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Title: Disruption of endogenous perlecan function improves differentiation of
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ABSTRACT

Heparan sulfate (HS) and heparan sulfate proteoglycans (HSPG) are necessary for normal cartilage development and chondrocyte differentiation. However, recent studies demonstrated that HSPG accelerate dedifferentiation and catabolism in chondrocytes from degenerative cartilage. In this study, we investigated the inhibitory effect of HSPG on chondrocyte differentiation *in vitro*. Rat articular chondrocytes were cultured at low (0.3×10^4 cells/cm²) and high (1.5×10^5 cells/cm²) density in the presence or absence of heparitinase I, an HS degrading enzyme. Cells cultured at low density dedifferentiated and exhibited an elongated morphology, and treatment with heparitinase I precluded cell elongation. Conversely, populations of chondrocytes cultured at high density exhibited either a dedifferentiated or differentiated phenotype. Glycosaminoglycan accumulation increased in heparitinase I-treated cells. To determine the function of perlecan, an important HSPG for cartilage development, in chondrocyte differentiation, rat chondrocyte cultures were exposed to an anti-perlecan antiserum to inhibit perlecan function. Western blotting analysis indicated that preventing perlecan activity increased type II collagen synthesis. Our results suggest that HSPG are negative regulators of chondrocyte differentiation *in vitro* and that perlecan contributes to chondrocyte dedifferentiation *in vitro*.

Keywords: culture, extracellular matrix, HS, HSPG, perlecan

INTRODUCTION

Chondrocyte differentiation is regulated by various extracellular signaling molecules, such as morphogens and growth factors (GF) that act in developing and adult cartilage (Ellman et al. 2008; Minina et al. 2001). During cartilage degeneration or *in vitro* expansion, these signaling factors are abnormally activated, resulting in a catabolic state and a dedifferentiated phenotype (Im et al. 2007; Yuasa et al. 2008). During adulthood, articular cartilage exhibits a limited repair potential, such that this tissue is prone to severe degeneration and osteoarthritis (OA) in response to trauma. Although chondrocytes are capable of regenerative responses, such as increased proliferation and collagen expression, as OA progresses these abilities are unable to prevent cartilage degeneration. Chondrocytes from osteoarthritic cartilage exhibit a catabolic state and dedifferentiated phenotype, elongated fibroblastic morphology, a reduced collagen type II to type I expression ratio and expression of proteoglycan (PG), and increased expression of collagen-degrading enzymes (Tesche & Miosge 2005). Similar phenotypic changes occur in chondrocytes expanded *in vitro* (Tesche & Miosge 2005). Autologous chondrocyte implantation is a possible treatment for degenerative cartilage diseases, but requires *in vitro* expansion of chondrocytes (Batty et al. 2011). However, the expansion procedure might result in fibrocartilaginous tissue formation that is inadequate to restore articular cartilage function. The ability of various factors, such as bone morphogenetic proteins (BMP) and fibroblast growth

factors (FGF), to induce a differentiated and anabolic phenotype in chondrocytes *in vitro* and *in vivo*, was investigated (Gouttenoire et al. 2010; Moore et al. 2005). However, despite these efforts, induction of a differentiated and anabolic articular chondrocyte phenotype remains difficult to attain.

During cartilage development, the distribution and function of extracellular signaling molecules are regulated by heparan sulfate proteoglycans (HSPG) (Koziel et al. 2004; Grobe et al. 2005). HSPG are composed of a core protein that is bound mainly to heparan sulfate (HS) chains. The core protein determines the distribution of HS, which interacts with heparin-binding molecules, such as FGF, BMP, and Wnts (Whitelock et al. 2008; Manon-Jensen et al. 2010). Thus, HSPGs modulate the presentation of heparin-binding molecules to their cognate receptors.

The importance of HSPG function in cartilage formation is documented by studies of mutations in exostosin-1 (EXT1), an enzyme responsible for HS synthesis (Nadanaka & Kitagawa 2008). Mice carrying an *Ext1* hypomorphic allele exhibit a delay in chondrocyte hypertrophy and skeletal growth retardation (Koziel et al. 2004). Accordingly, conditional knockout of *Ext1* in limb buds during early embryonic development impairs mesenchymal cell condensation and cartilaginous primordium formation (Matsumoto et al. 2010). Perlecan is a multifunctional HSPG that is essential for the normal development of various organs and is critical for cartilage development (Knox & Whitelock 2006). Disruption of the perlecan gene causes dwarfism and dyssegmental dysplasia in mice (Arikawa-Hirasawa et al. 1999). During

1 cartilage development, the amount of perlecan in the stromal extracellular
2 matrix (ECM) increases (Melrose et al. 2006). In addition, perlecan might
3 regulate the distribution and presentation of Indian hedgehog (Ihh) and
4 BMP (Melrose et al. 2008). Furthermore, multiple *in vitro* studies have
5 demonstrated that perlecan promotes BMP-stimulated chondrogenic
6 differentiation (Gomes et al. 2003, 2006; Yang et al. 2006). In addition, cell
7 membrane-associated HSPG, such as syndecans, contribute to cartilage
8 development by regulating the distribution of Ihh (Shimo et al. 2004). Mice
9 harboring individual *syndecan-2*, *-3*, or *-4* null alleles do not exhibit cartilage
10 defects, probably because of genetic compensation from the other syndecan
11 genes (Bertrand et al. 2013; Pap & Bertrand 2013).

12 Although HSPG are important for normal cartilage development, recent
13 studies suggest that HSPG inhibit cartilage repair in degenerative disease of
14 the joint. In a mouse model of OA, ablation of *syndecan-4* delayed cartilage
15 degeneration (Echtermeyer et al. 2009). Mice null for *endosulfatase-1*, which
16 encodes for a protein that impairs HS function by removing sulfate groups
17 from HS chains, exhibit more pronounced cartilage degeneration under
18 conditions of OA induction (Otsuki et al. 2010). These studies suggest that
19 HSPG primarily have negative effects on cartilage repair by dedifferentiated
20 and catabolic chondrocytes. Perlecan expression may increase in cartilage
21 from OA patients (Tesche & Miosge 2004), raising the possibility that
22 perlecan contributes to the progress of dedifferentiation and catabolic
23 responses in cartilage.

24 In this study, we cultured chondrocytes in the absence of inducers of

- 1 chondrocyte differentiation and examined the role of HSPG in chondrocyte
- 2 differentiation by disrupting the function of HS and perlecan.
- 3

MATERIALS AND METHODS

Chondrocyte culture

Rat articular chondrocytes were cultured as described by Gosset et al. (2008), with some modifications. Neonatal Wistar rats were euthanized with an overdose of sodium pentobarbital (Dainippon Sumitomo Pharma, Osaka, Japan), in accordance with the guidelines of the ethics committee of Hokkaido University (Japan), and articular cartilage was obtained from knee joints. The cartilage was treated with Dulbecco's modified Eagle's medium (DMEM; Sigma-Aldrich, St. Louis, MO, USA) containing 0.1% collagenase (Wako Pure Chemical Industries, Osaka, Japan) at 37°C for 30 min, and the surface of the cartilage was washed with phosphate-buffered saline (PBS; 137 mM NaCl, 2.7 mM KCl, 10 mM Na₂HPO₄, and 1.76 mM KH₂PO₄, pH 7.4). After treatment with 0.02% collagenase for 12 h, the cartilage was disrupted mechanically by pipetting. Dissociated chondrocytes were filtered through nylon meshes with 40-μm pores (BD Biosciences, Franklin Lakes, NJ, USA). Subsequently, cells were cultured in DMEM/F-12 (Sigma) containing 5% fetal bovine serum (FBS; Cell Culture Technologies, Gravesano, Switzerland), 164 μg/mL L-ascorbic acid phosphate magnesium salt n-hydrate (Wako), 63.3 μg/mL penicillin G potassium (Nacalai Tesque, Kyoto, Japan), and 100 μg/mL streptomycin sulfate (Nacalai Tesque). The cells were cultured at a low density (0.3×10^4 cells/cm²) to accelerate dedifferentiation, or at a high density (1.5×10^5 cells/cm²) to induce differentiation.

Normal human articular chondrocytes (NHAC) were purchased from Lonza (Basel, Switzerland). Cells were fully dedifferentiated by extensive expansion in DMEM containing 10% FBS, 10 ng/mL FGF-2 (BD biosciences), 63.3 µg/mL penicillin G potassium, and 100 µg/mL streptomycin sulfate. The redifferentiation of NHAC was induced by seeding on cell culture inserts (0.4-µm pore size; BD Biosciences) and co-culturing with rat primary chondrocytes previously seeded on 6-well cell culture plates (Thermofisher Scientific, Waltham, MA, USA), in chondrogenic differentiation medium (CDM) for 14 days. DMEM-high glucose containing 0.1% bovine serum albumin (BSA; Wako), 82 µg/mL L-ascorbic acid phosphate magnesium salt n-hydrate, 10 µg/mL insulin (Sigma), 10 µg/mL holo-transferrin (Sigma), 30 nM sodium selenite (Wako), and 10 ng/mL TGF-β1 (Wako) was used as CDM. The co-cultured cells were examined for perlecan mRNA expression and compared to monocultures in CDM. Co-cultures of rat primary chondrocytes and NHACs were routinely conducted at 37°C in a humidified atmosphere containing 5% CO₂. The media was replaced every other day.

Disruption of endogenous HS function

The function of HS chains expressed by chondrocytes was disrupted by addition of 1 mU/mL heparitinase I (Seikagaku, Tokyo, Japan), an HS degrading enzyme, and 100 µg/mL sodium heparin (Nacalai) to the culture medium. At this concentration, heparin interacts with various GF and cytokines leading to the disruption of HS function (Irie et al. 2003; De Wit et

al. 2005; Belleudi et al. 2007; Santiago et al. 2012).

