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**Title:** Human adipose-derived mesenchymal stem cells in a spheroid improve recovery in a mouse model of elastase-induced emphysema

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1 **Human adipose-derived mesenchymal stem cell spheroids improve recovery in a mouse**  
2 **model of elastase-induced emphysema**

3

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19 Conflicts of Interest: none

1 **ABSTRACT**

2 *Background/Purpose:* Emphysema, a pathologic component of chronic obstructive  
3 pulmonary disease, causes irreversible destruction. Many researchers have reported that  
4 mesenchymal stem cells can regenerate lung tissue after emphysema.

5 *Methods:* We evaluated if spheroid human adipose-derived mesenchymal stem cells (ASCs)  
6 showed greater regenerative effects than dissociated ASCs in elastase-induced emphysema  
7 mice. ASCs were administered via an intrapleural route.

8 *Results:* Mice injected with spheroid ASCs showed improved regeneration of lung tissue,  
9 increased expression of growth factors such as FGF2 and HGF, and a reduction in proteases  
10 with an induction of protease inhibitors when compared with mice injected with dissociated  
11 ASCs.

12 *Conclusions:* Our findings indicate that spheroid ASCs show better regeneration of lung  
13 tissue than dissociated ACSs in elastase-induced emphysema mice.

14  
15 **KEY WORDS:** Chronic obstructive pulmonary disease, adipose-derived mesenchymal stem  
16 cells, spheroid cultures, regeneration

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## 1 1. INTRODUCTION

2 Chronic obstructive pulmonary disease is the fourth leading cause of death worldwide and  
3 includes cases of chronic bronchitis and emphysema. Emphysema is characterized by alveoli  
4 damaged by external factors, such as smoking [1]. Matrix metalloproteases (MMPs) are  
5 extracellular matrix (ECM)-associated enzymes involved in the synthesis and degradation of  
6 connective tissue components for tissue remodeling and repair [2]. A recent study determined  
7 that secreted MMPs (MMP-2, 9, and 12) contributed to the development of emphysema by  
8 degrading the alveolar wall matrix [3]. In emphysema, regeneration of the alveolar wall is  
9 impaired; however, a mesenchymal stem cell (MSC) therapy for this condition is currently  
10 under development. MSCs that have been isolated from various organs, such as bone marrow,  
11 adipose tissue, and umbilical cord blood, can induce tissue repair via self-renewal,  
12 differentiation, and paracrine effects [4]. The recovery effects of MSCs have been confirmed  
13 in various lung disease models, including lipopolysaccharide (LPS)-, cigarette smoke-, and  
14 bleomycin-induced lung injury models [5-7].

15 We previously tracked adipose-derived mesenchymal stem cells (ASCs) that were  
16 injected *in vivo* via an intravenous route. Labeled ASCs were detected for up to 24 h post-  
17 injection [8]. Moreover, only 17% of cardiac sphere-derived stem cells survived up to 1 h  
18 after injection, and therapies using dissociated stem cells showed complications, including  
19 cell loss, in a myocardial infarction model [9, 10].

20 A spheroid is a self-assembled group of cells, and many studies have emphasized the  
21 differences between 2D and 3D culture environments, such as nutrient and oxygen gradients,  
22 cell-to-cell interactions, and matrix deposition [11, 12]. A recent study showed that spheroids  
23 increase anti-apoptotic and anti-inflammatory properties both *in vitro* and *in vivo* [13]. We  
24 intrapleurally injected in this report aggregated “spheroid” ASCs in a mouse model of  
25 elastase-induced emphysema to compare their therapeutic efficacy with that of dissociated

1 ASCs.

2

## 3 **2. MATERIALS AND METHODS**

### 4 **2.1 Mice**

5 Pathogen-free female C57BL/6 mice at 6 weeks of age with a body weight of 20 g  
6 (Seongnam, Korea) were used. All animals were cared for according to the guidelines of the  
7 Institutional Animal Care and Use Committee of Asan Medical Center (Seoul, Korea).

8

### 9 **2.2 ASC culture**

10 Human ASCs were purchased from Invitrogen (Carlsbad, CA, USA). ASCs were cultured in  
11 MesenPRO RSTM supplemented with Growth Supplement (Invitrogen) and 1% penicillin at  
12 37°C in a 5% CO<sub>2</sub> incubator. ASCs at passage 5 were used for all experiments.

13

### 14 **2.3 Spheroid formation**

15 Spheroids were formed using polydimethylsiloxane (PDMS)-based concave micro-well  
16 molds. Concave micro-wells with a diameter of 300 μm were coated in 70% (v/v) ethanol,  
17 followed by PBS and 3% (W/V) BSA to prevent cell attachment. Each concave micro-well  
18 contained 64 holes, and suspended ASCs were seeded at a density of  $1 \times 10^5$  per well. After  
19 several minutes, the remaining cells were removed using ASC culture media. Concave micro-  
20 wells seeded with ASCs were incubated at 37°C in a 5% CO<sub>2</sub> incubator for 24 h.

