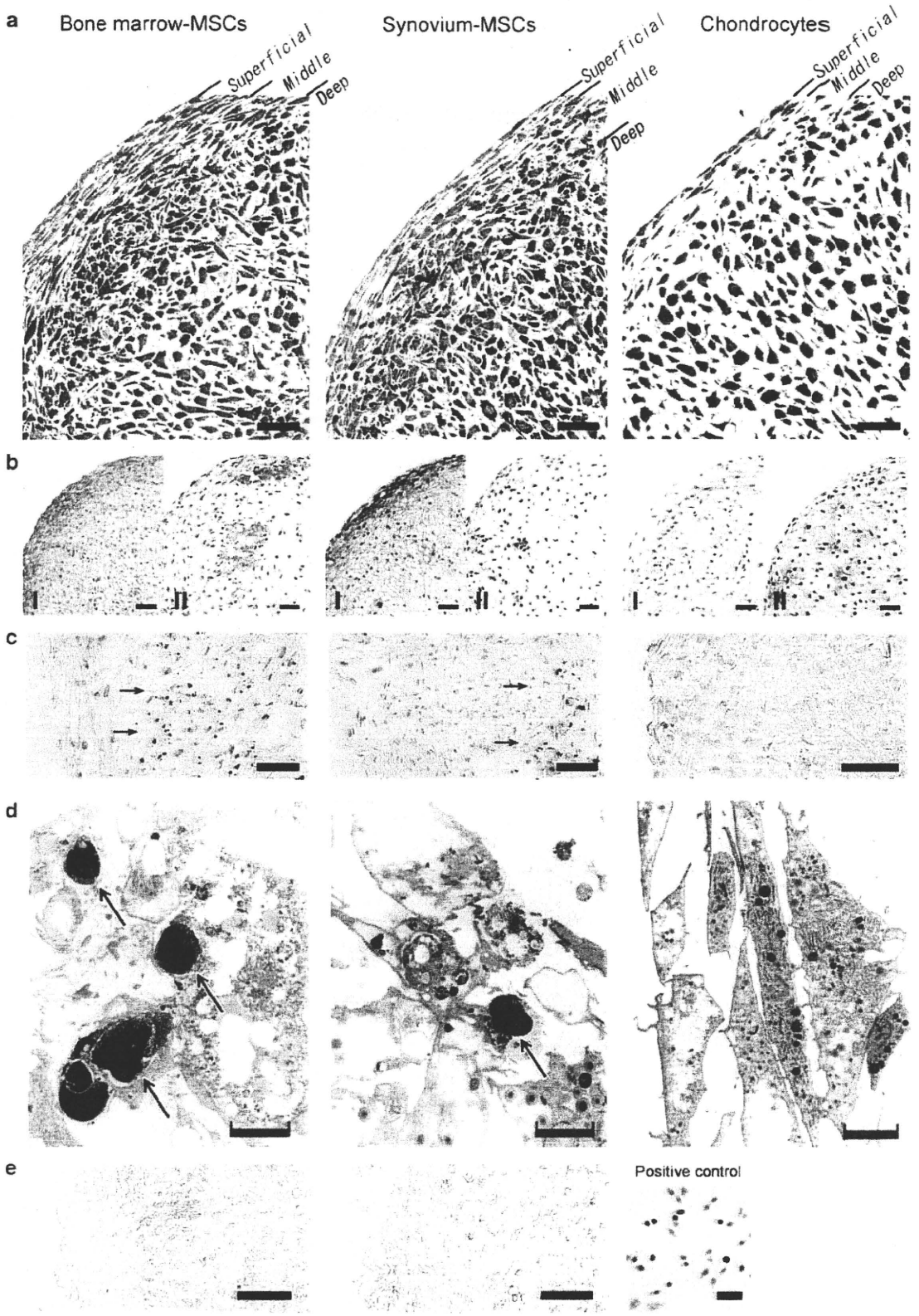

Figure 6 Morphology of pellets 7 days after induction of *in vitro* chondrogenesis. (**a**) Optical micrographs of pellets stained with toluidine blue. Scale bar = 50 μm. (**b**) Immunohistochemical staining for type I and II collagen. Scale bar = 50 μm. (**c**) TUNEL staining for apoptosis in the superficial and middle zone. TUNEL positive cells are shown as arrows. Scale bar = 50 μm. (**d**) TEM images in the middle zone. Apoptotic cells are shown as arrow. Scale bar = 5 μm. (**e**) Ki67 staining for proliferation in the superficial and middle zone. Hela cells are also shown as positive control. Scale bar = 50 μm.

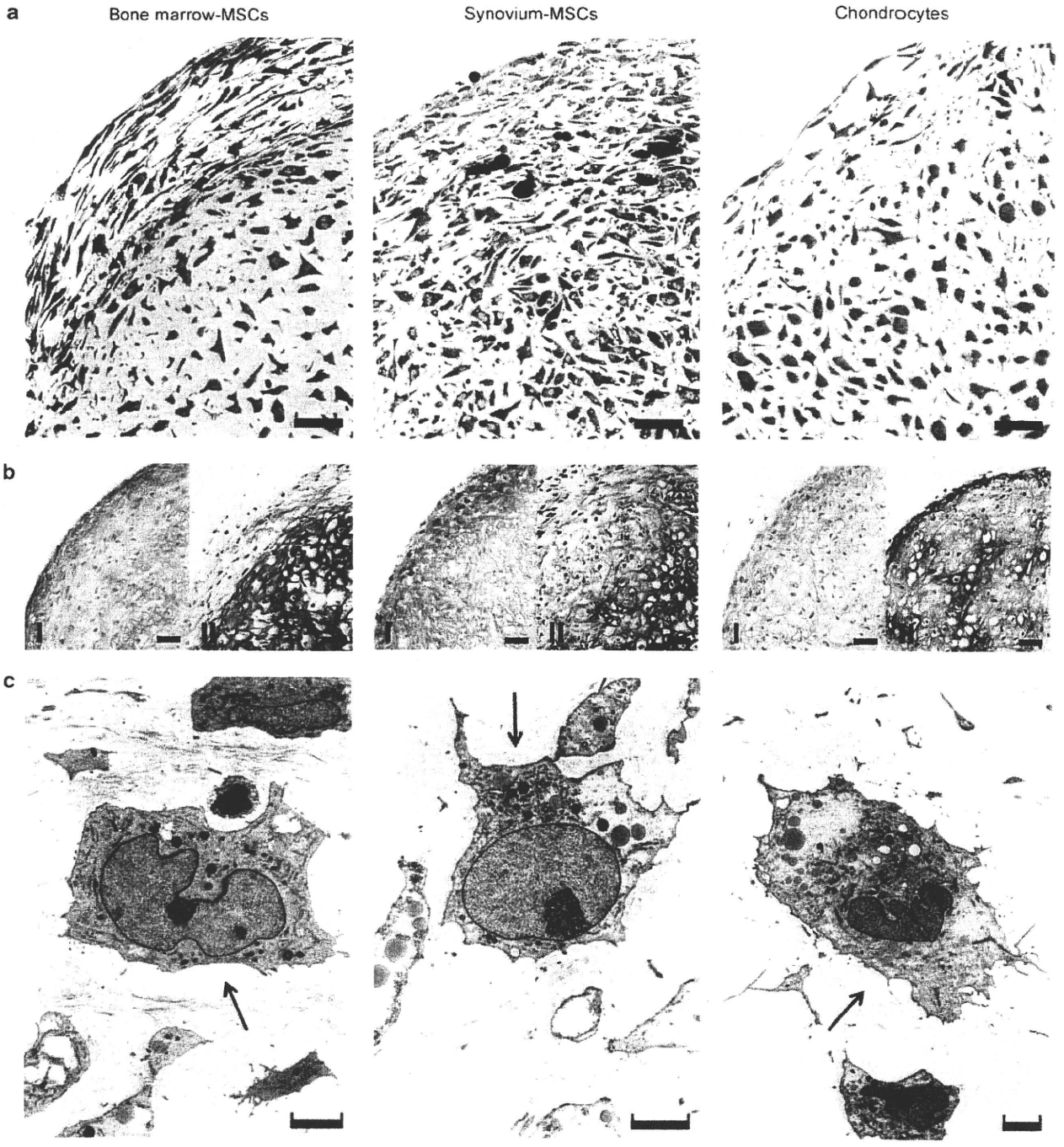

Figure 7 Morphology of pellets 21 days after induction of *in vitro* chondrogenesis. (**a**) Optical micrographs of pellets stained with toluidine blue. Scale bar = 50 μm. (**b**) Immunohistochemical staining for type I and II collagen. Scale bar = 50 μm. (**c**) TEM images in the deep zone. Mature chondrocyte-like cells are located at the center. Well-developed matrix fibers are shown as arrow. Scale bar = 5 μm.

largely within the first week and only slightly between 2 and 3 weeks because of apoptosis.