Blocking of endogenous perlecan function and supplementation of exogenous perlecan

Perlecan and anti-perlecan antiserum (anti-Pln) were produced as described previously (Nakamura et al. 2014). Blocking of perlecan function was carried out by adding 1/500 volume of anti-Pln to the culture medium every day. Pre-immune serum (PIS) was added as a control. Purified perlecan was dissolved in PBS and added to the culture medium at 5 µg/mL. PBS was added to the medium as a control.

Morphological analysis of chondrocyte differentiation

For morphological evaluation of chondrocyte differentiation, the roundness of chondrocytes was measured as described by Kino-Oka et al. (2009). Chondrocytes seeded on 96-well plates (Thermo Fisher Scientific) at a density of 0.3×10^4 cells/cm² were cultured for 2 days, fixed with 10% formalin, and stained with 1% toluidine blue solution for 1 h. Images of cells in each well were acquired with an EVOS fl AMF-4302 microscope (Advanced Microscopy Group, Bothell, WA, USA) equipped with a ×20 objective. The roundness of an individual cell (R_c) was defined by the following equation:

$$R_c = \frac{2(\pi A_c)^{1/2}}{l_c}$$

where the area (A_c) and peripheral length (l_c) of each cell were evaluated with ImageJ image analysis software (downloaded from the National

Institutes of Health, Bethesda, MD, USA; available at <http://rsb.info.nih.gov/ij/>). The Rc values of more than 100 cells in each well were evaluated. Cells exhibiting an $Rc > 0.9$ were defined as round-shaped, and the frequency of round-shaped cells was calculated.

Determination of glycosaminoglycan content

Chondrocytes seeded at a density of 1.5×10^5 cells/cm² on 96-well plates were cultured for 4 days. The cell/ECM layers were collected in sulfuric acid containing 0.95% boric acid, and the uronic acid content was determined by the carbazole reaction method of Bitter and Muir (1962). The glycosaminoglycan (GAG) content was estimated by doubling the uronic acid content.

Reverse transcriptase-polymerase chain reaction (RT-PCR)

NHAC were lysed in Isogen (Wako), and total RNA was isolated according to the manufacturer's instruction. First strand cDNA was synthesized from 1 µg of total RNA using an oligo d(T)₁₈ primer (New England BioLabs, Ipswich, MA, USA) and reverse transcriptase (M-MLV, RNase H⁺; Wako). For PCR amplification, FastStart Taq DNA Polymerase (Roche Diagnostics, Basel, Switzerland) was used according to the manufacturer's instruction. Specific primers were designed as follows: 5'-CGATGGATTCCAGTTCGAGTA-3' and 5'-GTTTACACGAAGCAGGCAGG-3' for type I collagen (*COL1A1*); 5'-GGAGACTACTGGATTGA-3' and 5'-GCGTGAGGTCTTCTGTG-3' for type II collagen (*COL2A1*); 5'-TCCAGGTAAAGTTGGTCCTCCG-3' and

1 5'-AAGAAATCCGCACTCCCTTCC-3' for type IX collagen (*COL9A2*);
 2 5'-GGTCCAGGTGGAAAACGAAAC-3' and
 3 5'-CTCTCACTTCTATCGAGGGGT-3' for type XI collagen (*COL11A1*);
 4 5'-TGGACACATTCGTACCTTTCTGA-3' and
 5 5'-ACTCCGACTCCAGCGTGTCT-3' for perlecan (*HSPG2*); and
 6 5'-GGTGAAGGTCGGTGTCAACGGATT-3' and
 7 5'-GATGCCAAAGTTGTCATGGATGACC-3' for glyceraldehyde-3-phosphate
 8 dehydrogenase (*GAPDH*). The resulting PCR products were electrophoresed
 9 on 2% agarose gels and stained with 0.5 µg/mL ethidium bromide (Life
 10 Technologies, Carlsbad, CA, USA).

12 Immunofluorescence and Alcian blue staining

13 Chondrocytes seeded at a density of 0.3×10^4 or 1.5×10^5 cells/cm² were
 14 cultured for 4 days and fixed with 10% formalin. The cells were incubated
 15 with the following primary antibodies at 4°C over night: rabbit anti-rat
 16 collagen type I (×100 dilution), rabbit anti-mouse collagen type II (×100
 17 dilution) (all purchased from LSL, Tokyo, Japan), and anti-Pln (×80 dilution).
 18 Subsequently, cells were then stained fluorescein isothiocyanate-conjugated
 19 anti-rabbit immunoglobulin G (×200 dilution; MP Biomedicals, Solon, OH,
 20 USA) and 4',6-diamidino-2-phenylindole (DAPI; ×500 dilution; Dojindo
 21 Laboratories, Kumamoto, Japan) at 37°C for 30 min. Fluorescent images
 22 were acquired using an inverted fluorescence microscope (EVOS xl core
 23 AMEX-1200; Advanced Microscopy Group). Because differentiated
 24 chondrocytes were embedded in a dense GAG matrix, which precludes

1 reaction of antibodies with pericellular ECM components, cells cultured at
2 high density were treated with PBS containing 1% hyaluronidase at 37°C for
3 30 min before exposure to primary antibodies. Following formalin fixation,
4 cells were stained with 1% Alcian blue dissolved in 3% acetic acid and
5 observed with an EVOS fl AMF-4302 microscope.

6

7 **Sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) and** 8 **western blotting**

9 Chondrocytes seeded at a density of 1.5×10^5 cells/cm² on 12-well plates
10 were cultured for 6 days. The layer of ECM and chondrocytes was collected in
11 a 0.5 N NaOH solution, and protein concentration was measured using the
12 Biuret method (Gorall et al. 1949). Samples containing equal amounts of
13 protein were subjected to SDS-PAGE with 5% polyacrylamide gels. For
14 western blotting analysis, separated proteins were blotted onto nitrocellulose
15 membranes, which were rinsed with PBS containing 0.5% Nonidet P-40 and
16 then with PBS containing 0.05% Tween 20 (T-PBS; pH 7.4). Membranes were
17 blocked with T-PBS containing 2% casein (Wako) and 1% BSA and then
18 incubated with primary antibodies. The membranes were washed with
19 T-PBS three times and exposed to horseradish peroxidase (HRP)-conjugated
20 anti-rabbit IgG, IgA, and IgM (MP Biomedicals). HRP was detected with
21 3,3'-diaminobenzidine (Dojindo Laboratories) and hydrogen peroxide (Wako).
22 For detection of high molecular weight proteoglycans, such as aggrecan and
23 hyaluronan, the gels were stained with Coomassie brilliant blue and then
24 with Alcian blue. Collagens secreted into the medium were extracted by

1 adding 1/3 volume of saturated ammonium sulfate solution and were
2 analyzed by western blotting.

3

4 **Statistical analysis**

5 Data are shown as means $\pm$ SD. Student's *t*-test was applied to determine
6 the statistical significance of differences between groups, and $p < 0.05$ was
7 considered significant.

RESULTS

Disruption of HS prevents chondrocyte dedifferentiation

To determine whether HSPG inhibited chondrocyte differentiation *in vitro*, HS function was disrupted by exposing cell cultures to heparitinase I and a high concentration of heparin. Rat primary chondrocytes cultured at a low density in control medium for 2 days began to dedifferentiate (Figs. 1a, 2a). Some cells retained a spherical, differentiated morphology and were intensely stained with toluidine blue. Conversely, other cells showed a dedifferentiated morphology, characterized by a flattened appearance, and faint toluidine blue staining. Exposure of chondrocyte cultures to 1 mU/mL heparitinase I or 100 µg/mL sodium heparin for 2 days increased the number of spherical cells (Figs. 1b, 2b) and the frequency of round-shaped cells (Figs. 1c, 2c).

After 2 days of culture at a high density in control medium, chondrocytes exhibited either an elongated or spherical appearance, and number of cells presenting either morphologies increased after 4 days (Figs. 3a, c, 4a, c). These observations suggest that dedifferentiation and differentiation were occurring in the culture system. Cultures treated with heparitinase I or heparin exhibited a higher number of spherical cells (Figs. 3b, d, 4b, d) and higher levels of GAG accumulation than control cultures (Figs. 3e, 4e). SDS-PAGE analysis revealed that high molecular weight PG increased in the cell/ECM layer of heparin-treated cells (Fig. 4f).

1 **Perlecan expression by dedifferentiated chondrocytes**

2 Perlecan is an essential HSPG for cartilage development that is
3 upregulated in cartilage from OA patients (Tesche & Miosge 2004). Therefore,
4 we examined whether perlecan is upregulated during chondrocyte
5 dedifferentiation *in vitro*. NHAC fully dedifferentiated by *in vitro* expansion
6 were induced to differentiate by co-culture with rat primary chondrocytes.
7 Type II, IX, and XI collagen mRNA levels were higher in co-cultured NHAC
8 than in cultures of NHAC without other cells (Fig. 5). Conversely type I
9 collagen mRNA expression was not different between co-cultures and
10 monocultures (Fig. 5). These results indicate that co-culture of NHAC with
11 rat primary chondrocytes induced NHAC redifferentiation. Perlecan mRNA
12 expression was low in the co-cultured NHAC, indicating that
13 dedifferentiation increases perlecan mRNA expression in chondrocytes.

14 The distribution of perlecan in dedifferentiated and differentiated rat
15 chondrocytes was examined by immunofluorescence. Cells cultured at a low
16 density for 4 days showed extensive dedifferentiation (Fig. 6a). Morphology
17 was flattened and elongated, and Alcian blue staining was not observed in
18 the ECM, although it was present in the nucleus. Type II collagen staining
19 was faint (Fig. 6c), but type I collagen staining revealed the presence of an
20 extensive extracellular network (Fig. 6e). In dedifferentiated cells, perlecan
21 staining indicated the presence of a fine extracellular network (Fig. 6g).
22 Primary high-density chondrocytes cultures presented spherical cells
23 intensely stained with Alcian blue and elongated cells exhibiting faint Alcian
24 blue staining (Fig. 6b). Without pre-treatment with hyaluronidase, spherical

cells exhibited faint type II collagen and perlecan staining, whereas staining for type I collagen and perlecan revealed the presence of an extracellular network surrounding the elongated cells (Supplemental data Fig. S1). Staining for type II collagen in hyaluronidase-treated cells was intense around spherical cells (Fig. 6d). Type I collagen staining exposed a complex network in the proximity of elongated cells, but was not observed in the surroundings of spherical cells (Fig. 6f). Similar to findings in rat normal cartilage (Melrose et al. 2006), perlecan was detected around the spherical, differentiated cells, whereas it formed a network connecting elongated cells (Fig. 6h).