21

### 22 **2.4 An elastase-induced mouse model of emphysema and ASC transplantation**

23 C57BL/6 mice were anesthetized intraperitoneally (i.p.) with 16 μL of Zoletil 50 (Virbac  
24 Laboratories, Carros, France) and 4 μL of Rompun (Bayer Korea, Ansan, Korea). Next, mice  
25 were intratracheally (i.t.) administered porcine pancreatic elastase (0.4 U, 8 U/mL; Sigma–

1 Aldrich, St. Louis, MO, USA) at day 0. After 7 days, mice were intrapleurally injected with  
2 dissociated or spheroid ASCs ( $1 \times 10^5$  cells) using a syringe equipped with a 26 gauge needle.

3

#### 4 **2.5 Gene expression analysis by quantitative polymerase chain reaction (qPCR)**

5 Total RNA from lung tissues and ASCs was extracted using an RNeasy Mini Kit (Qiagen,  
6 Düsseldorf, Germany) and synthesized into cDNA using a cDNA synthesis kit (Thermo  
7 Fisher Scientific, Waltham, MA, USA). qPCR analyses were performed with a real-time  
8 LightCycler 480 with SYBR Green I master mix (Roche Diagnostics) and primers. The list of  
9 primers used is shown in Supplementary Table 1.

10

#### 11 **2.6 Detection of MMP activity assay using zymography**

12 To detect MMP activity in the mouse lung, tissues were homogenized in radio  
13 immunoprecipitation assay buffer (RIPA; Cell Signaling Technology, Danvers, MA, USA)  
14 without a protease inhibitor and quantified using a BCA kit (Thermo Scientific). Samples  
15 containing 10  $\mu$ g of protein were subjected to 10% SDS-PAGE using a gelatin-based gel  
16 (Sigma–Aldrich). To develop the zymogram, the gels were incubated in 1 $\times$  zymogram  
17 development buffer (Bio-Rad) at 37°C for 12 h. Next, gels were stained with 0.5%  
18 Coomassie blue R-250 (Bio-Rad) in 30% ethanol and 10% acetic acid for 1 h. Destaining was  
19 performed with 30% ethanol and 10% acetic acid.

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#### 21 **2.7 Enzyme-linked immunosorbent assay (ELISA)**

22 A total of 10  $\mu$ g of protein from mouse tissue and 30  $\mu$ g of total protein from  $1 \times 10^6$  ASCs  
23 were used for ELISAs (R&D Systems; Minneapolis, MN) according to the manufacturer's  
24 instructions. The measured proteins included human and mouse growth factors (FGF-2, HGF,  
25 and VEGF).

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## **2.8 Western blotting**

Lysates of tissues and cells were homogenized in RIPA buffer and quantified using the BCA assay. Thirty microgram samples were separated by SDS-PAGE using a 10–15% gel and then transferred to a PVDF membrane. Primary antibodies against BAX, Bcl-2, FGF2, VEGF, MMP-2, and MMP-9 (Cell Signaling Technology, Danvers, MA) and their corresponding secondary antibodies were incubated with the membrane overnight at 4°C and for 1 h at room temperature, respectively. Membranes were scanned with LAS software using film to detect the protein signals.

## **2.9 Histology and quantification of emphysema**

The histology of the lungs was completed using a previously described method [8]. Briefly, the perfused lungs were inflated with 0.5% low-melting agarose, fixed with 4% formalin, and embedded in paraffin. Lung sections with a thickness of 6 µm were stained with H and E. The mean linear intercepts (MLI) were determined from the microscopic images.

## **2.10 Data analysis**

Statistical analyses were performed using the GraphPad Prism ver. 5 (GraphPad software, La Jolla, CA, USA). The data are presented as the mean ± SEM. The Mann–Whitney test was used to compare groups, and statistical significance was set at  $p < 0.05$ .

### 3. RESULTS

#### 3.1 Characterization of dissociated and spheroid ASCs

A monolayer of ASCs cultured for 3 days (Supplementary Fig. 1A) were seeded into PDMS concave micro-wells coated with 3% BSA. Five minutes after seeding, unattached ASCs were removed using ASC-conditioned medium. Cells began to aggregate within 1 h of seeding (Supplementary Fig. 1B). After 24 h, generally homogenous spheroid ASCs were observed (Supplementary Fig. 1C).

To characterize the dissociated and spheroid ASCs, we measured the expression of cell survival-related apoptosis proteins and growth factors in protein samples extracted from ASCs. Bcl-2 inhibits interactions between mitochondria and BAX in the cytosol. The Western blot images suggested that BAX expression was similar in spheroid and dissociated ASCs, whereas Bcl-2 expression was increased in spheroid ASCs (Fig. 1A). ImageJ was used to quantify protein levels. We determined that BAX expression was significantly decreased and BCL2 expression was significantly increased in spheroid ASCs when compared with dissociated ASCs. Furthermore, the Bcl-2/BAX ratio was significantly increased in spheroid ASCs (Fig. 1B). FGF-2 and VEGF levels were also significantly increased in spheroid ASCs (Figs. 1C and D). To measure the levels of secreted growth factors, the culture medium of dissociated and spheroid ASCs was concentrated, and growth factors were measured by ELISA (Fig. 1F). VEGF secretion was increased in spheroid ASCs when compared with dissociated ASCs. FGF2 was not detected in the media from either group.