At the early phase of differentiation, pellets of bone marrow- and synovium-MSCs showed higher density of cells in the middle zone and demonstrated different features from that of chondrocytes. Was there any difference in cell proliferation between the cells? The answer is no. We examined Ki67 expressions for proliferation but did not observe any Ki67 expressions in the three populations. This indicates that different features between two populations of MSCs and chondrocytes in the middle zone were not due to cell proliferation. In our earlier report of bone

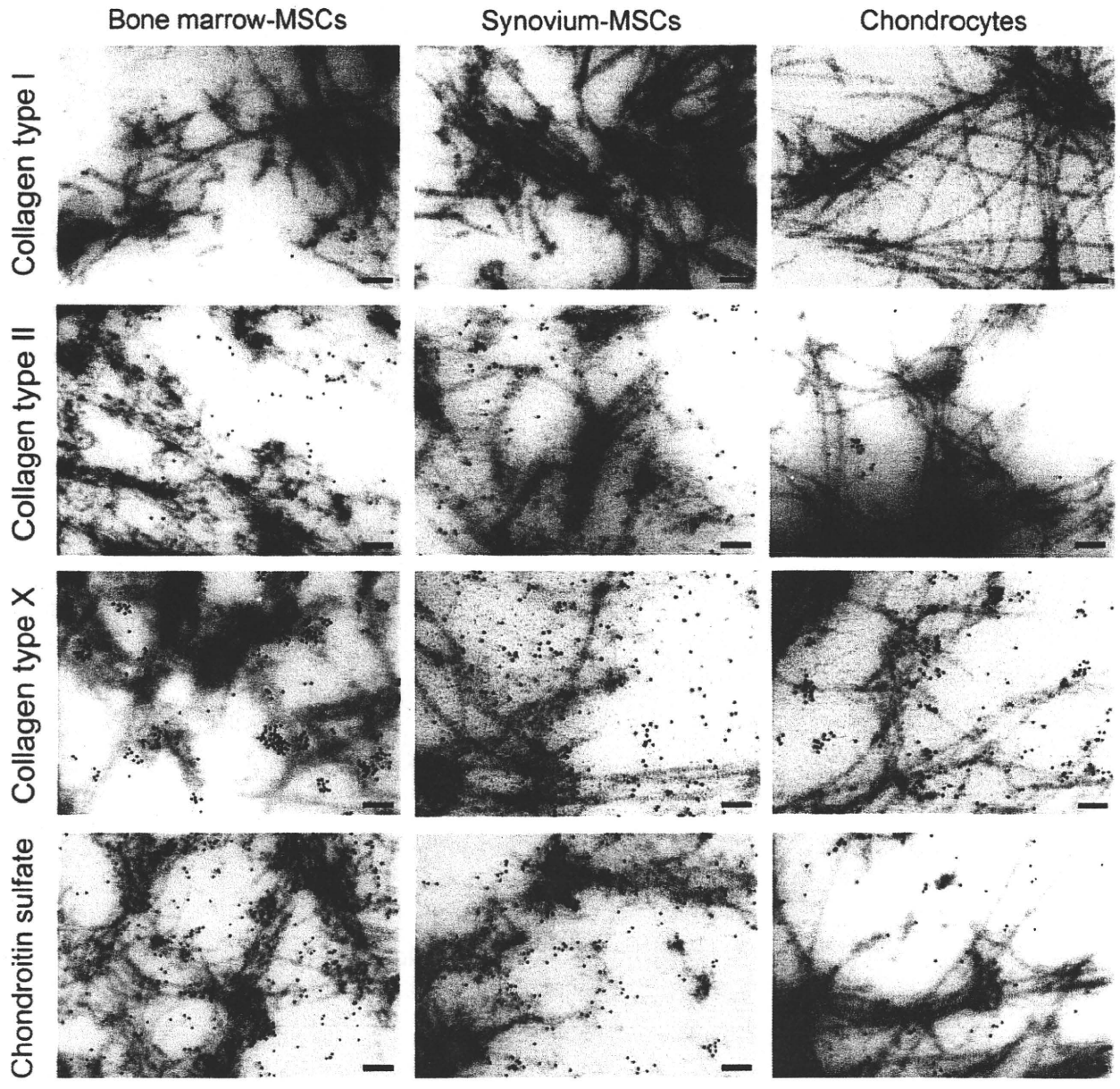

Figure 8 Immunoelectron microscopic images for pellets 21 days after induction of *in vitro* chondrogenesis. Expressions of collagen type I, II, X, and chondroitin sulfate proteoglycan in the deep zone by the gold particle deposition are shown. Scale bar = 100 nm.

marrow-MSCs, a pulse-labeled and chase experiment with [^{3}H] thymidine indicated that there was a 25% decrease in the specific activity of cellular DNA between day 0 and day 7, but thereafter the values remained constant,[17] demonstrating that bone marrow-MSCs did not divide at the early phase.

We performed all experiments in three donors with osteoarthritis, and similar results were obtained. To account for variances among donors and among procedures,[5] we harvested bone marrow, synovium, and cartilage simultaneously after total knee arthroplasty, performed the procedures, and analyzed the cells from bone marrow, synovium, and cartilage at the same time. It would be intriguing to examine whether similar results could be obtained in cells derived from young donors; however, it is not easy to harvest bone marrow, synovium, and especially cartilage from young donors simultaneously. The confirmation in young donors would be practically difficult.

Ectopic cartilage formation is one of the pathological conditions in articular joints.[14] Candidate cell sources for the ectopic cartilage formations are stem cells in bone marrow and synovium, in addition to chondrocytes. A comparison of the morphology of cartilage formation between *in vitro* chondrogenesis of these cells and the ectopic cartilage for-

Table 1 Critical differences of morphologies during *in vitro* chondrogenesis

Days	Zone	Bone marrow-MSCs	Synovium-MSCs	Chondrocytes
0		Round cells with a large number of processes at the cell surface		
1	Superficial zone	Spindle cells parallel to the surface		
	Deep zone	Round cells without intercellular space	Elongated cells with intermediate intercellular spaces	Oval and polygonal cells with intercellular spaces
		Intermediate junctions	Small desmosome	Small desmosome
7	Superficial zone	Spindle cells parallel to the surface		
	Middle zone	Higher cell density	Higher cell density	Lower cell density
		Apoptotic cells	Apoptotic cells	No apoptotic cells
	Deep zone	Intermediate intercellular space	Relatively narrow intercellular space	Large intercellular space
21	Superficial zone	Obvious	Unclear	Narrow
	Deep zone	Polygonal cells with pericellular matrix		