Suppression of perlecan function prevents chondrocyte dedifferentiation

To determine whether perlecan is involved in the dedifferentiation of chondrocytes, perlecan function was suppressed with anti-Pln. Rat primary chondrocytes cultured at a low density in the presence of anti-Pln for 2 days appeared less elongated than cells cultured with PIS (Fig. 7a, b). The frequency of round-shaped cells was higher in the context of perlecan inhibition than under basal conditions (Fig. 7c). Perlecan inhibition had no effect on cellular morphology in chondrocytes cultured at a high density for 4 days (Fig. 8a, b). However, perlecan-blocking insignificantly increased GAG accumulation by chondrocytes cultured at a high density (Fig. 8c). The addition of bovine kidney perlecan to the culture medium did not decrease GAG accumulation by chondrocytes (data not shown), probably because the amount of endogenous perlecan expressed by chondrocytes was sufficient.

1 Although anti-Pln, unlike heparitinase I and heparin, did not have
 2 statistically significant effects on frequency of round-shaped cells and GAG
 3 accumulation, the possibility that perlecan inhibits chondrocyte
 4 differentiation *in vitro* cannot be excluded. After 6 days of culture, the
 5 number of spherical cells was higher in the context of perlecan inhibition
 6 than under basal conditions (Fig. 9a, b). Type I and II collagen expression
 7 was analyzed by western blotting (Fig. 9c, d). Type I collagen bands of
 8 similar sizes and intensities were observed in media and cell/ECM layers
 9 from cultures exposed to anti-Pln and from control cultures. More than 5
 10 bands for collagen type II were detected in the media and in the cell/ECM
 11 layer samples from control and experimental cultures. In accordance with a
 12 report by Aubert-Foucher (2014), the bands between 116 and 200 kDa were
 13 identified as the $\alpha 1$ chains of procollagen type IIA/D [Pro- $\alpha 1$ (II)A/D] and IIB
 14 [Pro- $\alpha 1$ (II)B], the C-terminal-processed forms of Pro- $\alpha 1$ (II)A/D [P_N- $\alpha 1$ (II)A/D]
 15 and Pro- $\alpha 1$ (II)B [P_N- $\alpha 1$ (II)B], the N-terminal-processed form of
 16 Pro- $\alpha 1$ (II)A/B/D [P_C- $\alpha 1$ (II)], and the $\alpha 1$ chain of mature collagen type IIA/B/D
 17 [$\alpha 1$ (II)]. The levels of the type II collagen precursors [Pro- $\alpha 1$ (II)A/D and
 18 P_N- $\alpha 1$ (II)B] in the media were higher in the presence than in the absence of
 19 anti-Pln. Levels of precursor and mature type II collagen levels were higher
 20 in the cell/ECM layer of cultures in the context of perlecan inhibition than
 21 under basal conditions. These findings suggest that perlecan inhibition
 22 increases both *de novo* and net type II collagen synthesis. In addition, an
 23 increase in the levels of the procollagen type IIB isoform, which is
 24 predominantly expressed in mature chondrocytes (Gouttenoire et al. 2004),

1 was observed in the presence of anti-Pln. Finally, Alcian blue staining
2 revealed higher levels of high molecular weight PG in the cell/ECM layer in
3 the context of perlecan inhibition than under basal conditions (Fig. 9d).

4

DISCUSSION

Although perlecan and other HSPG are important for cartilage development, our data indicate that these molecules inhibit chondrocyte differentiation *in vitro*.

Disruption of HS chains and perlecan function either prevented dedifferentiation or promoted differentiation of chondrocytes either cultured at a low or a high density, respectively. Previous studies have reported that endogenous perlecan promotes the chondrogenic effects of BMP-2 on the C3H10T1/2 mesenchymal cell line (Yang et al. 2006). In contrast, our results suggest that endogenous HSPG preferentially mediate extracellular signaling events that inhibit chondrocyte differentiation in the absence of strong chondrogenic factors, such as BMP. Because HS chains of perlecan and other HSPG interact with various molecules (Knox & Whitelock 2006), the identity of the factors interacting with HSPG in cultured chondrocytes is elusive. Dedifferentiated chondrocytes express low levels of chondrogenic BMP-2 and BMP-4, and exhibit activation of canonical Wnt signaling, which promotes dedifferentiation (Yuasa et al. 2008; Cheng et al. 2012). Consequently, these observations suggest that changes in the expression pattern of HS-binding molecules during chondrocyte dedifferentiation contribute to further advance this process.

The mechanisms whereby HSPG disrupted chondrocyte differentiation under high density culture conditions are not apparent, since these culture conditions are commonly chondrogenic. One possible explanation is that high

1 density PG aggregates define microenvironments that either favor
2 differentiation or dedifferentiation. We showed that chondrocytes cultured at
3 a high density contained both dedifferentiated and differentiated cell
4 populations. The differentiated population was observed in association with
5 high-density PG aggregates, which prevented infiltration of the antibodies
6 used for immunofluorescent staining. Therefore, PG aggregation might
7 prevent contact with factors that promote dedifferentiation, such as selected
8 Wnt molecules (Yuasa et al. 2008) secreted by dedifferentiated cells.
9 Moreover, because perlecan contains negatively charged GAG chains (Knox
10 & Whitelock 2006), we speculate that high-density PG aggregates repel
11 perlecan expressed by dedifferentiated chondrocytes. Negatively charged
12 molecules do not readily penetrate the cartilage ECM (Bansal et al. 2011).
13 Therefore, it is probable that perlecan expressed by dedifferentiated
14 chondrocytes preferentially mediates reactions occurring in proximity of
15 these cells.

16 Therapeutic antibodies are utilized for the treatment of various diseases. In
17 2011, the global market for these drugs was reported to be valued about 44.6
18 billion dollars (BCC research 2012). Intravenous injection of Tanezumab, an
19 antibody against nerve growth factor, improved pain of OA in a phase III
20 clinical trial (Spierings et al. 2013). Moreover, an antibody against
21 syndecan-4 has been reported to prevent OA progression in the mouse knee.
22 Our results and recent reports demonstrating that HSPG contribute to
23 chondrocyte dedifferentiation suggest that antibodies against perlecan or
24 HSPG are candidate drugs to prevent or correct cartilage degeneration.

1 Autologous chondrocyte implantation requires *in vitro* preparation of
2 well-differentiated chondrocytes, so that disruption of endogenous
3 perlecan/HSPG function in culture may provide a suitable cell source for this
4 procedure.

5 Although it remains unclear whether OA induces perlecan or other HSPG
6 in any joint other than knee, endosulfatase-1 and -2 prevented knee and
7 temporomandibular OA progression (Otsuki et al. 2010). Therefore,
8 disruption of HSPG function might be effective for treatment of OA
9 irrespective of joint location.

10 In conclusion, perlecan inhibits chondrocyte differentiation in a
11 dedifferentiative environment. Inhibiting the function of perlecan and/or
12 other HSPG may promote chondrocyte differentiation.

13

References

- Arikawa-Hirasawa E, Watanabe H, Takami H, Hassell JR, Yamada Y. 1999. Perlecan is essential for cartilage and cephalic development. *Nature Genetics* **23**, 354-358.
- Aubert-Foucher E, Mayer N, Padeloup M, Pagnon A, Hartmann D, Mallein-Gerin F. 2014. A unique tool to selectively detect the chondrogenic IIB form of human type II procollagen protein. *Matrix Biology* **34**, 80-88.
- Bansal PN, Stewart RC, Entezari V, Snyder BD, Grinstaff MW. 2011. Contrast agent electrostatic attraction rather than repulsion to glycosaminoglycans affords a greater contrast uptake ratio and improved quantitative CT imaging in cartilage. *Osteoarthritis and Cartilage* **19**, 970-976.
- Batty L, Dance S, Bajaj S, Cole BJ. 2011. Autologous chondrocyte implantation: an overview of technique and outcomes. *ANZ Journal of Surgery* **81**, 18-25.
- BCC research. 2012. Antibody Drugs: Technologies and Global Markets-BIO016H BCC Research, Wellesley, MA, USA; [cited at 26 May 2014]. Available from URL: <http://www.bccresearch.com/mobile/market-research-report/biotechnology/antibody-drugs-technologies-markets-bio016h.html>
- Belleudi F, Leone L, Nobili V, Raffa S, Francescangeli F, Maggio M, Morrone S, Marchese C, Torrisi MR. 2007. Keratinocyte growth factor receptor ligands target the receptor to different intracellular pathways. *Traffic* **8**, 1854-1872.
- Bertrand J, Stange R, Hidding H, Echtermeyer F, Nalesso G, Godmann L, Timmen M, Bruckner P, Dell'Accio F, Raschke MJ, Pap T, Dreier R. 2013. Syndecan 4 supports bone fracture repair, but not fetal skeletal development, in mice. *Arthritis & Rheumatology* **65**, 743-752.
- Bitter T, Muir HM. 1962. A modified uronic acid carbazole reaction. *Analytical Biochemistry*

4, 330-334.

Cheng T, Maddox NC, Wong AW, Rahnama R, Kuo AC. 2012. Comparison of gene expression patterns in articular cartilage and dedifferentiated articular chondrocytes. *Journal of Orthopaedic Research* **30**, 234-245.