#### 3.2 Spheroid ASCs improved lung recovery in an elastase-induced mouse model of emphysema

Emphysema was induced by elastase in C57BL/6 mice (day 0). After 7 days, mice were intrapleurally injected with  $1 \times 10^5$  dissociated or spheroid ASCs. On day 14, mice were

1 euthanized (Fig. 2A), and lung tissues were collected. The H and E-stained lungs of the  
2 elastase-treated group showed severe alveolar destruction (Fig. 2C) when compared with the  
3 control group (Fig. 2B). The mice treated with the two types of ASCs showed recovery from  
4 the alveolar damage (Figs. 2 D and E). We used the mean linear intercept (MLI) method to  
5 quantify this recovery. The MLI was reduced in the dissociated ASC-infused group (97.9  $\mu\text{m}$ )  
6 and spheroid ASC-infused group (78.2  $\mu\text{m}$ ) when compared with the elastase only group  
7 (109.6  $\mu\text{m}$ ). The MLI of the spheroid ASC-infused group showed a stronger reduction than  
8 the dissociated ASC-infused group. These findings suggest that the recovery between the  
9 dissociated and spheroid ASC groups differed (Fig. 2F).

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### 11 **3.3 Effects of injected ASCs on the lungs of mice with elastase-induced emphysema**

12 The harvested lung tissues from mice with or without elastase-induced emphysema were  
13 analyzed by ELISA and Western blotting (data not shown) to identify changes in host cells  
14 after the transplantation of dissociated or spheroid ASCs. The protein levels of mouse FGF-2,  
15 HGF, and VEGF were quantified using ELISA. Mouse FGF-2 was significantly increased in  
16 the spheroid ASC-injected group when compared with the dissociated ASC-injected group  
17 (Fig. 3A). Mouse HGF and VEGF levels were not significantly different between dissociated  
18 and spheroid ASC-injected groups (Figs. 3B and C). The growth factor levels in the three  
19 treatment groups were not significantly different from the control (-) group.

20

### 21 **3.4 Effects of injected ASCs on the regulation of MMP production**

22 To observe the effects of ASCs on tissue regeneration, the mRNA transcript levels of MMP-2,  
23 -9, and -12 in lung tissue were measured by qPCR. MMP-2 mRNA expression tended to be  
24 lower in the injected ASC group when compared with the negative control group. MMP-12  
25 expression was significantly lower in the spheroid ASC-injected group when compared with

1 the dissociated ASC-injected group (Fig. 4A). Protein expression levels were evaluated by  
2 Western blotting (Fig. 4B) and zymography (Fig. 4C). MMP-9 expression at the mRNA and  
3 protein level was similar between the dissociated and spheroid ASC-injected groups. Both  
4 groups also showed reduced MMP-2 expression and activity. Additionally, the spheroid ASC-  
5 injected group showed a greater reduction in MMP-2 activity when compared with the  
6 dissociated ASC injected group. To extend these findings, we tested the expression levels of  
7 tissue inhibitor of metalloproteinase-1 (TIMP-1) and secretory leukocyte protease inhibitor  
8 (SLPI), which both inhibit MMPs (Fig. 4D). Surprisingly, the injection of either dissociated  
9 or spheroid ASCs significantly increased the mRNA transcript levels of TIMP-1, which  
10 encodes a protease inhibitor. The transplantation of spheroid ASCs resulted in a greater  
11 increase in TIMP-1 and SLPI expression when compared with dissociated ASCs.

12

#### 13 **4. DISCUSSION**

14 In the current study, we examined if spheroid ASCs showed improved therapeutic efficacy in  
15 a mouse elastase-induced model of emphysema. Classically, MSCs have been cultured as a  
16 two-dimensional (2D) monolayer using coated culture plates. However, 2D cultures are  
17 disadvantaged by the fact that MSCs lose their stemness properties (e.g., replication potential  
18 and differentiation capacity) when grown in this manner; notably, this phenomenon does not  
19 occur in humans or mice *in vivo* [14]. To overcome this problem, many researchers have tried  
20 to adopt three-dimensional (3D) spheroid cultures. The effect of spheroid formation on  
21 cellular differentiation and cell-cell interactions has been studied. The formation of a spheroid  
22 prevented apoptosis, and thus facilitated differentiation, because of the conservation of cell-  
23 cell interactions that were important for survival and colony formation [15, 16].