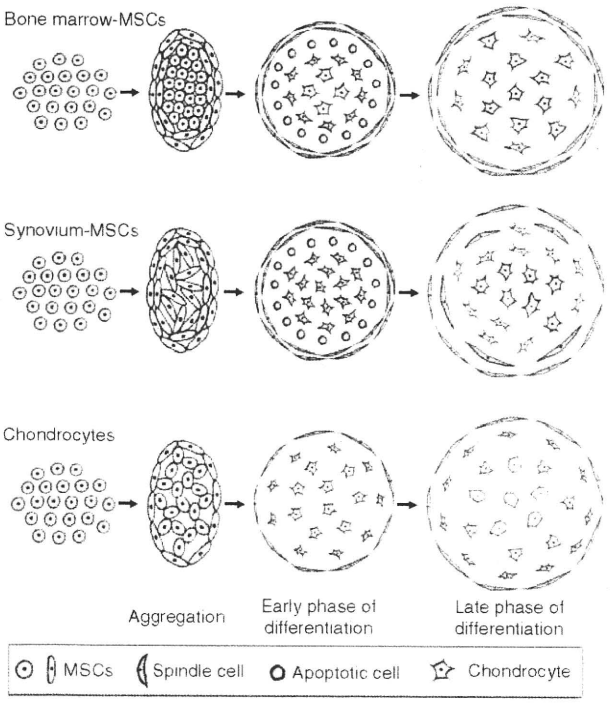

Figure 9 Scheme for morphological events during *in vitro* chondrogenesis of bone marrow-, synovium-MSCs, and chondrocytes. Explanations are summarized in Table 1.

mation could possibly clarify the cell source and the mechanisms of the ectopic cartilage formation.

The chondrogenic medium used in the study was previously demonstrated to be suitable for MSCs derived from bone marrow[16,18] and synovium.[23] This chondrogenic medium may not be optimal for chondrocytes. However, in this study, we demonstrated that colony-forming cells derived from cartilage produced cartilage matrix in the condition we used. If we had performed *in vitro* chondrogenesis of chondrocytes with a medium more suitable for chondrocytes, we could not have concluded that morphological differences are due to a different origin of the cells, because different culture medium may affect the morphology of the cells. Therefore, we used common chondrogenic medium for *in vitro* chondrogenesis of bone marrow-MSCs, synovium-MSCs, and chondrocytes.

There were some differences of histological patterns between toluidine blue and type II collagen staining, both of which were supposed to be correlated principally. We embedded histological samples in Epon for toluidine blue staining in order to enable detailed analysis, and in paraffin for immunohistology.[19] We did not use serial sections for toluidine blue and type II collagen staining, resulting in different patterns between in toluidine blue and type II collagen staining.

For treatment of cartilage defect, transplantation of MSCs is an effective strategy. Among a variety of MSC sources, bone marrow and synovium are useful for high chondrogenic potential of their MSCs. The two MSCs contain common features, but distinguishing properties dependent on their origin are emerging.[6–9,11,12] Colony-forming efficiency was higher in synovium-MSCs but colony size was larger in bone marrow-MSCs.[7] Expression of PDGF receptor-α was higher in synovium-MSCs based on flow cytometrical analysis.[12] In this study, we demonstrated morphological differences during *in vitro* chondrogenesis of bone marrow- and synovium-MSCs. Biologically, these differences are due to their different gene profiles. We previously compared gene profiles of bone

marrow- and synovium-MSCs. The expression levels of chitinase 3-like 1 (CHI3L1), aggrecan 1, WINT1-inducible signaling pathway protein 2 (WISP2), fibulin 1, and S100 calcium-binding protein were extremely low in bone marrow-MSCs and high in synovium-MSCs.[10]

Cytologically, differences of cell–cell junctions at the aggregation phase in the three populations were interesting. Wuchter *et al* recently reported novel type cell junctions. They demonstrated that bone marrow-MSCs under monolayer conditions were interconnected by special tentacle-like cytoplasmatic protrusions and invaginations.[24] Wagner and Ho[25] described that the frequency and morphology of these conjunction complexes were greatly affected by culture conditions. In our experiments, further detailed investigation would provide new insight into the nature of cell junctions in MSCs during the chondrogenesis.

Conclusions

In this study, we revealed morphological differences of bone marrow-MSCs, synovium-MSCs, and chondrocytes during *in vitro* chondrogenesis. The most obvious differences in the three populations were observed at the aggregation phase in the deep zone.

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DISCLOSURE/CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Osteoarthritis and Cartilage

Magnesium enhances adherence and cartilage formation of synovial mesenchymal stem cells through integrins

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SUMMARY

Objective: We previously reported that more than 60% of synovial mesenchymal stem cells (MSCs) placed on osteochondral defects adhered to the defect within 10 min and promoted cartilage regeneration. The efficiency of adherence is considered to depend on the interaction between cells and extracellular matrix (ECM), in which integrins may play some important roles. Divalent cations such as calcium, magnesium, and manganese may affect functions of integrins, and the integrins may be involved in differentiation of MSCs. Among divalent cations, magnesium is used in clinical practice as a therapeutic agent and increases the affinity of integrin to ECM. In this study, we investigated whether magnesium enhanced adherence and chondrogenesis of synovial MSC through integrins.

Methods: We performed assays for adherence of human synovial MSCs to collagen-coated slides, *in vitro* chondrogenesis, *ex vivo* assays for adherence of human synovial MSCs to osteochondral defect, and *in vivo* assays for adherence and cartilage formation of synovial MSCs in a rabbit osteochondral defect model.

Results: Magnesium increased adhesion of human synovial MSCs to collagen, and this effect was inhibited by neutralizing antibodies for integrin α3 and β1. Magnesium also promoted synthesis of cartilage matrix during *in vitro* chondrogenesis of synovial MSCs, which was diminished by neutralizing antibodies for integrin β1 but not for integrin α3. *Ex vivo* analyses demonstrated that magnesium enhanced adherence of human synovial MSCs to osteochondral defects. *In vivo* studies in rabbits showed that magnesium promoted adherence at 1 day and cartilage formation of synovial MSCs at 2 weeks.

Conclusion: Magnesium enhanced adherence of synovial MSCs through integrins, which promoted synthesis of cartilage matrix at an early phase.

Introduction

Mesenchymal stem cells (MSCs) are useful cell sources for regenerative medicine[1–3]. Synovium is a practical MSC source for cartilage regeneration because of its superior proliferation potential with autologous human serum and high chondrogenic ability[4–10]. Current cell therapy for cartilage regeneration requires invasive procedures, periosteal coverage, and the use of scaffold[11,12]. We recently reported that more than 60% of synovial MSCs suspended in phosphate buffered saline (PBS) placed on the osteochondral defect adhered to the defect in 10 min and promoted cartilage regeneration[13]. This method makes it possible to transplant synovial MSCs on the osteochondral defect arthroscopically; however, any improvement in its efficiency for cell adhesion remains in question.

Integrins are a family of cell surface molecules which mediate adhesive interaction with extracellular matrix (ECM), activate intracellular pathways, and play important roles in many biological processes including differentiation[14–16]. Some functions of integrins are dependent on interaction with divalent cations such as calcium, magnesium, and manganese through a metal ion dependent adhesion site (MIDAS) and MIDAS-like motives[17,18]. Among divalent cations, calcium and magnesium are widely used in clinical practices as therapeutic agents, and magnesium increases the affinity of integrins for ligands including ECM in a millimolar concentration[19], while calcium reverses the increased affinity in some cases[20].

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We hypothesized that the addition of magnesium to MSC suspension might enhance adherence of synovial MSCs to osteochondral defect, increase cartilage matrix synthesis of synovial MSCs, and finally accelerate cartilage regeneration. The purpose of this study was to investigate the effect of magnesium on adherence and cartilage formation of synovial stem cells through integrins. The results will clarify some novel functions of integrins and provide some clues for obtaining better clinical outcome for cartilage regeneration with synovial MSCs.