De Wit J, De Winter F, Klooster J, Verhaagen J. 2005. Semaphorin 3A displays a punctate distribution on the surface of neuronal cells and interacts with proteoglycans in the extracellular matrix. *Molecular and Cellular Neuroscience* **29**, 40-55.

Echtermeyer F, Bertrand J, Dreier R, Meinecke I, Neugebauer K, Fuerst M, Lee YJ, Song YW, Herzog C, Theilmeier G, Pap T. 2009. Syndecan-4 regulates ADAMTS-5 activation and cartilage breakdown in osteoarthritis. *Nature Medicine* **15**, 1072-1076.

Ellman MB, An HS, Muddasani P, Im HJ. 2008. Biological impact of the fibroblast growth factor family on articular cartilage and intervertebral disc homeostasis. *Gene* **420**, 82-89.

Gomes RR Jr., Farach Carson MC, Carson DD. 2003. Perlecan-stimulated nodules undergo chondrogenic maturation in response to rhBMP-2 treatment in vitro. *Connective Tissue Research* **44 Suppl 1**, 196-201.

Gomes RR Jr., Joshi SS, Farach-Carson MC, Carson DD. 2006. Ribozyme-mediated perlecan knockdown impairs chondrogenic differentiation of C3H10T1/2 fibroblasts. *Differentiation* **74**, 53-63.

Gornall AG, Bardwill CJ, David MM. 1949. Determination of serum proteins by means of the biuret reaction. *The Journal of Biological Chemistry* **177**, 751-766.

Gosset M, Berenbaum F, Thirion S, Jacques C. 2008. Primary culture and phenotyping of murine chondrocytes. *Nature Protocols* **3**, 1253-1260.

- Gouttenoire J, Bougault C, Aubert-Foucher E, Perrier E, Ronziere MC, Sandell L, Lundgren-Akerlund E, Mallein-Gerin F. 2010. BMP-2 and TGF-beta1 differentially control expression of type II procollagen and alpha 10 and alpha 11 integrins in mouse chondrocytes. *European Journal of Cell Biology* **89**, 307-314.
- Gouttenoire J, Valcourt U, Ronziere MC, Aubert-Foucher E, Mallein-Gerin F, Herbage D. 2004. Modulation of collagen synthesis in normal and osteoarthritic cartilage. *Biorheology* **41**, 535-542.
- Grobe K, Inatani M, Pallerla SR, Castagnola J, Yamaguchi Y, Esko JD. 2005. Cerebral hypoplasia and craniofacial defects in mice lacking heparan sulfate Ndst1 gene function. *Development* **132**, 3777-3786.
- Im HJ, Muddasani P, Natarajan V, Schmid TM, Block JA, Davis F, van Wijnen AJ, Loeser RF. 2007. Basic fibroblast growth factor stimulates matrix metalloproteinase-13 via the molecular cross-talk between the mitogen-activated protein kinases and protein kinase Cdelta pathways in human adult articular chondrocytes. *The Journal of Biological Chemistry* **282**, 11110-11121.
- Irie A, Habuchi H, Kimata K, Sanai Y. 2003. Heparan sulfate is required for bone morphogenetic protein-7 signaling. *Biochemical and Biophysical Research Communications* **308**, 858-865.
- Kino-Oka M, Maeda Y, Sato Y, Maruyama N, Takezawa Y, Khoshfetrat AB, Sugawara K, Taya M. 2009. Morphological evaluation of chondrogenic potency in passaged cell populations. *Journal of Bioscience and Bioengineering* **107**, 544-551.
- Knox SM, Whitelock JM. 2006. Perlecan: how does one molecule do so many things? *Cellular and Molecular Life Sciences* **63**, 2435-2445.
- Koziel L, Kunath M, Kelly OG, Vortkamp A. 2004. Ext1-dependent heparan sulfate

regulates the range of Ihh signaling during endochondral ossification.
Developmental Cell **6**, 801-813.

Manon-Jensen T, Itoh Y, Couchman JR. 2010. Proteoglycans in health and disease: the
multiple roles of syndecan shedding. *FEBS Journal* **19**, 3876-3889.

Matsumoto Y, Matsumoto K, Irie F, Fukushi J, Stallcup WB, Yamaguchi Y. 2010.
Conditional ablation of the heparan sulfate-synthesizing enzyme Ext1 leads to
dysregulation of bone morphogenic protein signaling and severe skeletal defects.
The Journal of Biological Chemistry **285**, 19227-19234.

Melrose J, Hayes AJ, Whitelock JM, Little CB. 2008. Perlecan, the "jack of all trades"
proteoglycan of cartilaginous weight-bearing connective tissues. *BioEssays* **30**,
457-469.

Melrose J, Roughley P, Knox S, Smith S, Lord M, Whitelock J. 2006. The structure, location,
and function of perlecan, a prominent pericellular proteoglycan of fetal, postnatal,
and mature hyaline cartilages. *The Journal of Biological Chemistry* **281**,
36905-36914.

Minina E, Wenzel HM, Kreschel C, Karp S, Gaffield W, McMahon AP, Vortkamp A. 2001.
BMP and Ihh/PTHrP signaling interact to coordinate chondrocyte proliferation and
differentiation. *Development*. **128**, 4523-4534.

Moore EE, Bendele AM, Thompson DL, Littau A, Waggle, KS, Reardon B, Ellsworth JL.
2005. Fibroblast growth factor-18 stimulates chondrogenesis and cartilage repair in
a rat model of injury-induced osteoarthritis. *Osteoarthritis Cartilage* **13**, 623-631.

Nadanaka S, Kitagawa H. 2008. Heparan sulphate biosynthesis and disease. *Journal of*
Biochemistry **144**, 7-14.

Nakamura R, Nakamura F, Fukunaga S. 2014. Contrasting effect of perlecan on adipogenic

and osteogenic differentiation of mesenchymal stem cells *in vitro*. *Animal Science Journal* **85**, 262–270.

Otsuki S, Hanson SR, Miyaki S, Grogan SP, Kinoshita M, Asahar, H, Wong CH, Lotz MK. 2010. Extracellular sulfatases support cartilage homeostasis by regulating BMP and FGF signaling pathways. *Proceedings of the National Academy of Sciences of the United States of America* **107**, 10202-10207.

Pap T, Bertrand J. 2013. Syndecans in cartilage breakdown and synovial inflammation. *Nature Reviews Rheumatology* **9**, 43-55.

Santiago B, Izquierdo E, Rueda P, Del Rey MJ, Criado G, Usategui A, Arenzana-Seisdedos F, Pablos JL. 2012. CXCL12gamma isoform is expressed on endothelial and dendritic cells in rheumatoid arthritis synovium and regulates T cell activation. *Arthritis & Rheumatology* **64**, 409-417.

Shimo T, Gentili C, Iwamoto M, Wu C, Koyama E, Pacifici M. 2004. Indian hedgehog and syndecans-3 coregulate chondrocyte proliferation and function during chick limb skeletogenesis. *Developmental Dynamics* **229**, 607-617.

Spierings EL, Fidelholtz J, Wolfram G, Smith MD, Brown MT, West CR. 2013. A phase III placebo- and oxycodone-controlled study of tanezumab in adults with osteoarthritis pain of the hip or knee. *Pain* **154**, 1603-1612.

Tesche F, Miosge N. 2004. Perlecan in late stages of osteoarthritis of the human knee joint. *Osteoarthritis and Cartilage* **12**, 852-862.

Tesche F, Miosge N. 2005. New aspects of the pathogenesis of osteoarthritis: the role of fibroblast-like chondrocytes in late stages of the disease. *Histology and Histopathology* **20**, 329-337.

Whitelock JM, Melrose J, Iozzo RV. 2008. Diverse cell signaling events modulated by

1 perlecan. *Journal of Biochemistry* **144**, 7-14

2 Yang W, Gomes RR, Brown AJ, Burdett AR, Alicknavitch M, Farach-Carson MC, Carson DD.

3 2006. Chondrogenic differentiation on perlecan domain I, collagen II, and bone

4 morphogenetic protein-2-based matrices. *Tissue Engineering* **12**, 2009-2024.

5 Yuasa T, Otani T, Koike T, Iwamoto M, Enomoto-Iwamoto M. 2008. Wnt/beta-catenin

6 signaling stimulates matrix catabolic genes and activity in articular chondrocytes:

7 its possible role in joint degeneration. *Laboratory Investigation* **88**, 264-274.

8

Figure 1 Heparitinase treatment prevents chondrocyte dedifferentiation. Rat primary chondrocytes seeded at a density of 0.3×10^4 cells/cm² were cultured in the presence or absence of 1 mU/mL heparitinase I for 2 days and stained with toluidine blue. Representative images of control (a) and heparitinase-treated (b) cells. Bars, 50 μ m. Frequency of round-shaped cells (c). Data represent means $\pm$ SD (n = 3). *, $P < 0.05$.

Figure 2 Heparin treatment prevents chondrocyte dedifferentiation. Rat primary chondrocytes seeded at a density of 0.3×10^4 cells/cm² were cultured in the presence or absence of 100 μ g/mL heparin for 2 days and stained with toluidine blue. Representative images of control (a) and heparin-treated (b) cells. Bars, 50 μ m. Frequency of round-shaped cells (c). Data represent means $\pm$ SD (n = 3). *, $P < 0.05$.

Figure 3 Heparitinase treatment increases GAG accumulation in chondrocytes. Rat primary chondrocytes seeded at a density of 1.5×10^5 cells/cm² were cultured in the presence or absence of 1 mU/mL heparitinase I for 4 days. Representative phase contrast microscopy images of control (a, c) and heparitinase-treated (b, d) cells. Bars, 50 μ m. GAG accumulation in the cell/ECM layers was assessed using the carbazole reaction method (e). Data represent means $\pm$ SD (n = 3). *, $P < 0.05$.