24 Here we compared the expression of apoptotic and growth factors between  
25 dissociated and spheroid ASCs. A previous report showed that spheroid ASCs decreased

1 BAX protein expression when compared with dissociated ASCs [17]. Our Western blot  
2 results showed no significant difference in BAX protein levels and increased Bcl-2 protein  
3 expression in spheroid ASCs when compared with dissociated ASCs. The correlation of BAX  
4 and Bcl-2 expression was not determined.

5 Growth factors perform an important role in tissue regeneration. FGF-2 is a basic  
6 fibroblast growth factor involved in multiple biological activities, including angiogenesis,  
7 migration, proliferation, and anti-apoptosis [18-20]. VEGF is involved in vascular regulation  
8 in angiogenesis, cell-cell and cell-matrix interactions, and the proliferation of endothelial  
9 cells in injured lung tissue. VEGF was reported as a crucial regulatory factor in the  
10 aggravation or recovery of emphysema [21-23]. We observed an increase in FGF-2 and  
11 VEGF in cells and tissues without a release of FGF2 in the culture medium.

12 In various animal models, the major advantage of spheroid MSCs is their higher  
13 level of stemness and anti-inflammatory properties and exertion of stronger therapeutic  
14 effects, such as increased growth factor secretion in the recipient and greater differentiation  
15 capacity [13, 16, 17, 24]. We did not assess stemness in our current study; however, the  
16 effects of injected spheroid ASCs were confirmed by the increased growth factor expression  
17 in the host tissue when compared with dissociated ASCs.

18 The use of spheroid ASCs in our current study significantly attenuated emphysema  
19 in a mouse elastase-induced model when compared with dissociated ASCs at a similar dose  
20 of  $1 \times 10^5$  cells. To characterize this therapeutic mechanism, we measured growth factor and  
21 MMP expression in mouse lung tissue lysates.

22 The expression of each growth factor was significantly enhanced and the expression  
23 of MMPs (-2 and -12) was diminished when compared with the dissociated ASC-injected  
24 group. In contrast, the expression and activity of the protease inhibitors TIMP-1 and SLPI  
25 were significantly enhanced in spheroid ASC-injected mice. Previous studies revealed that

1 exogenous growth factors, i.e., EGF, VEGF, and HGF as an angiogenic factor, enhanced the  
2 expression of MMPs *in vitro* and *in vivo* via cell migration and proliferation and ECM  
3 remodeling [25-27]. The MMPs (-2, -9, and -12) assayed in our current analyses are proteases  
4 with major roles in emphysema. These MMPs are secreted by various cells, including  
5 epithelial cells, neutrophils, eosinophils, and alveolar macrophages, and they can degrade  
6 matrix components in normal and abnormal states [28]. MMP-12 helps macrophages to  
7 invade tissues and thus contributes to the degradation of the alveolar wall. In a recent report,  
8 the pathogenesis of emphysema was blocked at an early stage by ablating the MMP-12 gene  
9 or inhibiting MMP-9 and MMP-12 in a smoke-induced emphysema animal model [29-31].  
10 TIMP-1 inhibits the activity of most MMPs, including MMP-12, but not the membrane-type  
11 MMPs (-14, -15, -16, -17), whereas SLPI inhibits the activity of elastase [32]. Some reports  
12 have shown that proteins secreted by MSCs can protect tissues by inhibiting the activity of  
13 endogenous and exogenous MMPs and proteases via the ERK1/2 pathway and other proteins,  
14 such as erythropoietin, TIPMs, and VEGF *in vitro* [2, 33, 34].

15 Our current findings suggest that dissociated or spheroid ASCs injected in a mouse  
16 elastase-induced model of emphysema inhibit MMPs via TIMP-1 and SLPI and induce  
17 regeneration via growth factor production. Moreover, the use of spheroid cells resulted in an  
18 improved therapeutic efficacy *in vivo* when compared with dissociated cells.

19

## 20 5. CONCLUSION

21 Spheroid ASCs enhanced recovery in an elastase-induced mouse model of emphysema by  
22 increasing growth factor production and anti-proteases when compared with dissociated  
23 ASCs at the same dose. Thus, spheroid ASCs have potential as a future treatment of  
24 emphysema.

25

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3 expertise.

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## 10 Figure legends

11 **Fig. 1.** The expression of apoptotic markers and growth factors. (A) Western blotting images  
12 and (B) protein band quantification for BAX and Bcl-2. (C) Western blotting images and (D)  
13 protein band quantification for FGF-2 and VEGF. (E) FGF-2 and VEGF production was  
14 measured in conditioned media.

16 **Fig. 2.** Improved recovery efficacy of ASCs in an elastase-induced mouse model of  
17 emphysema. (A) Experimental protocol. (B–E) Lung histology with H and E staining: (B)  
18 control (n = 5); (C) elastase only (n = 12); (D) elastase+dissociated ASCs (n = 10); and (E)  
19 spheroid ASCs (n = 11) (10×). (F) Mean linear intercept (mean ± SEM). Scale bar = 0.5 mm.  
20 \*p < 0.05 and \*\*\*p < 0.001 for comparisons between 2 groups.