Materials and methods

Isolation and culture of MSCs

The study was approved by an institutional review board, and informed consents were obtained from all subjects. Human synovium harvested from three donors (27 and 34-year-old males and a 28-year-old female) during arthroscopic surgery was digested with 3 mg/ml Collagenase D (Roche Diagnostics, Mannheim, Germany) for 3 h. The nucleated cells were cultured at a clonal density in 150 cm^2 culture dishes (Nalge Nunc International, Rochester, NY) in 20 ml α-minimum essential medium (MEM) (Invitrogen, Carlsbad, CA) containing 10% fetal bovine serum (FBS) (Invitrogen) for 14 days, then replated at 50 cells/cm^2, cultured for 14 days, and cryopreserved. The frozen cells were slowly thawed, plated, and incubated for 4 days. The cells were replated at 50 cells/cm^2 again and cultured for 14 days for analyses.

Skeletally mature Japanese white rabbits weighing 3.0 kg on average were used. Animal care was in accordance with our institutional guidelines. Synovium harvested from the right knees under anesthesia was digested in a 3 mg/ml collagenase type V (Sigma Aldrich, St. Louis, MO) solution for 3 h. After filtering, the nucleated cells were cultured at 3×10^6 cells/cm^2 for 7 days, replated at 50 cells/cm^2, and cultured for 14 days for analyses.

Cell differentiation

One hundred human synovial MSCs were plated in 60-cm^2 dishes and cultured for 2 weeks. For adipogenesis, the medium was changed to adipogenic medium. The cells were cultured for an additional 3 weeks and stained with Oil red O solution. For osteogenesis, the medium was changed to osteogenic medium. The cells were cultured for an additional 4 weeks and stained with alizarin red solution[4,8]. For *in vitro* chondrogenic differentiation, 300,000 human synovial MSCs were pelleted and cultured for 7 and 21 days in chondrogenic medium containing 500 ng/ml bone morphogenetic protein (BMP)-7, (Stryker Biotech, Boston, MA), 10 ng/ml transforming growth factor (TGF)β3 (R&D Systems, Minneapolis, MN), and 100 nM dexamethasone (Sigma–Aldrich). The concentration of magnesium was adjusted by adding $MgCl_2$. For analyses of involvement of integrins, the cells were pre-incubated with or without 20 μg/ml neutralizing antibodies for integrin β1 (P5D2, R&D Systems) or α3 (P1B5, Santa Cruz Biotechnology, Santa Cruz, CA) for 1 h, then the cells were pelleted and cultured in chondrogenic medium containing 0.8 or 5 mM magnesium for 21 days. No antibodies were re-added during the culture.

Surface epitopes

One hundred thousand synovial MSCs suspended in 200 μl PBS containing 20 μg/ml of antibody were incubated for 20 min at 4°C and subsequently incubated with R-phycoerythrin-coupled anti mouse IgG (AbD Serotech, Oxford, UK) for 20 min. Antibodies used in neutralizing against integrin β1 (P5D2, R&D Systems), α3 (P1B5, Santa Cruz Biotechnology), α4 (HP2/1, AbD Serotech), α5 (JBC5, AbD Serotech) and isotype control (R&D Systems) were used to detect epitopes. FITC conjugated antibody for the integrin α2 (AK7, AbD Serotech), CD44 and CD106 (eBioscience, San Diego, CA); CD105 and CD166 (Ancell corporation, Bayport, MN), CD45, CD34, CD90 and isotype control (Becton Dickinson, Franklin Lakes, NJ) were used. In double-staining for integrin α2 and α3, phycoerythrin (PE)-conjugated antibody for integrin α3 (BioLegend, San Diego, CA) was used.

In vitro *cell adhesion assay*

One hundred thousand human synovial MSCs suspended in 10 μl PBS with 0, 0.1, 1, 5, and 10 mM magnesium were placed on 8-well culture slides with or without type I collagen coating (Becton-Dickinson) for 10 min. After washing slides with PBS, the number of cells in 4 high power fields (HPFs) was counted, and the mean was determined. For neutralizing against adhesion molecules, cells were pre-incubated in PBS 20 μg/ml antibody for integrin β1 (P5D2, R&D Systems), vascular adhesion molecule 1 (VCAM-1; BBIG-V1, R&D Systems), activated leukocyte-cell adhesion molecule (ALCAM; 105901, R&D Systems), integrin α2 (P1E6, Abcam, Cambridge, UK), α3 (P1B5, Santa Cruz Biotechnology), α4 (HP2/1, AbD Serotech), α5 (JBC5, AbD Serotech) and isotype control (R&D Systems) for 1 h.

Immunocytochemical analysis

Ten thousand human synovial MSCs adhering to collagen-coat slides under 10 mM magnesium were fixed with 99.5% acetone for 15 min. The slides were stained with the integrin α2 (P1E6, Abcam) or α3 (P1B5, Santa Cruz Biotechnology) (1:1000) for 1 h. After washing, the slides were stained with goat anti-mouse IgG labeled with Alexa fluor 488 (Invitrogen) for 1 h. The nuclei were stained with Hoechst 33342 (Invitrogen). The number of integrin-positive cells and nuclei was counted using 3 HPFs.

Assay for sulfated glycosaminoglycan (sGAG) content of pellets

After 21 days of culture, pellets were digested for 24 h at 60°C in papain buffer (200 μg/ml papain (Sigma–Aldrich) and dissolved in 50 mM phosphate buffer containing 1 M NaCl, 5 mM cysteine–HCl and 1 mM EDTA). The GAG concentration of supernatant was determined by the Blyscan-assay (Biocolor Ltd, Newtonabbay, Ireland) according to manufacturer's instructions.

Real-time polymerase chain reaction (PCR) analysis

Total RNA was extracted from the pellets cultured for 3 weeks using QIAzol (Qiagen, Hiden, Germany) and the RNeasy micro kit (Qiagen). cDNA was synthesized with oligo-dT primer from total RNA using the Transcriptor High Fidelity cDNA Synthesis kit (Roche Diagnostics) according to the manufacturer's protocol. Reverse transcription (RT) was performed by 30 min incubation at 55°C, followed by 5 min incubation at 85°C. Real-time PCR was performed in a LightCycler 480 instrument (Roche Diagnostics) using FastStart TaqMan Probe Master and TaqMan probes for COL2A1 (#75) and β-Actin (#64) (Roche Diagnostics). After an initial denaturation step (95°C for 10 min), amplification was performed for 40 cycles (95°C for 15 s, 60°C for 60 s).

DNA content of pellets

Undifferentiated MSCs and pellets at 21 days were digested with 3 mg/ml collagenase, and DNA was prepared with a QIAamp DNA mini kit (Qiagen). The DNA content was calculated from the absorbance at 260 nm.

Ex vivo *analyses of cells adhered to osteochondral defect*

Human osteochondral fragments at the lateral femoral condyle were harvested during total knee arthroplasty, and osteochondral defects at 2.5 mm in diameter were created. Then the defects were filled with 1.5×10^5 synovial MSCs labeled with DiI (Molecular Probes, Eugene, OR) in 8 μl PBS with 0, 1, and 10 mM magnesium. After 10 min, the fragments were turned over for 10 min. The DiI-positive cells in the dish were counted after trypsinization, and the number of the cells attached to the defects was calculated. The fluorescence images of the entire defect were photographed. The total fluorescence intensity of the remaining cells in the defect was determined by measuring the brightness in the defect using Image J software (National Institutes of Health, Bethesda, MD).