Figure 4 Heparin treatment increases GAG accumulation in chondrocytes. Rat primary chondrocytes seeded at a density of 1.5×10^5 cells/cm² were

cultured in the presence or absence of 100 $\mu\text{g/mL}$ heparin for 4 days. Representative phase contrast microscopy images of control (a, c) and heparin-treated (b, d) cells. Bars, 50 μm . GAG accumulation in the cell/ECM layers was assessed using the carbazole reaction method (e). Data represent means $\pm$ SD (n = 3). *, $P < 0.05$. The accumulation of high molecular weight PG in the cell/ECM layers of control (lane 1), and heparin-treated (lane 2) cells was examined by SDS-PAGE (f). High molecular weight PG stained with Alcian blue are indicated by an arrow.

Figure 5 Perlecan mRNA expression increases in dedifferentiated NHAC. NHAC were cultured independently (lane 1) or co-cultured with rat primary chondrocytes (lane 2) for 14 days, and the mRNA levels of collagen type II (*COL2A1*), type IX (*COL9A2*), type XI (*COL11A1*), type I (*COL1A1*), and perlecan (*HSPG2*) were examined by RT-PCR. *GAPDH* expression was used as an internal control.

Figure 6 Distribution of perlecan in dedifferentiated and differentiated chondrocytes. Rat primary chondrocytes seeded at a density of 1.2×10^4 cells/ cm^2 (low density; a, c, e, g) and 1.5×10^5 cells/ cm^2 (high density; b, d, f, h) were cultured for 4 days. GAG was stained with Alcian blue (a, b). Collagen type II (c, d), collagen type I (e, f), and perlecan (g, h) were stained with specific antibodies. Bars, 50 μm .

Figure 7 The effect of perlecan inhibition on dedifferentiating chondrocytes

morphology. Rat primary chondrocytes seeded at a density of 0.3×10^4 cells/cm² on 96-well plates were cultured with PIS or anti-Pln and stained with toluidine blue. Representative images of PIS-treated (a) and anti-Pln-treated (b) cells. Bars, 50 μ m. Frequency of round-shaped cells (c). Data in c represent means $\pm$ SD (n = 3).

Figure 8 The effect of perlecan inhibition on GAG accumulation in differentiating chondrocytes. Rat primary chondrocytes seeded at a density of 1.5×10^5 cells/cm² were cultured for 4 days, and perlecan was blocked in the last 2 days. Representative phase contrast microscopy images of cells cultured with PIS (a) and anti-Pln (b). Bars, 50 μ m. GAG accumulation in the cell/ECM layers was assessed using the carbazole reaction method (c). Data represent means $\pm$ SD (n = 3).

Figure 9 Perlecan inhibition increased expression of cartilaginous ECM by chondrocytes. Rat primary chondrocytes seeded at a density of 1.5×10^5 cells/cm² were cultured for 6 days, and perlecan was blocked in the final 4 days of culture. Representative phase contrast microscopy images of cells treated with PIS (a) or cultured under conditions of perlecan function inhibition (b); arrows indicate flattened cells. Bars, 50 μ m. The expression of cartilaginous ECM components in cells treated with PIS (lane 1) or cultured under conditions of perlecan function inhibition (lane 2) was examined by SDS-PAGE and western blotting (c, d). Levels of collagen type I (Col I) and type II (Col II) in the media between 5 and 6 days of culture (c), and in the

1 cell/ECM layers (d) were examined by western blotting. GAG accumulation
2 in the cell/ECM layers was examined by staining SDS-PAGE gels with Alcian
3 blue (AB) (d). An arrow indicates high molecular weight PG stained with
4 Alcian blue.

Fig1

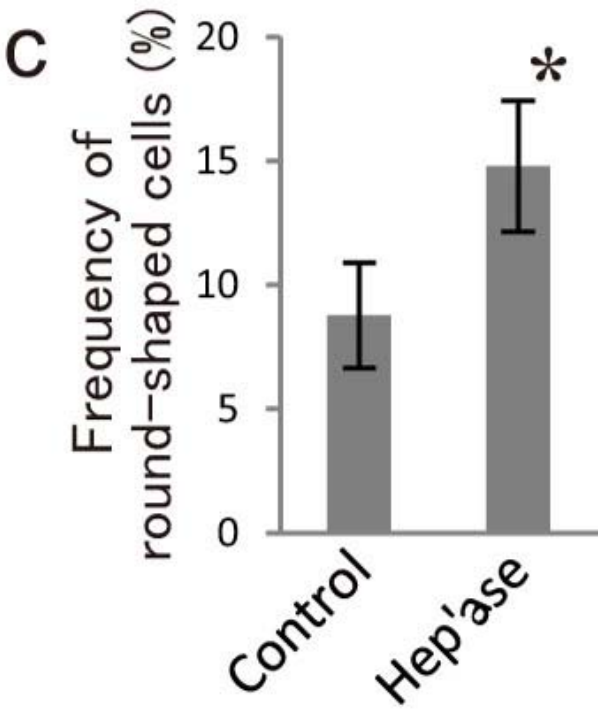
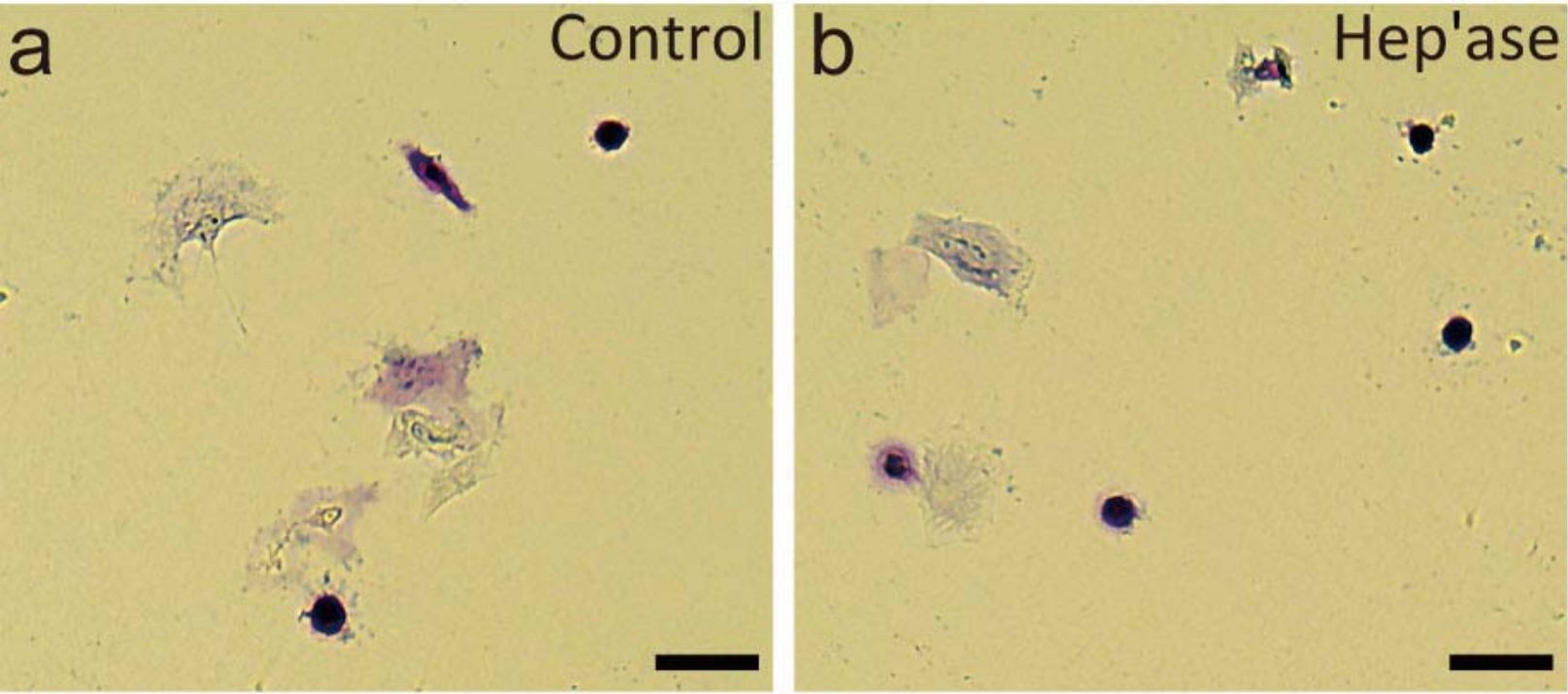