22 **Fig. 3.** Growth factor production in lungs with emphysema: (A) FGF-2, (B) HGF, and (C)  
23 VEGF. \*p < 0.05 and \*\*p < 0.01 for comparisons between 2 groups.

25 **Fig. 4.** Effects of ASCs on MMPs, TIMP-1 and SLPI expression in lungs with emphysema.  
26 (A) The mRNA levels of MMP-2, MMP-9, and MMP-12 in the lung. (B) and (C)

1 Representative images for western blotting and gelatin zymography. (D) The mRNA  
2 expression of TIMP-1 and SLPI. \* $p < 0.05$ , \*\* $p < 0.01$ , and \*\*\* $p < 0.001$  for comparisons  
3 between 2 groups.

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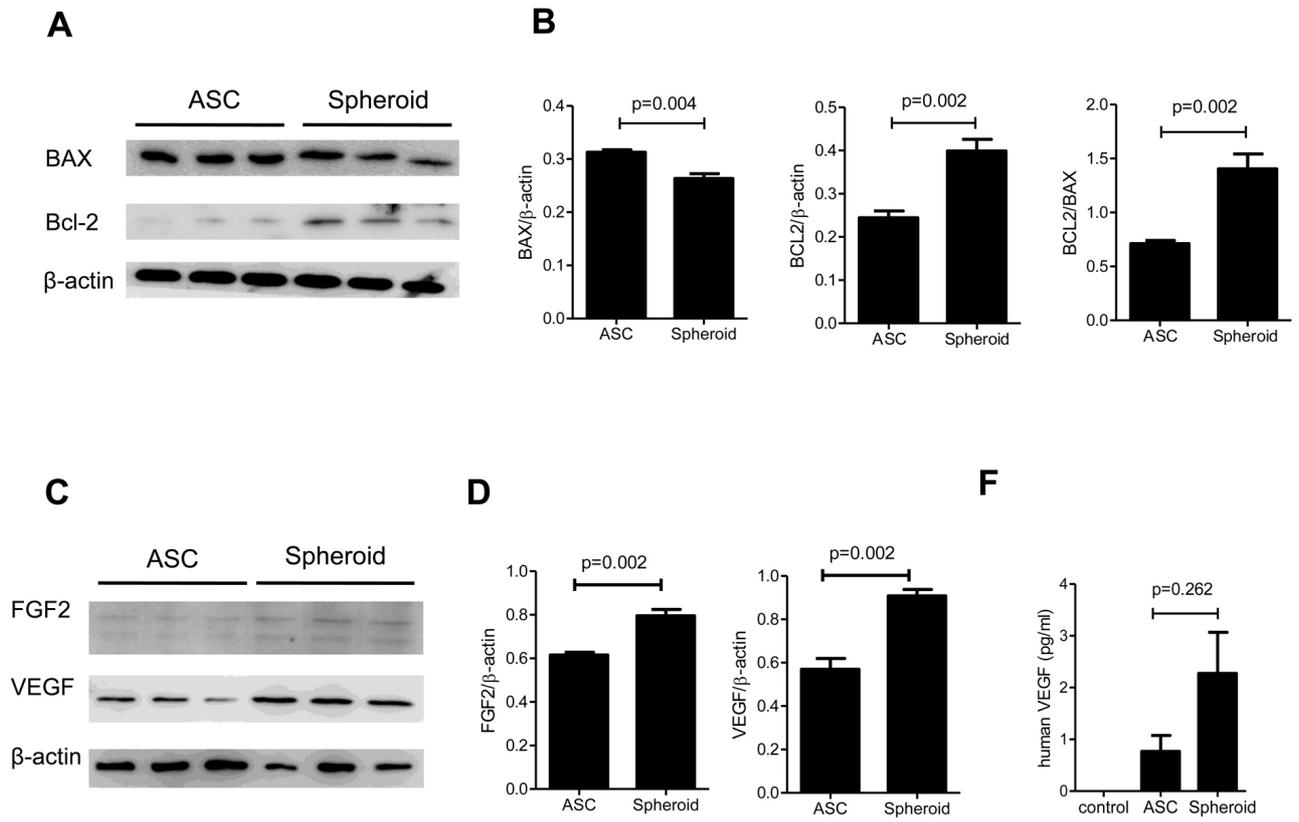