In vivo *analyses for adherence and cartilage formation*

Knees of rabbits were approached medially under anesthesia. Osteochondral defects (5 × 5 mm, 1.5 mm deep) were created in the trochlear groove. To transplant cells, the defect was filled with synovial MSCs suspension, and the knees were held stationary for 10 min with the defect facing upward. For adhesion analyses at 1 day, 2×10^6 allogenic DiI-labeled cells at passage 1 suspended in 30 μl PBS with 5 mM magnesium or in PBS in the contralateral knee were used. Total fluorescence intensity over the defect was evaluated by measuring the brightness of the entire defect using Image J software. The ratio of the fluorescence positive area over the defect was evaluated by measuring the square measure of the entire defect and the fluorescence positive area at 1 day. For analyses of cartilage regeneration at 14 and 28 days, 5×10^6 autologous synovial MSCs at passage 0, suspended in PBS with or without 5 mM magnesium were transplanted in the left knee 7 days after harvest of synovium from the right knee.

Histological analyses

The specimens were fixed with 4% paraformaldehyde solution, decalcified, and embedded in paraffin. Sections were stained with safranin-o/fast green. Image J was used for measurement of defects and safranin-o positive areas. Sections without staining were used for fluorescence.

For immunohistochemistry, sections were treated with 0.4 mg/ml proteinase K (DAKO, Carpinteria, CA) in Tris–HCl and normal horse serum after deparaffinization. Primary antibodies for type II collagen (Daiichi Fine Chemical, Toyama, Japan) and a secondary antibody of biotinylated horse anti-mouse IgG (Vector Laboratories, Burlingame, CA) were employed. Immunostaining was detected with VECTASTAIN ABC reagent (Vector Laboratories) followed by 3,3′-diaminobenzidine staining.

Transmission electron microscopy

Cartilage pellets and regenerated cartilage were fixed with 2.5% glutaraldehyde and post-fixed with 1% OsO_4. After dehydration, they were embedded in Epon 812. Ultrathin (90 nm) sections were collected on copper grids, double-stained with uranyl acetate and lead citrate, and then examined by transmission electron microscopy (H-7100, Hitachi, Hitachinaka, Japan)[18].

Immunoelectron microscopy

After fixation in 4% paraformaldehyde and 0.1% glutaraldehyde, pellets were immersed in 2.3 M sucrose for 24 h and frozen in liquid nitrogen. The frozen sections mounted on silane-coated glass were placed on droplets of 1% BSA on a Parafilm sheet and subsequently transferred to droplets of mouse antibody against collagen type I, type II (diluted to 1:20, Fuji Yakuhin, Japan) and chondroitin sulfate-proteoglycans (diluted to 1:50, Seikagaku Kogyo, Japan) for 48 h. They were then incubated with goat anti-mouse IgG + IgM conjugated with 10–15 nmΦ gold colloidal particles (diluted to 1:50 with 1% BSA in 0.1 M PBS, British Bio Cell International, UK) for 24 h. The sections were fixed in 2.5% glutaraldehyde, post-fixed in a 1% OsO_4 solution, and dehydrated in a graded series of ethanol. Then they were embedded in Epon 812, stained with uranyl acetate, and examined by TEM[21].

Statistical analyses

Mann–Whitney U tests were used. A value of $P < 0.05$ was considered significant.

Results

Magnesium increases adhesion of human synovial MSCs through integrin α3 and β1

Human synovial cells had a colony forming ability and multi-differentiation potentials [Fig. 1(A)]. Flow cytometric analyses demonstrated that human synovial cells expressed CD44, 90, 105, 166 highly, and CD34, 45, 106 at a low level [Fig. 1(B)]. These findings demonstrated that human synovial cells had characteristics similar to those of MSCs.

Magnesium increased the number of synovial MSCs attached to collagen-coated slides dose-dependently [Fig. 1(C)]. Time lapse analysis showed that 5 mM magnesium caused thinning of cell shape and spread the cells on collagen-coated slides within 5 min, while the cell was still thick and round even after 25 min without magnesium or collagen-coating [Fig. 1(D)]. Human MSCs also expressed integrin α5, β1 highly, integrin α2, α3 modestly, and integrin α4 at a low level [Fig. 1(B)]. The effect of magnesium on attachment of synovial MSCs was diminished by the neutralizing antibodies for integrin α3 and β1 [Fig. 1(E)]. Some studies have reported that α2 integrin was a collagen receptor[14,15], therefore, we attempted more detailed examinations of antibodies for integrin α2 and α3. Double staining flow cytometric assay showed that the double positive rate was only 17% [Fig. 1(F)]. Immunocytochemical analysis showed that the α2 positive cell rate was 38%, and the α3 positive cell rate was 73% among cells adhering to the collagen slide in the presence of 10 mM magnesium [Fig. 1(G)].

Magnesium enhances chondrogenesis of human synovial MSCs

In pellet culture for *in vitro* chondrogenesis, the weight of the pellets at 7 days was affected by magnesium concentration, and 5 mM magnesium had the greatest effect [Fig. 2(A)]. The weight of the pellets cultured in 5 mM magnesium for 21 days was also heavier than those cultured in 0.8 mM magnesium in three other donors [Fig. 2(B left)]. Pellets cultured in 5 mM magnesium produced more sGAG than pellets cultured in 0.8 mM magnesium [Fig. 2(B, right)].

Pretreatment with neutralizing antibody for integrin β1 resulted in a decrease of pellet weight, sGAG content and safranin-o staining in pellets cultured in 5 mM magnesium at 21 days [Fig. 2(C)]. Pellets cultured in 5 mM magnesium showed higher COL2A1 expression than pellets cultured in 0.8 mM magnesium [Fig. 2(D)]. The DNA content of pellets greatly decreased in 3 weeks, and no significant difference was observed between pellets cultured in 0.8 and 5 mM magnesium [Fig. 2(E)].

Transmission electron microscopy revealed polygonal cells with short processes, containing well-developed rough