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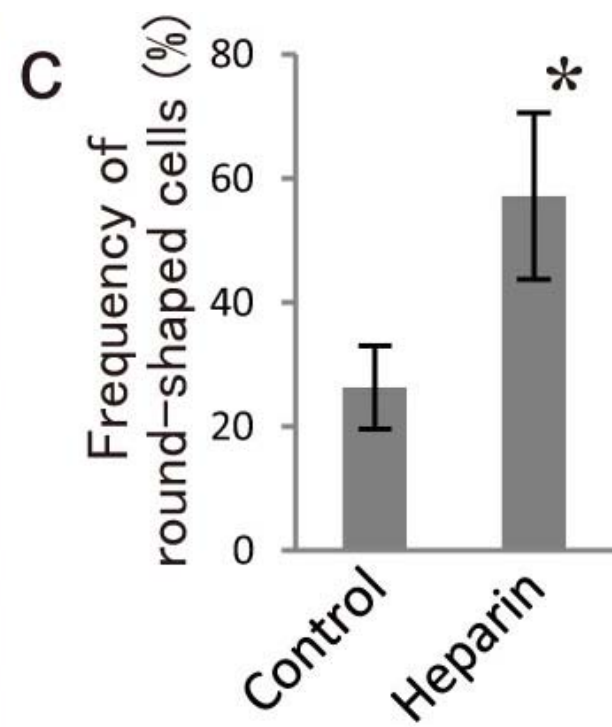
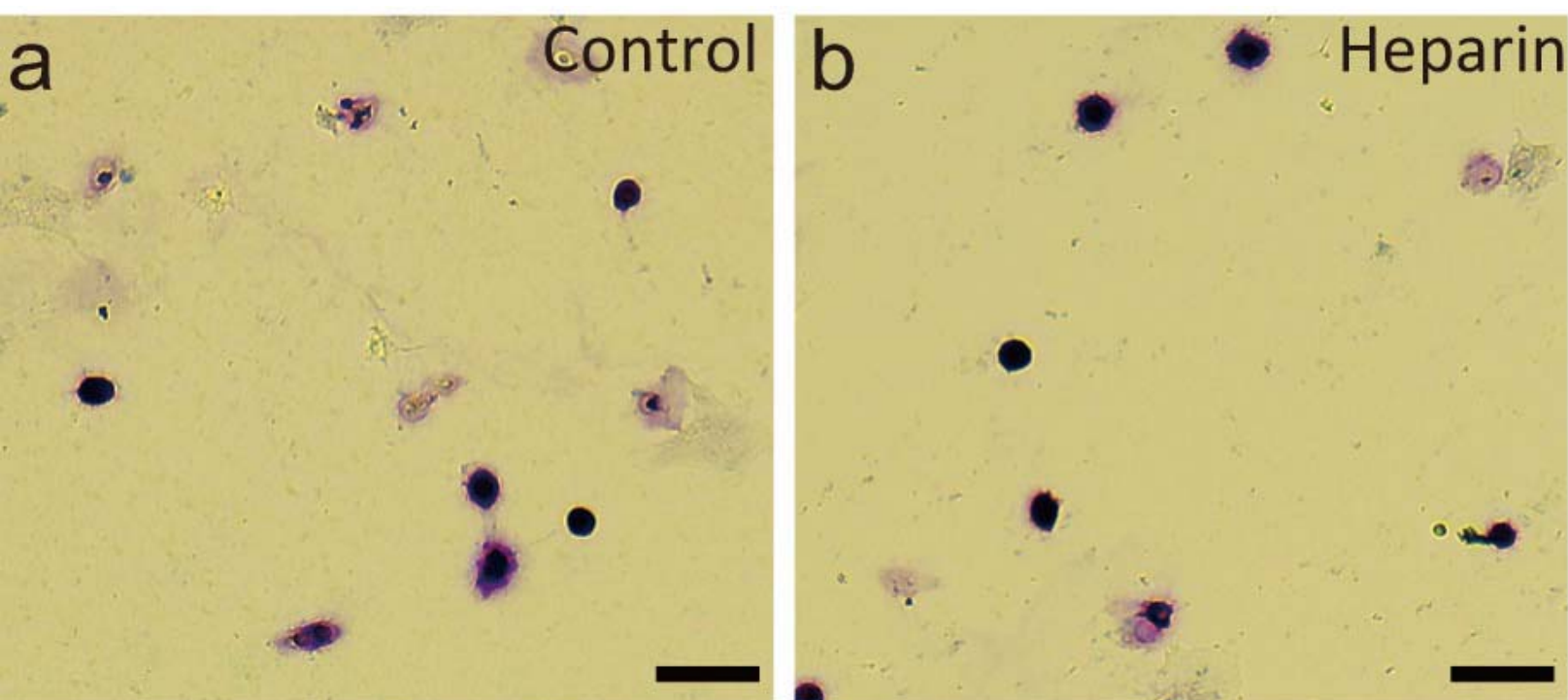


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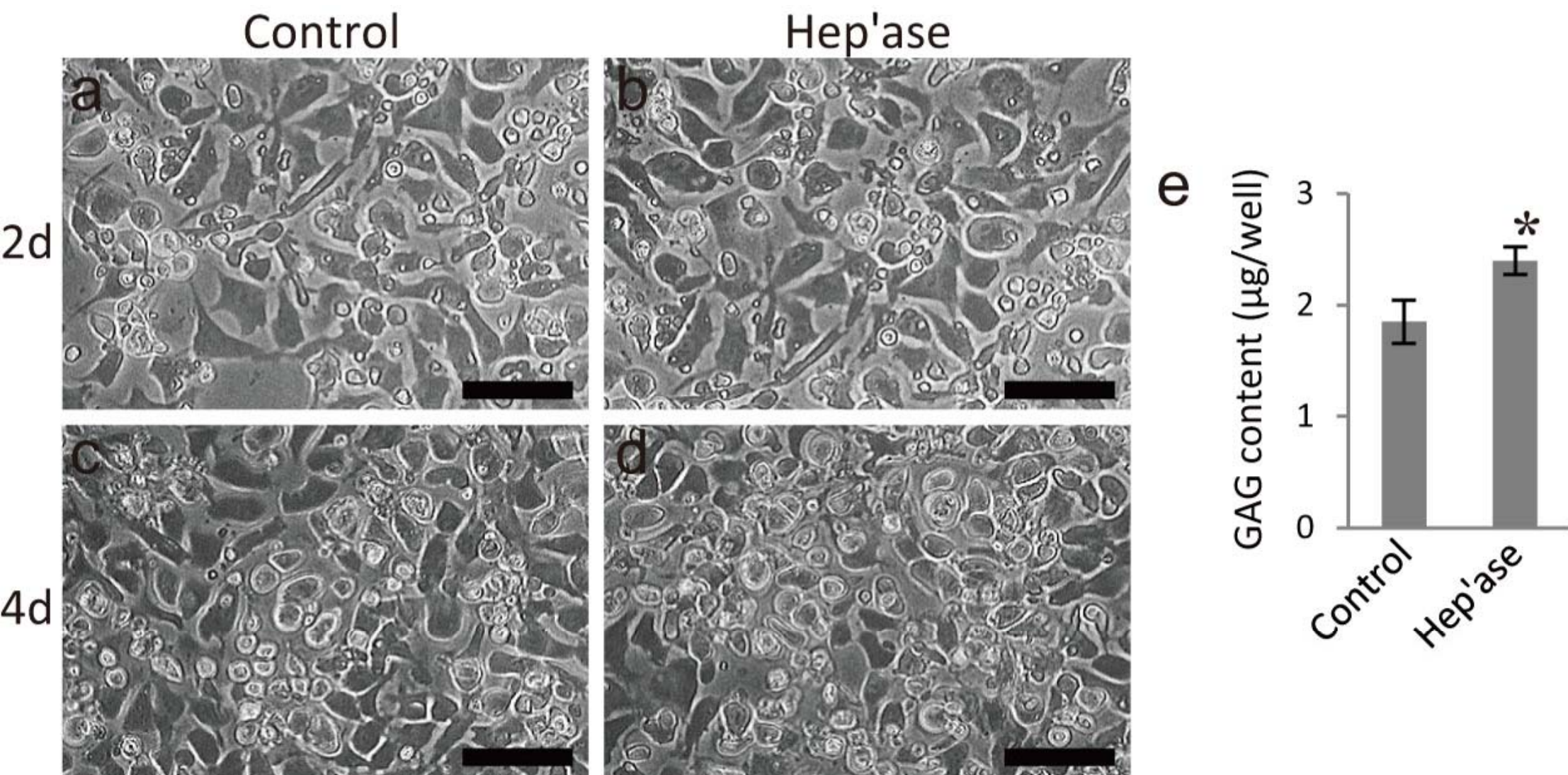