Fig. 1 Figure 1

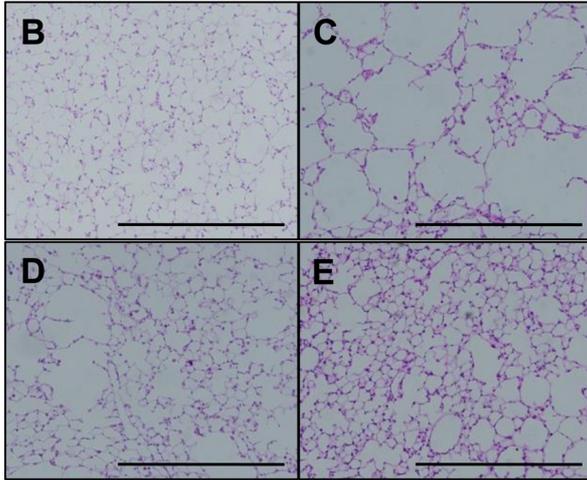
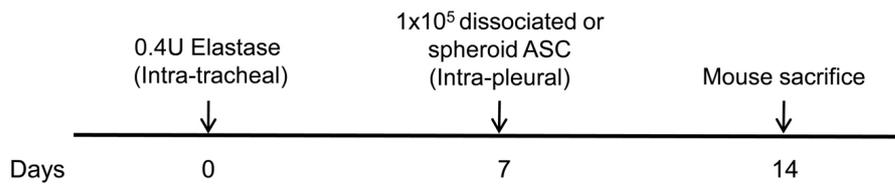
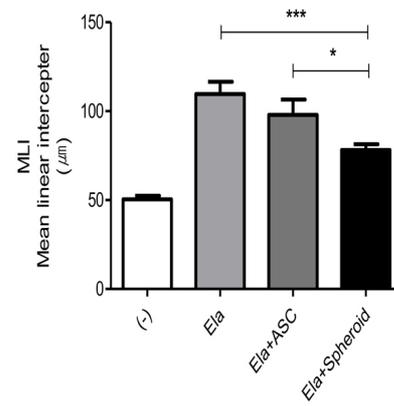
**A****F**