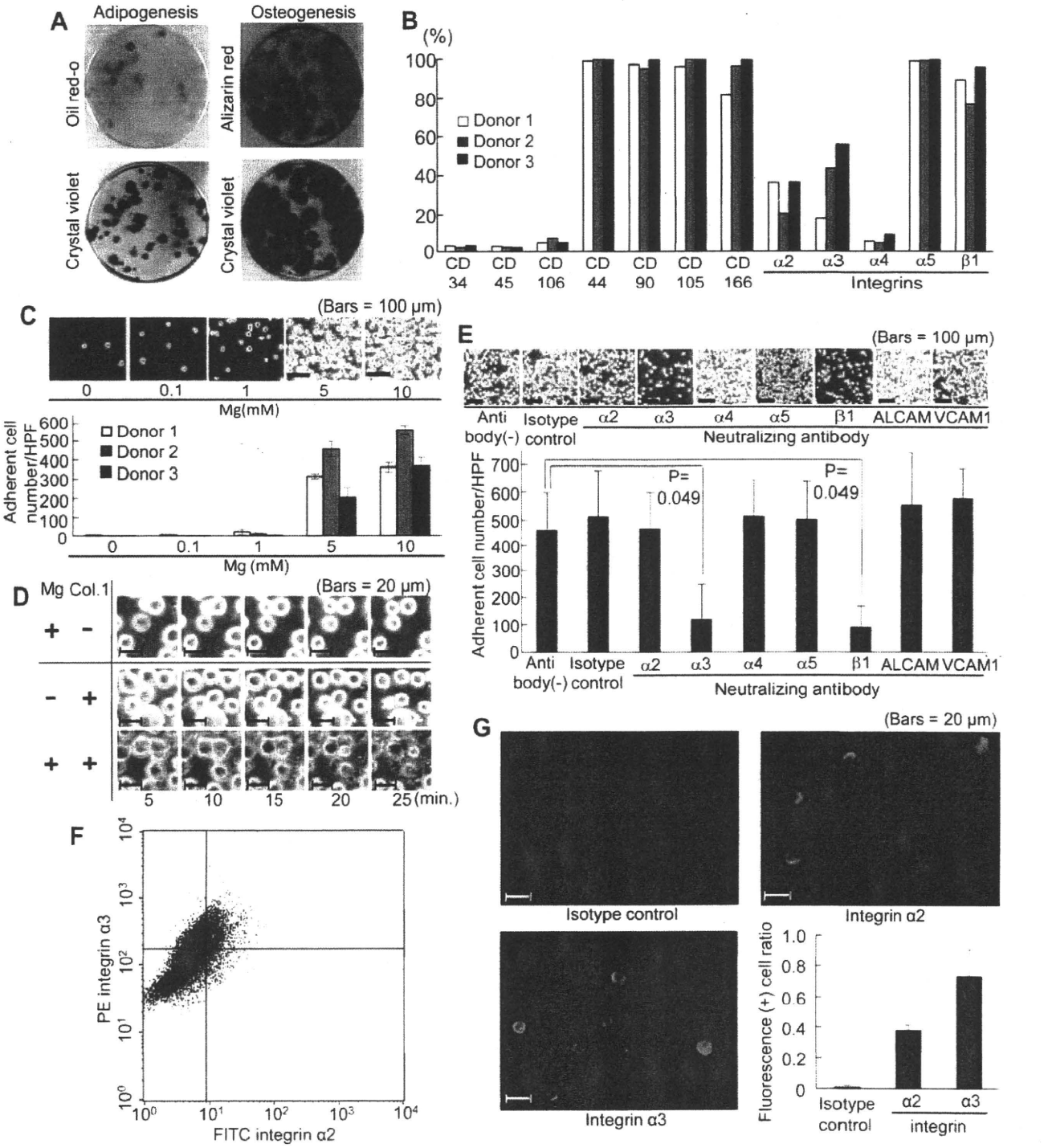

Fig. 1. Properties of human synovial MSCs and magnesium effects on adherence. (A) Macroscopic images of adipogenic and osteogenic differentiation of colony forming cells. (B) Surface epitopes. (C) Microscopic images and quantification of adherent cells on collagen-coated slides at indicated concentrations of magnesium. Values are means with 95% confidence interval (CI) ($n = 3$). (D) Time-lapse analyses of cell morphology during their adhesion on collagen coated slides with or without magnesium. (E) Microscopic images and quantification of adherent cells pretreated with neutralizing antibodies. Values are means with 95% CI ($n = 3$). (F) Two-dimensional plotting for integrin α2 and α3 (red), and for the isotype controls (blue). (G) Immunocytochemical analysis for integrin α2 and α3 of adhering cells on collagen-coated slides in the presence of 10 mM magnesium. The number of positive cells (green) and nuclei (blue) was counted using 3 HPFs, and the integrin positive ratio was calculated. Values are means with 95% CI ($n = 3$).

endoplasmic reticulum (rER), and surrounded by thin, faintly striated collagen fibrils in pellets cultured for 21 days even in 0.8 mM magnesium. Thick collagen bundles consisting of a large number of parallel collagen fibers characteristic for fibrocartilage[22,23] could not be seen [Fig. 2(F, upper panels)]. Immunoelectron microscopic analysis demonstrated expressions of type II collagen, chondroitin sulfate, and the absence of type I collagen in ECM [Fig. 2(F, lower panels)]. These results indicate that pellets of synovial MSCs differentiated into hyaline cartilage.

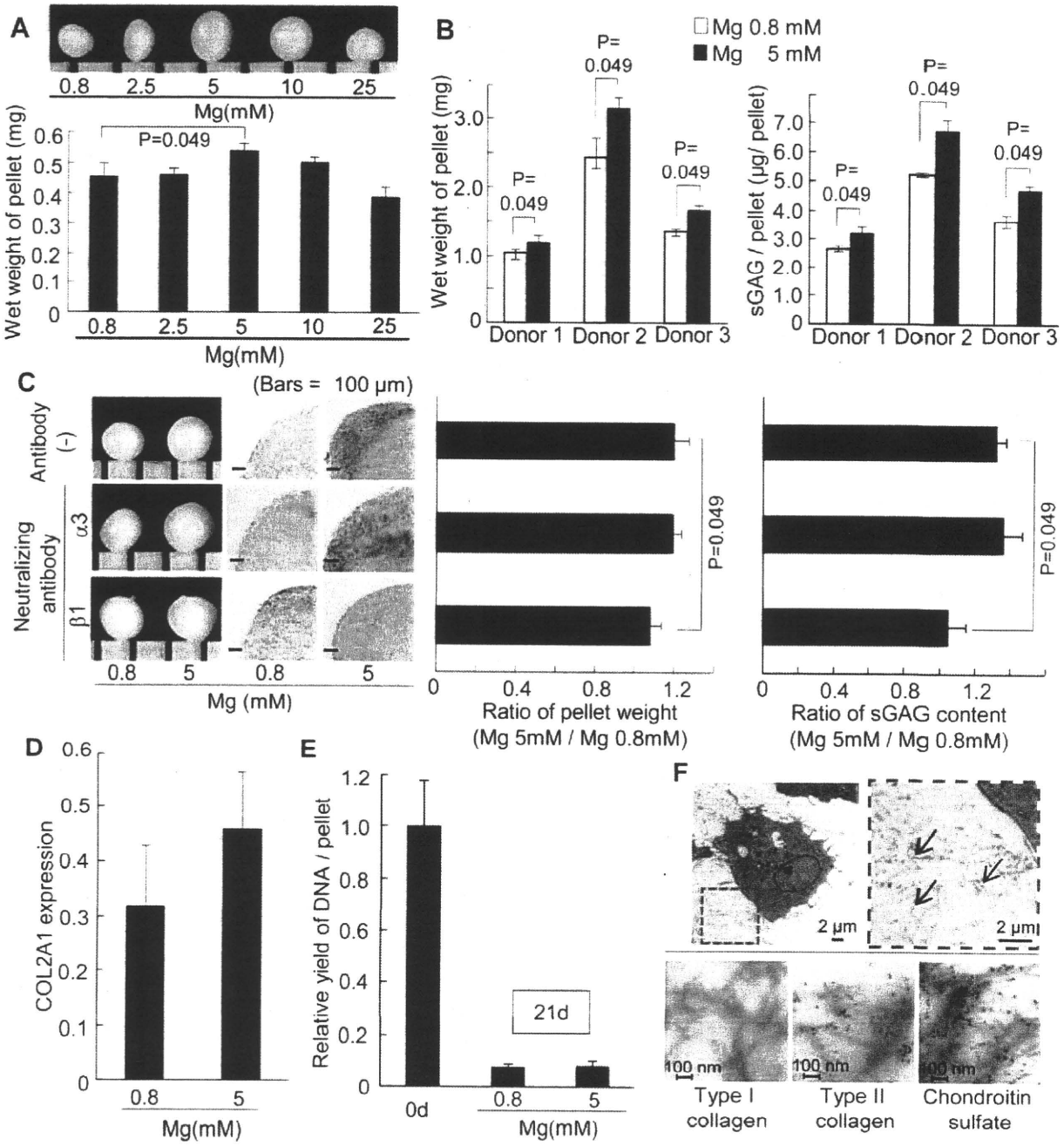

Fig. 2. Magnesium effects on *in vitro* chondrogenesis of human synovial MSCs. (A) Pellet cultured in chondrogenic medium at indicated concentration of magnesium. Macroscopic images at 1 week (upper, scale = 1 mm) and quantification of wet weight of pellets at 1 week (lower). Values are means with 95% CI for three pellets from one donor. (B) Wet weight (left) and sGAG content (right) of pellets cultured for 21 days in 0.8 and 5 mM magnesium. Values are means with 95% CI for three pellets from each donor. (C) Pellets of MSCs pretreated with antibodies. Pretreated pellets were cultured in chondrogenic medium at 0.8 and 5 mM magnesium for 21 days. Macroscopic images with 1 mm scale (left), histologies stained with safranin-o (middle), and relative weight and sGAG content of pellets cultured in 5 mM magnesium to those cultured in 0.8 mM magnesium (right). Values are means with 95% CI ($n = 3$). (D) Real time PCR analysis for gene expression of Col2A1 in pellets cultured for 21 days in 0.8 or 5 mM magnesium. β-Actin was used as an internal control. Values are means with 95% CI ($n = 3$). (E) DNA content of pellets at day 0 and day 21. Values are means with 95% CI ($n = 3$). (F) Transmission electron microscopic image (upper left), the magnified image (upper right) and immunoelectron microscopic images (lower) of pellets cultured for 21 days in chondrogenic medium containing 0.8 mM magnesium. The arrows indicate collagen fibrils (upper right).