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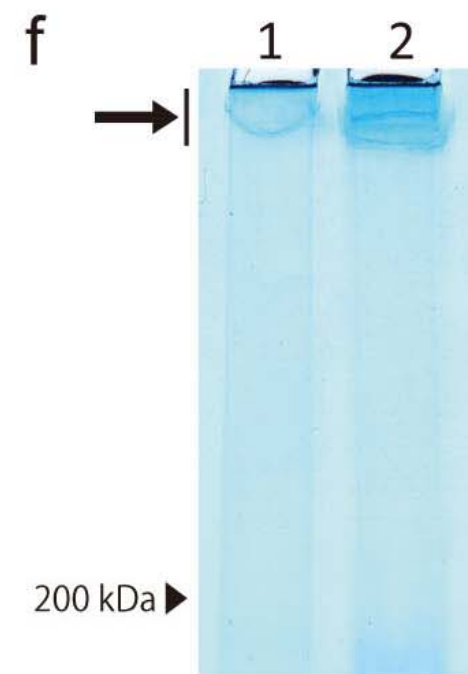
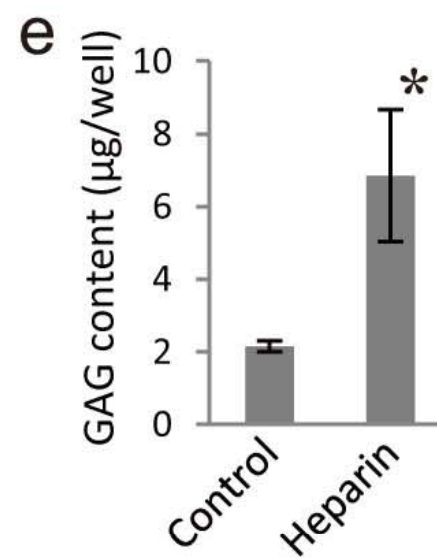
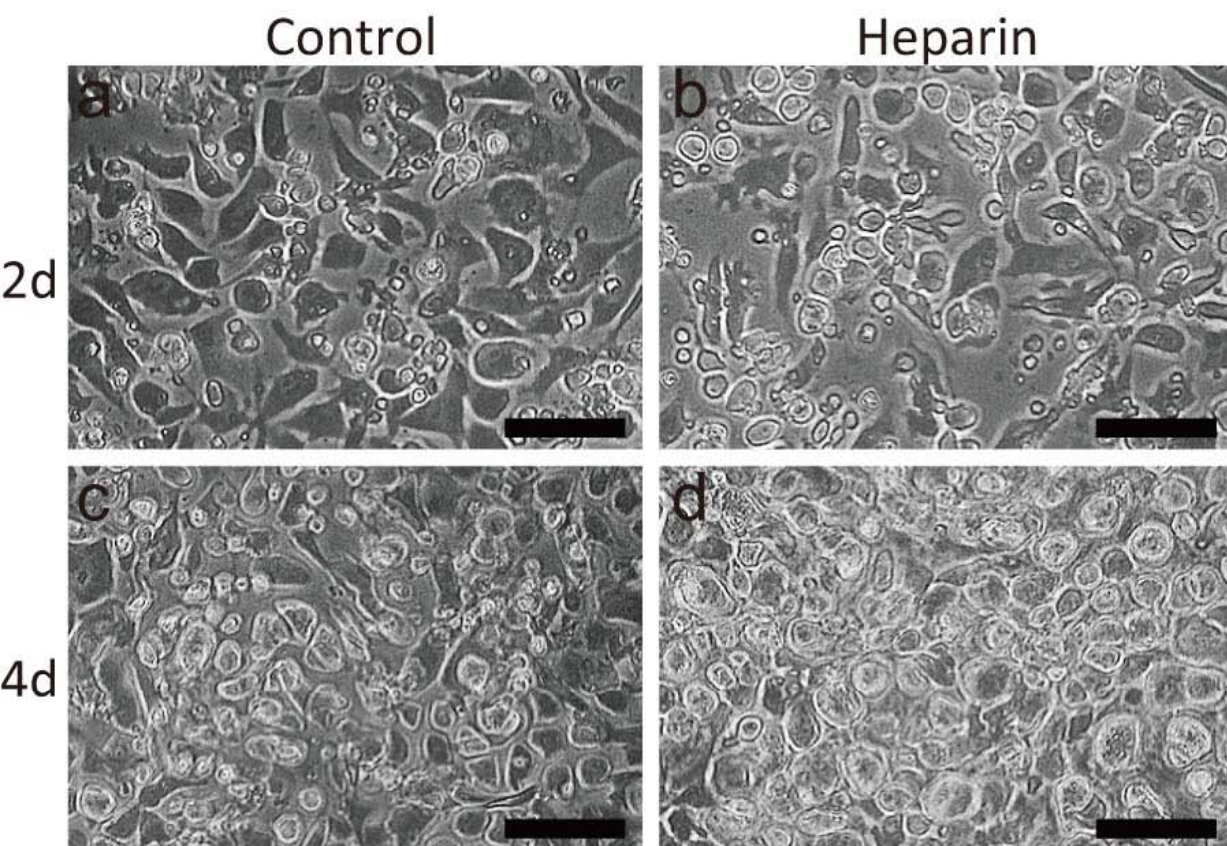
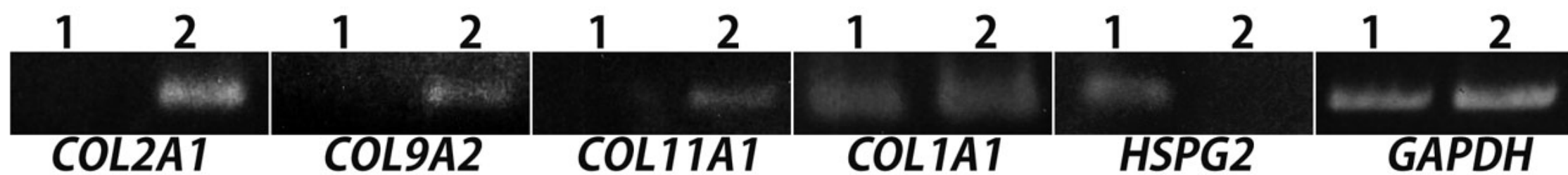


Fig5



Low density

High density

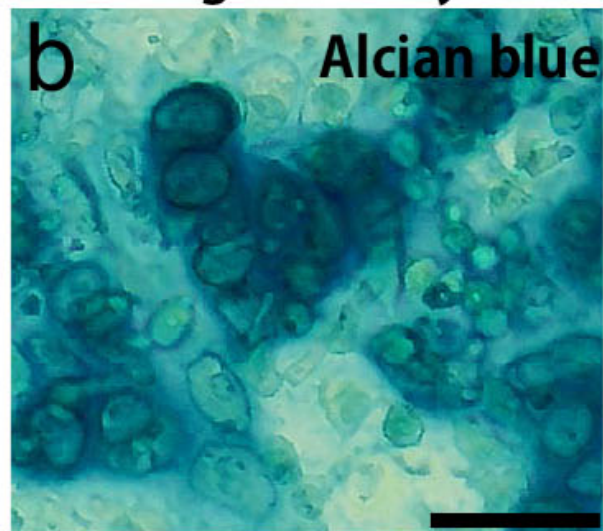
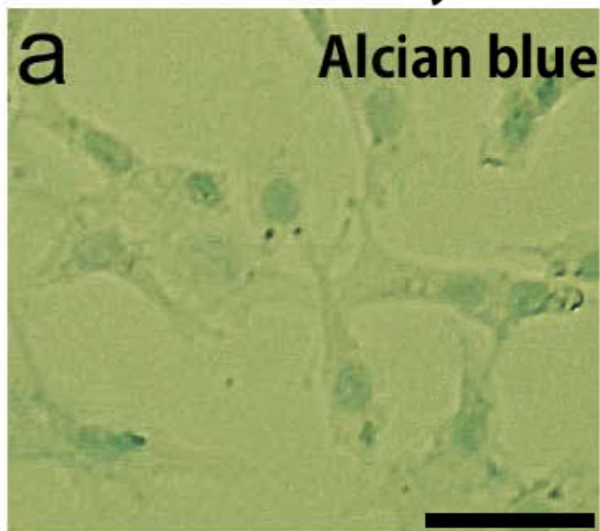


Fig6

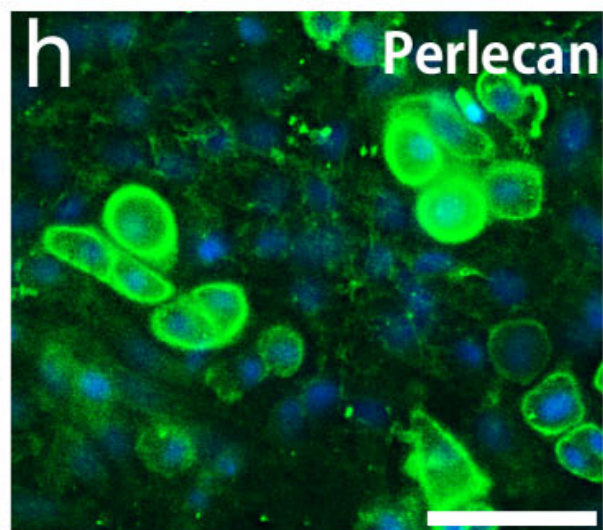
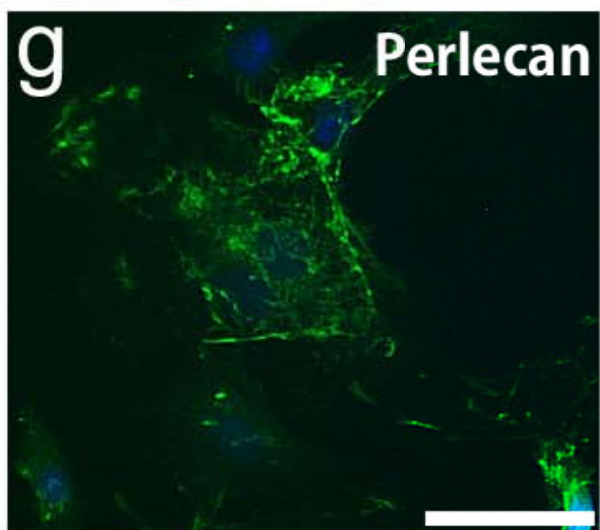
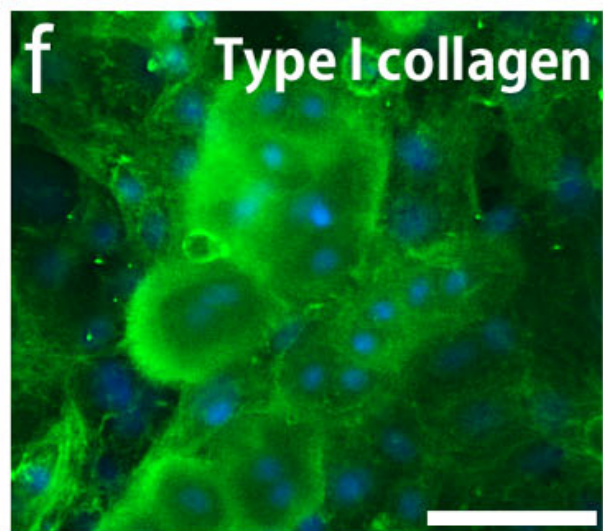
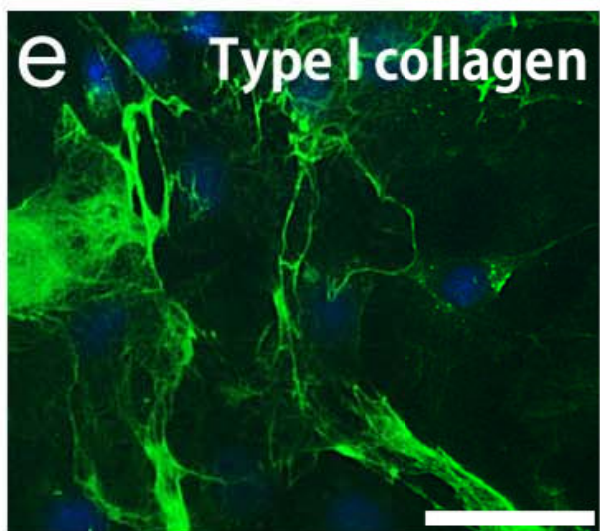
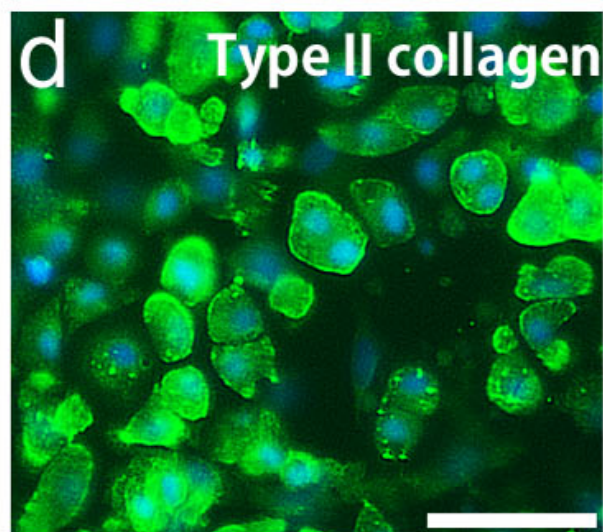
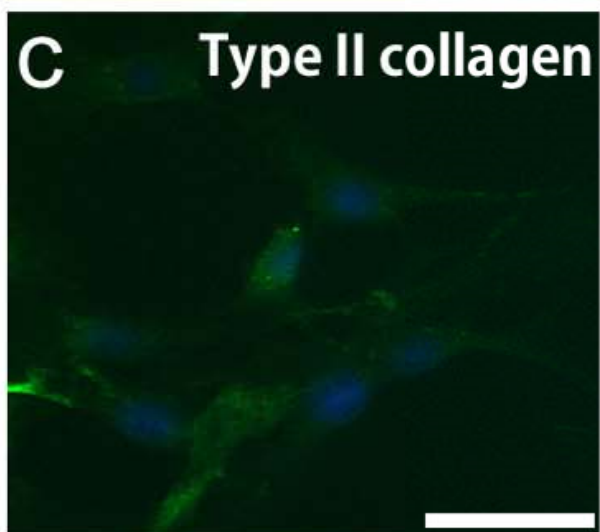