Fig. 2 Figure 2

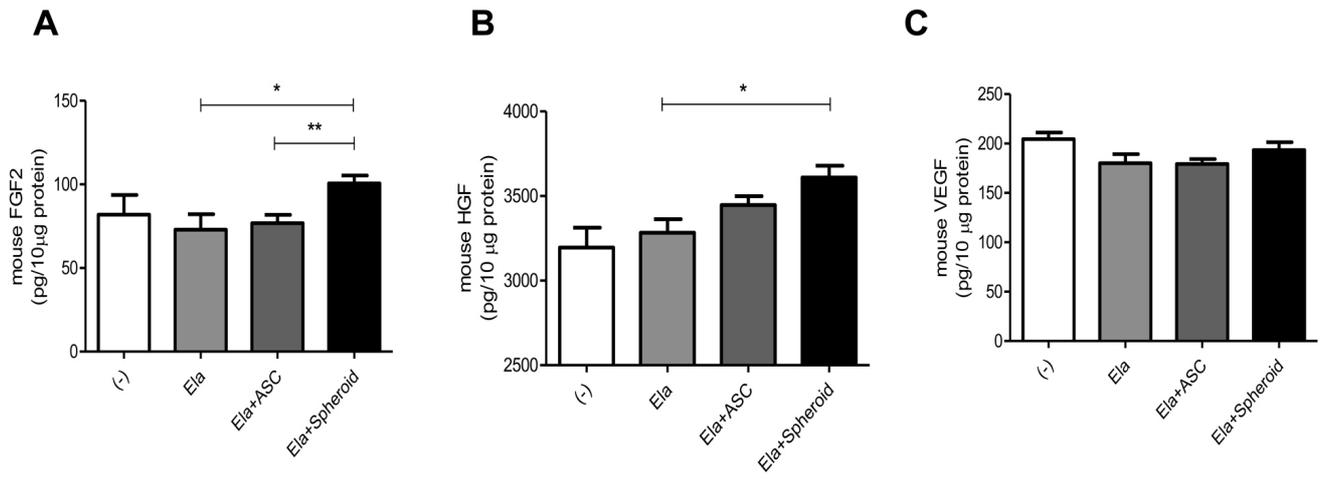


Fig. 3 Figure 3

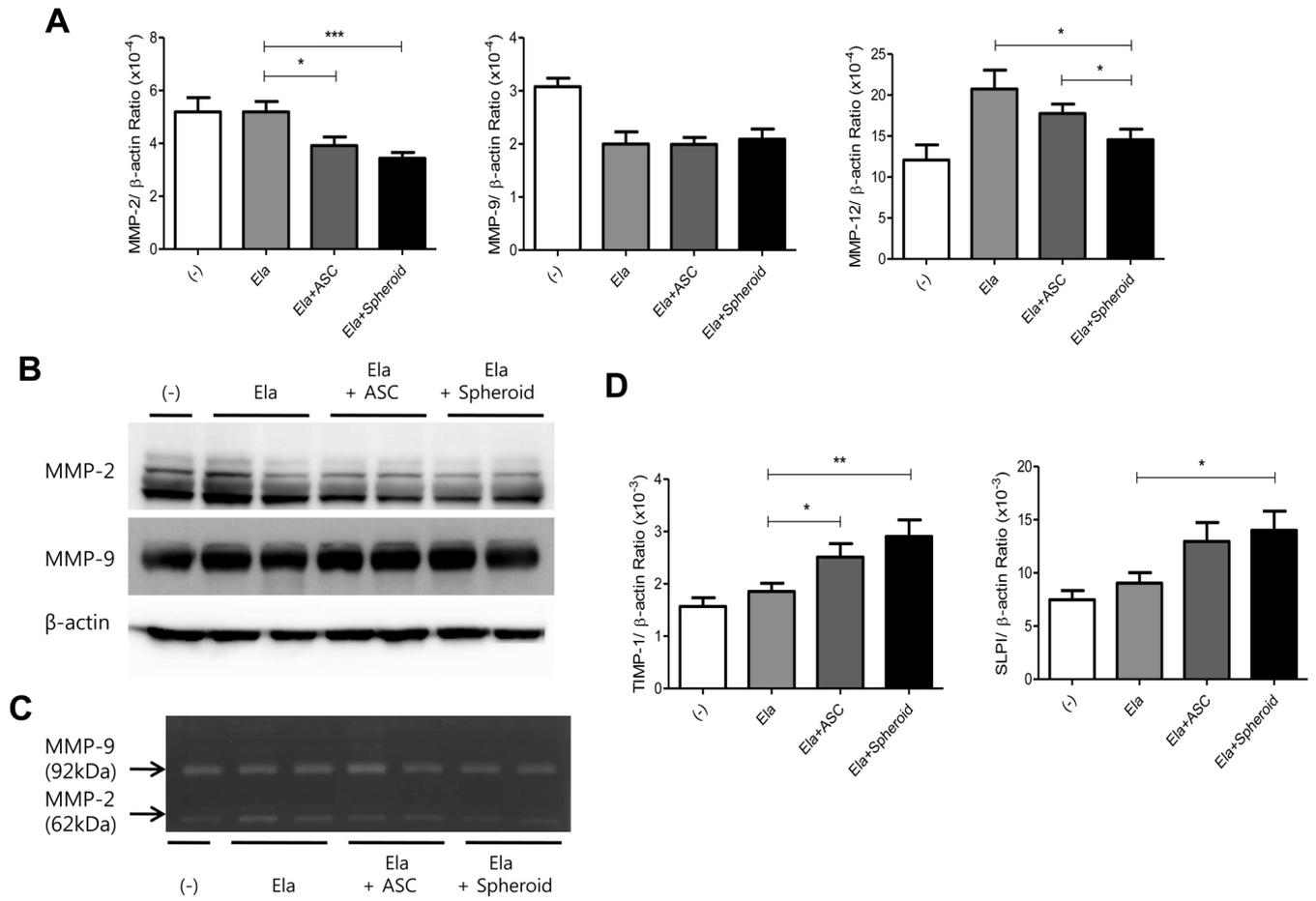
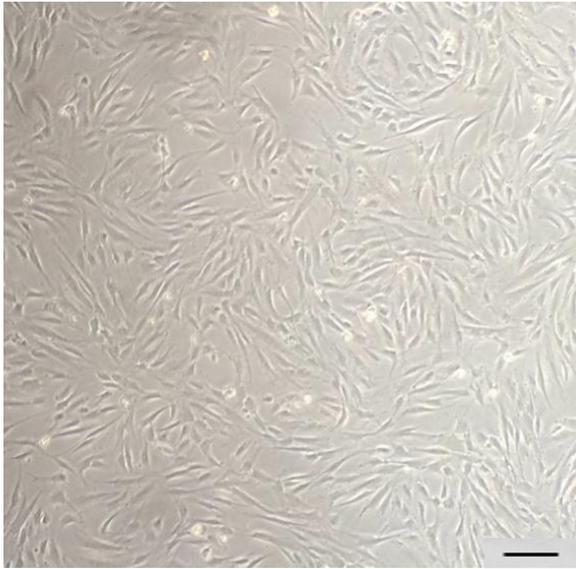