Magnesium promotes adherence of human synovial MSCs on osteochondral defects in vitro

Macroscopic and fluorescence observations indicated that DiI labeled MSCs in the defect increased along with magnesium concentration. The intensity of DiI fluorescence of MSCs suspended in 10 mM magnesium was significantly higher than that in PBS without magnesium [Fig. 3(A)]. Histological analyses also indicated an increase of DiI-labeled cells in the defect along with magnesium concentration, and that the number of adherent MSCs in 10 mM magnesium was significantly higher than that in PBS without magnesium [Fig. 3(B)]. The fluorescence intensity of the defects significantly decreased with antibodies for integrin α3 or β1 [Fig. 3(C)].

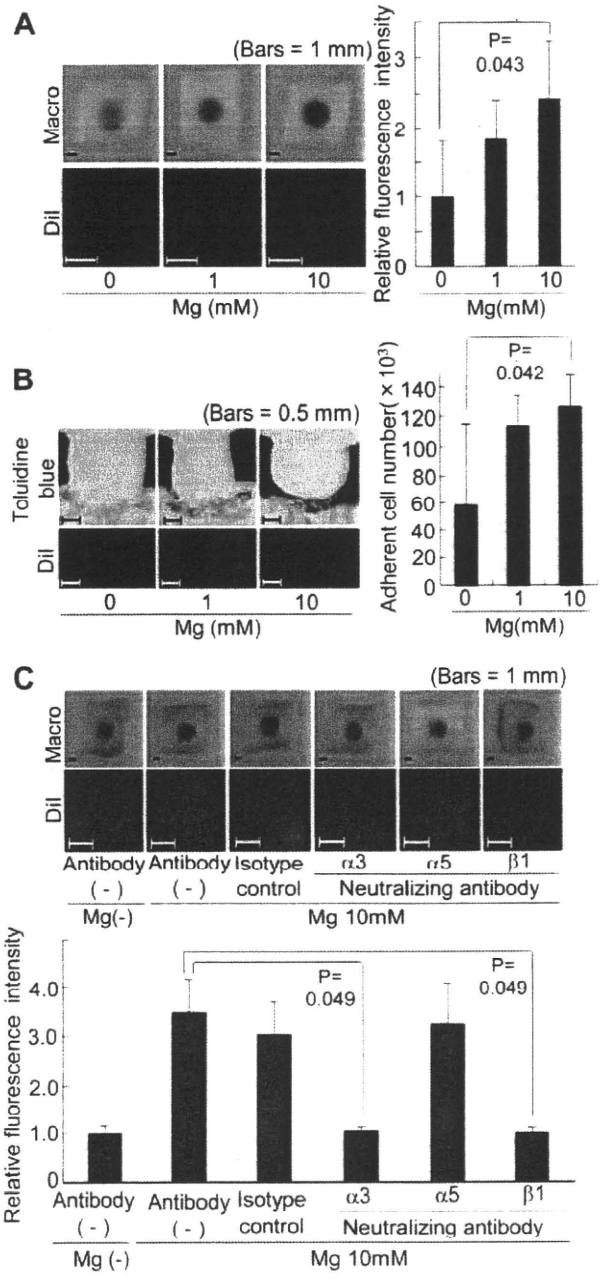

Fig. 3. *Ex vivo* studies for magnesium effects on adherence of human synovial MSCs on osteochondral defects. (A) Top side view of the osteochondral defects without fluorescence (left upper), with fluorescence (left lower), and quantification of the relative fluorescence intensity of DiI labeled MSCs in the defects (right). Values are means with 95% CI. Four pieces of osteochondral fragments were used for each group. (B) Histological analyses and quantification of attached cell number. Toluidine blue staining (left upper), the fluorescence image for DiI (left lower), and quantification of adherent cell number (right). Values are means with 95% CI. Four pieces of osteochondral fragments were used for each group. (C) Effects of the neutralizing antibodies. Top side view of the defects without fluorescence (upper) and with fluorescence (middle). The relative fluorescence intensities of cells in the defects were quantified (lower). Values are means with 95% CI. Three pieces of osteochondral fragments were used for each group.

Magnesium enhances adherence of rabbit synovial MSCs in osteochondral defects in vivo

Osteochondral defects in the rabbit knee joint were filled with DiI-labeled MSCs suspended in PBS with or without 5 mM magnesium, held stationary for 10 min [Fig. 4(A)], and then the joint capsule was closed. Under fluorescence at day 1, the DiI positive area was more distinct [Fig. 4(B, upper panels)], and the fluorescence intensity of defects [Fig. 4(B, lower left)] and the ratio of fluorescence positive area over the defect [Fig 4(B, lower right)] were significantly greater in the defect treated with magnesium. Histologically, a greater number of DiI-positive cells adhered to the defect treated with magnesium. Furthermore, a greater number of cells accumulated on the layer of cells which are attached to the basement of defects in the presence of magnesium [Fig. 4(C)].

Addition of magnesium results in a greater amount of cartilage matrix by MSCs in vivo

At 2 weeks, cartilage matrix stained with safranin-o appeared more distinct in the osteochondral defect treated with synovial MSCs suspended with magnesium than in the defect treated with synovial MSCs suspended without magnesium [Fig. 5(A)]. The safranin-o positive area ratio was significantly higher in the defect treated with magnesium [Fig. 5(B)]. At 4 weeks, the amount of cartilage matrix increased, and the difference of the ratio of the safranin-o positive area to the defect area lessened in both groups. The matrix of regenerated cartilage was positive for type II collagen in both groups [Fig. 5(C)]. Regenerated cartilage consisted of polygonal cells containing well-developed rER, with short processes, and surrounded with thin, faintly striated collagen fibrils [Fig. 5(D)]. These results indicate that the osteochondral defect was regenerated with hyaline cartilage.

Discussion

MSCs are defined as having been derived from mesenchymal tissue and by their functional capacity to self-renew and to generate a number of differentiated progeny[1,10]. Since the earliest studies by Friedenstein *et al.*, the standard assay used to identify the self-renewal ability of MSCs is the colony forming unit fibroblast assay[24]. Although clonal colonies of MSCs are readily prepared, they rapidly become heterogeneous as they expand[9,25,26]. We collected bulk colony-forming cells, and the cells used in the present study showed both colony-forming ability and multipotentiality. Surface markers were also identical to those of MSCs published elsewhere[1,4,7–10]. Therefore, the synovial cells we used were defined as MSCs, though the cells were not clonal. This point should be considered when our study is discussed in the field of "stem cells".

It was reported that magnesium enhanced adhesion of some tumor cells or lineage cell lines to collagen and fibronectin coated slides. Grzesiak *et al.* demonstrated that human fibroblast WI38 bound to type I collagen under regulation by shift in the concentrations of extracellular divalent cations. In their report, cells adhered to collagen more effectively along with the concentration of magnesium through integrins[20]. However, there have been no reports demonstrating that magnesium enhanced adhesion of MSCs to collagen coated slides or osteochondral defects. Furthermore, improvement of the efficiency of attachment of stem cells is currently one of the topics for stem cell biology and regenerative medicine. An increase in adherence of cells leads to the improvement of "efficiency of transplantation," a factor of increasing interest in cell based regenerative medicine[27]. We believe that this paper contributes greatly to the field of cell therapy for regenerative medicine.