Fig7

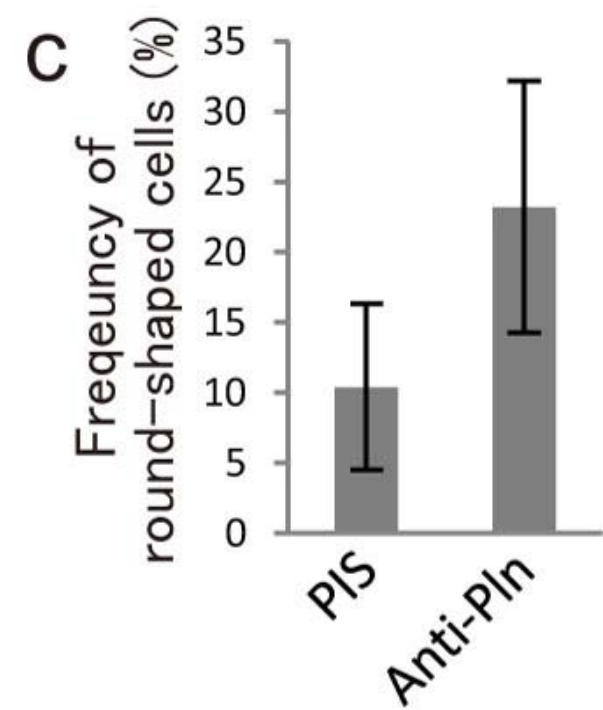
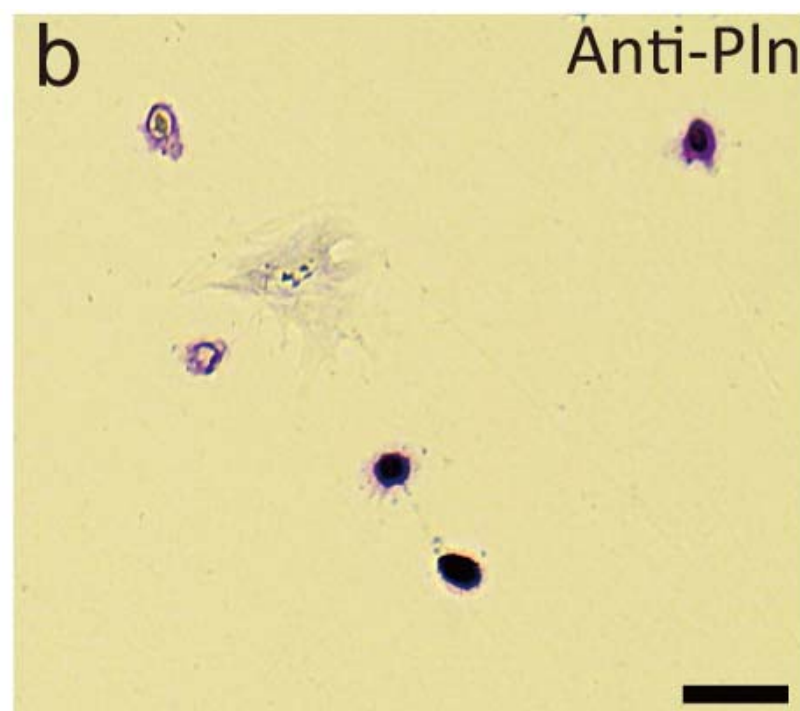
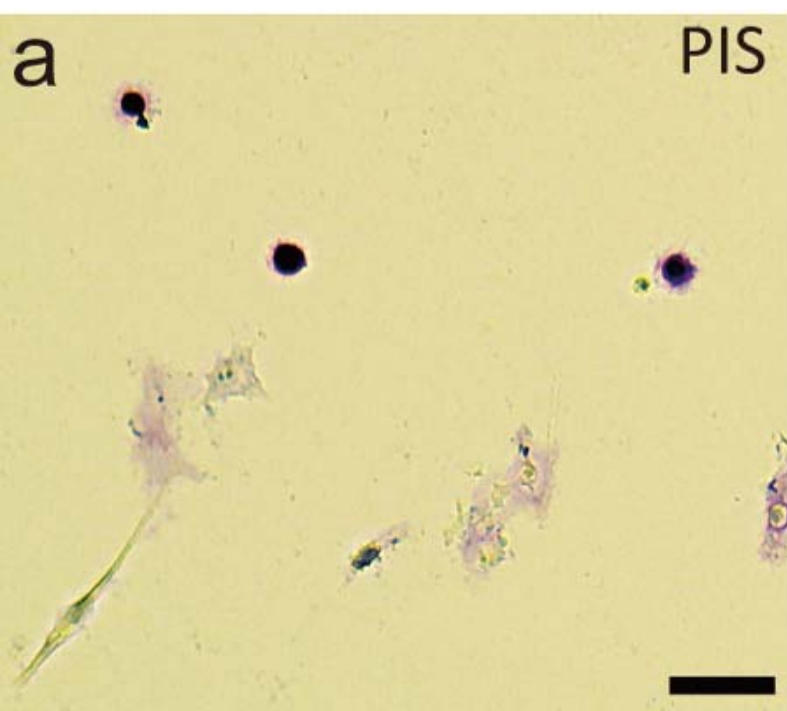


Fig8

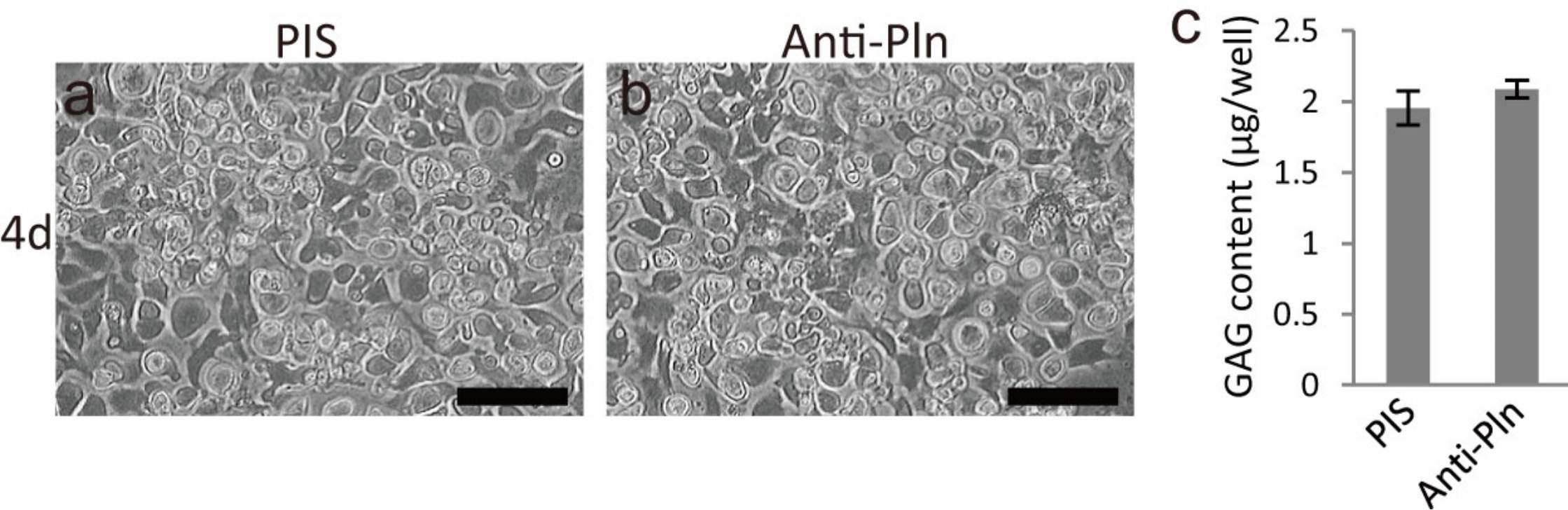


Fig9