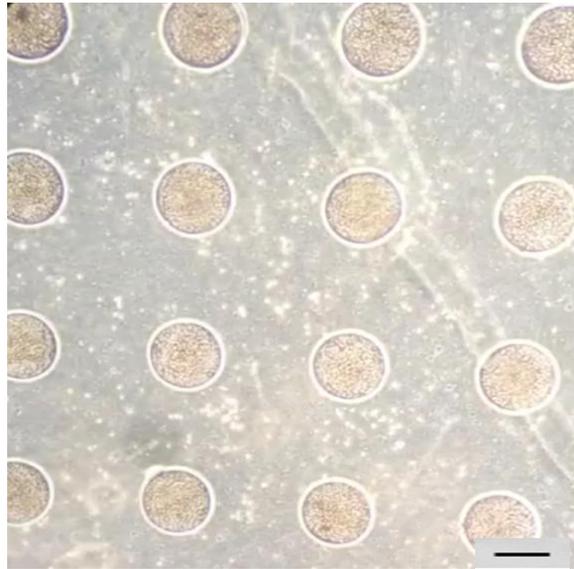
Fig. 4 Figure 4

# Supplementary figure 1

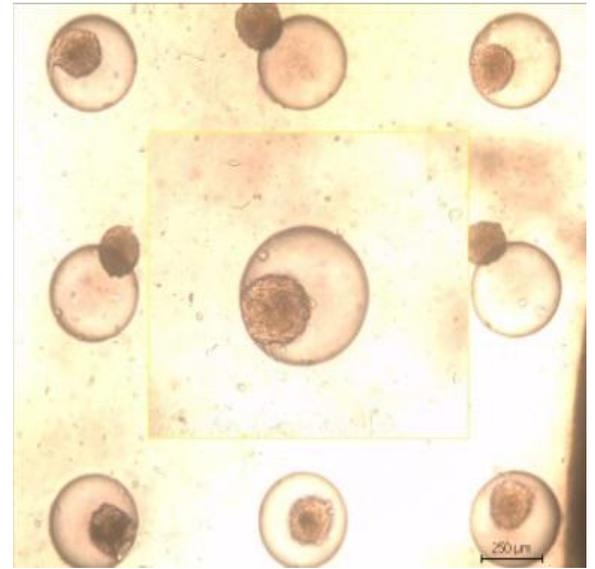
**A**



**B**



**C**



# Supplementary Table 1. Primer list

## Human

Gene	Forward primer	Reverse primer
GAPDH	ACCACAGTCCATGCCATC	TCCACCACCCTGTTGCTG
BAX	TGGCAGCTGACATGTTTTCTGAC	CGTCCCAACCACCCTGGTCT
Bcl-2	AGATGTCCAGCCAGCTGCACCTGAC	AGATAGGCACCAGGGTGAGCAAGCT
FGF2	GGCCACTTCAAGGACCCCAAG	TCAGCTCTTAGCAGACA
HGF	GCTATCGGGGTAAAGACCTA	CGTAGCGTACCTCTGGATTG
VEGF	TCGGGCCTCCGAAACCATGA	CCTGGTGAGAGATCTGGTTC

## Mouse

Gene	Forward primer	Reverse primer
$\beta$ -actin	TGGAATCCTGTGGCATCC	TAAAACGCAGCTCAGTAA
MMP2	ACAAGTGGTCCGCGTAAA	CGGTCATCATCGTAGTTG
MMP9	CTCGCGGCAAGTCTTCAGAG	AGTTGCTTCTAGCCCAAAGAAC
MMP12	TGGTATTCAAGGAGATGC	GGTTTGTGCCTTGAAAAC
TIMP1	GCAACTCGGACCTGGTCATA	CGGCCCGTGATGAGAACT
SLPI	GGCCTTTTACCTTTACGGT	TACGGCATTGTGGCTTCTCA
Fgf2	GCGACCCACACGTCAAAC	TCCCTTGATAGACACAAC
Hgf	AACAGGGGCTTTACGTTTAC	CGTCCCTTTATAGCTGCCTC

**Supplementary Fig. 1.** A formed spheroid of human adipose-derived mesenchymal stem cells (ASCs) by self-assembly (A) A monolayer of adipose-derived mesenchymal stem cells was cultured in T175 plates. (B) and (C) are generation process of spheroid ASCs. After 1h, aggregation of ASCs was observed in PDMS concave micro-wells (B). The spheroid ASCs formed in PDMS concave micro-well after 24h(C). Scale bar= 250  $\mu\text{m}$ .

Supplementary Table 1. Primer list

Human		
Gene	Forward primer	Reverse primer
GAPD	ACCACAGTCCATGCCATC	TCCACCACCCTGTTGCTG
H		
BAX	TGGCAGCTGACATGTTTTCTGAC	CGTCCCAACCACCCTGGTCT
Bcl-2	AGATGTCCAGCCAGCTGCACCTG	AGATAGGCACCAGGGTGAGCAAG
	AC	CT
FGF2	GGCCACTTCAAGGACCCCAAG	TCAGCTCTTAGCAGACA
HGF	GCTATCGGGGTAAAGACCTA	CGTAGCGTACCTCTGGATTG
VEGF	TCGGGCCTCCGAAACCATGA	CCTGGTGAGAGATCTGGTTC
Mouse		
Gene	Forward primer	Reverse primer
$\beta$ -actin	TGGAATCCTGTGGCATCC	TAAAACGCAGCTCAGTAA
MMP2	ACAAGTGGTCCGCGTAAA	CGGTCATCATCGTAGTTG
MMP9	CTCGCGGCAAGTCTTCAGAG	AGTTGCTTCTAGCCCAAAGAAC
MMP1	TGGTATTCAAGGAGATGC	GGTTTGTGCCTTGAAAAC
2		
TIMP1	GCAACTCGGACCTGGTCATA	CGGCCCGTGATGAGAACT
SLPI	GGCCTTTTACCTTTCACGGT	TACGGCATTGTGGCTTCTCA
Fgf2	GCGACCCACACGTCAAAC	TCCCTTGATAGACACAAC
Hgf	AACAGGGGCTTTACGTTTAC	CGTCCCTTTATAGCTGCCTC