Although Pittenger *et al.* reported that bone marrow MSCs expressed integrins α1, α2, α3, and β1, integrins expressed in human synovial MSCs have not been reported[1]. In this study, surface epitope analyses revealed that synovial MSCs expressed integrin α5 and β1 highly, and α2 and α3 moderately.

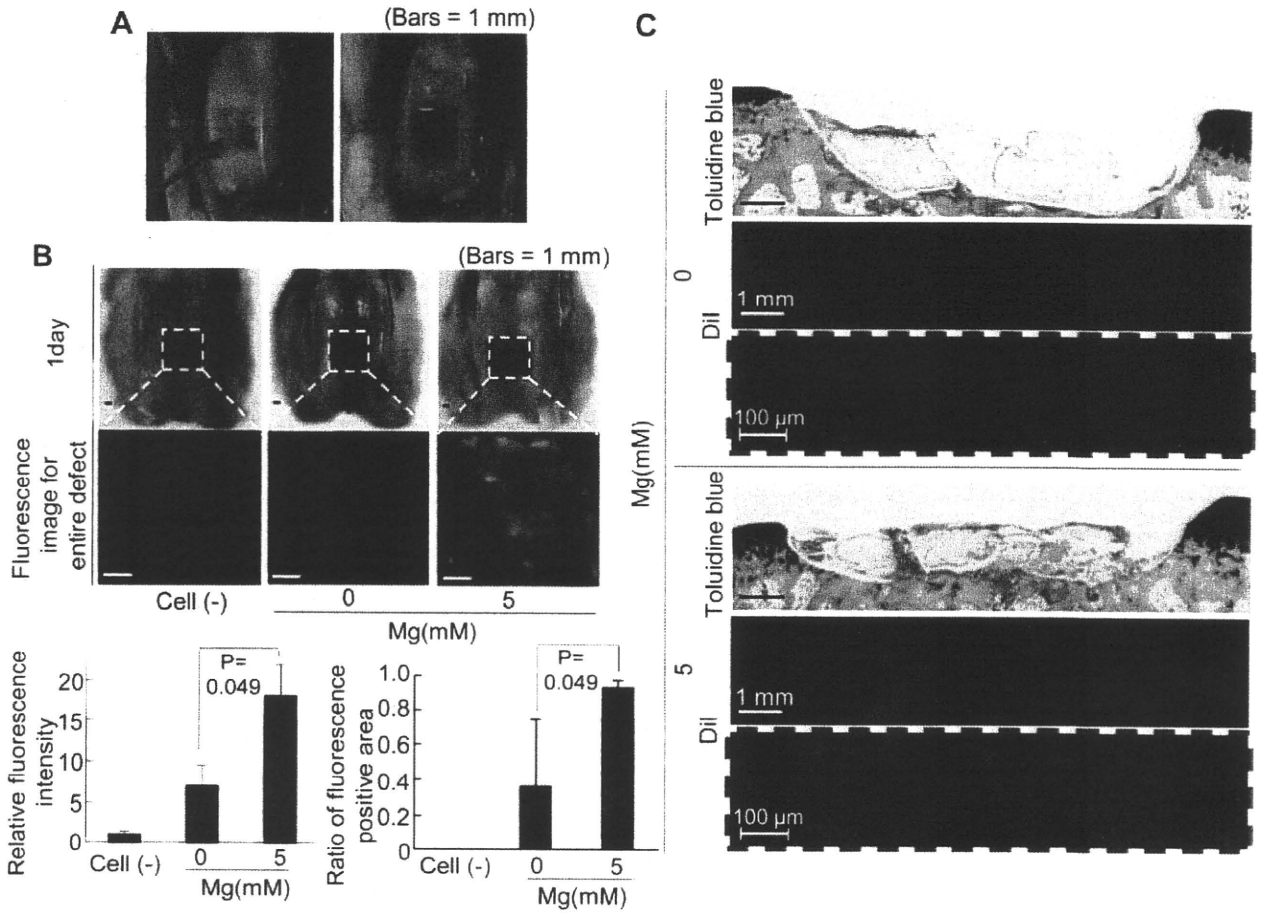

Fig. 4. *In vivo* analyses for magnesium effects on adherence of rabbit synovial MSCs on osteochondral defects. (A) Procedure for cell transplantation. Osteochondral defect was created, and needle was prepared over the defect (left). Cell suspension was dripped onto the defect, and this position was kept for 10 min (right). (B) Macroscopic and macroscopic fluorescence images of the defect for DiI labeled MSCs (upper six panels), quantification of relative fluorescence intensity over the defect at 1 day (lower left) and the ratio of fluorescence positive area over the defect at 1 day (lower right). The ratio was evaluated by measuring the square measure of the entire defect and the fluorescence positive area within the defect. Values are means with 95% CI ($n = 3$). (C) Sagittal sections of histologies stained with toluidine blue (upper), for DiI (middle) and the magnified image (lower).

Previous reports indicated that integrin α3β1 was a promiscuous cell adherent receptor. Wayner *et al.* first identified Integrin α3β1 as a receptor for type I, and IV collagen, laminin, and fibronectin[28]. Berdichevsky *et al.* reported that antibody for integrin α3 inhibited adhesion to polymerized collagen in mammary epithelial cells[29]. Carter *et al.* reported that human keratinocytes cultured on fibronectin, collagen, or laminin were detached from cover slips in the presence of anti integrin α3 antibody[30]. Though integrin α2β1 is also considered as one of the collagen receptors[14,15], our results demonstrated that neutralizing antibodies for α3 and β1 inhibited adhesion of synovial MSCs on collagen-coated slides. This indicates that integrin α3β1 functions as an adherence factor of synovial MSCs to type I collagen-coated slides under a higher concentration of magnesium.

In this study, we evaluated *in vitro* chondrogenesis potential as pellet weight. We intensively investigated pellet culture of MSCs. During *in vitro* chondrogenesis of MSCs, the pellets increased in size and weight. Conversely, the DNA yield per pellet decreased. The radioactivity per DNA in the cells, assessed by prelabeling with 3H-thymidine, was stable during *in vitro* chondrogenesis of MSCs. The increase in pellet size can be attributed to production of ECM and not to the proliferation of the cells[5,31]. Pellet weight is always correlated with expressions of cartilage related mRNAs such as COL2A1, aggrecan, link protein, SOX5, SOX6, and SOX9. Pellet weight is also correlated with proteoglycan staining by safranin-o, type II collagen by immunostaining, protein expressions of chondroitin 4-sulfate, chondrotitin 6-sulfate, and hyaluronan by ELISA as we previously reported[4–9,25,32]. All the results demonstrate that the weights of the pellets are quantitative indicators for chondrogenesis of MSCs.

While magnesium did not affect the DNA content of pellets, magnesium increased the wet weight, sGAG content, and gene expression for type II collagen of pellets. The effect was significantly diminished after pretreatment with neutralizing antibody for integrin β1 without re-adding antibodies. We investigated sequential gene expression profiles of MSCs during *in vitro* chondrogenesis within 24 h, and a large number of gene expressions were dramatically altered within a few hours (data not shown). Also, our morphological analysis demonstrated that the ultrastructure was altered most dramatically within 1 day[21]. We speculated the effect of neutralizing antibody for integrin β1 as follows: The neutralizing antibody for β1 integrin affected *in vitro* chondrogenesis at an early period, and this influence remained at a later stage, resulting in a difference of synthesis of cartilage matrix. We examined the magnesium effect on adherence of rabbit synovial MSCs on osteochondral defects *in vivo*. DiI-labeled MSCs suspended in PBS with or without 5 mM magnesium were placed on the defects for 10 min, and then the rabbit was allowed to move freely after operation. The distributions of DiI positive MSCs in the defects at 1 day were less homogenous compared with the results of *ex vivo*