Title page

Platelet-derived adenosine 5’-triphosphate suppresses activation of human hepatic stellate cell - in vitro study -

Naoya Ikeda[1], Soichiro Murata[1], Takehito Maruyama[1], Takafumi Tamura[1], Reiji Nozaki[1], Takuya Kawasaki[1], Kiyoshi Fukunaga[1], Tatsuya Oda[1], Ryoko Sasaki[1], Masato Homma[2], and Nobuhiro Ohkohchi[1]

[1] Department of Surgery, Graduate School of Comprehensive Human Sciences, University of Tsukuba, Tsukuba, Japan

[2] Department of Pharmaceutical Sciences, Graduate School of Comprehensive Human Sciences, University of Tsukuba, Tsukuba, Japan

Corresponding author:

Nobuhiro Ohkohchi, M.D., Ph.D.

Department of Surgery, Graduate School of Comprehensive Human Sciences, University of Tsukuba.

1-1-1 Tennodai, Tsukuba, Ibaraki, 305-8575, Japan

Tel: +81-29853-3221 / Fax: +81-29853-3222

E-mail: nokochi3@md.tsukuba.ac.jp

A running title:

Platelets control hepatic stellate cells

ABSTRACT

Aim: Activated hepatic stellate cells (HSC) play a critical role in liver fibrosis. Suppressing abnormal function of HSC or reversion from activated to quiescent form is a hopeful treatment for liver cirrhosis. The interaction between platelets and HSC remains unknown although platelets go through hepatic sinusoids surrounded by HSC. This study aimed at clarifying hypothesis that platelets control activation of HSC.

Methods: We used human platelets, platelet extracts, and primary or immortalized human HSC. We examined the effect of platelets on the activation, DNA synthesis, type I collagen production, and fibrosis-relating gene expressions of HSC. We investigated what suppressed activation of HSC within platelets and examined the mechanism of controlling activation in vitro.

Results: Platelets and platelet extracts suppressed activation of HSC. Platelets decreased type I collagen production without affecting DNA synthesis. Platelets increased the expression of matrix metallopeptidase 1. As platelet extracts co-cultured with an enzyme of degrading adenosine 5'-triphosphate (ATP) suppressed activation, we detected adenine nucleotides within platelets or on their surfaces and confirmed the degradation of adenine nucleotides by HSC and the production of adenosine. Adenosine and platelets increased the intracellular cyclic adenosine 5'-monophosphate (cAMP) which is important in quiescent HSC. Much amount of adenosine and ATP also suppressed activation of HSC.

Conclusion: Activation of human HSC is suppressed by human platelets or platelet-derived ATP via adenosine-cAMP signaling pathway in vitro. Therefore, platelets have the possibility to be used in the treatment of liver cirrhosis.

Key words: adenosine, ATP, cAMP, hepatic stellate cell, and liver fibrosis

INTRODUCTION

Hepatic fibrosis is often observed under chronic liver damage induced by hepatitis viruses, alcohols, or obstructive jaundice.[1] Since severe liver cirrhosis (LC) impairs liver function and can induce hepatocellular carcinoma, the reduction of fibrosis may eradicate them.[2,3] Unfortunately, the clinical solution of established LC nowadays seems to be only liver transplantation.[4]

Hepatic stellate cells (HSC) play a major role in hepatic fibrogenesis.[5] A lot of experimental studies have focused on suppressing abnormal function of HSC, but they are not applied in clinical use.[6-10] The characteristic features of activated HSC are the spindle-like shape, extensive extracellular matrix production, loss of cytoplasmic fat droplets, and active expression of alpha smooth muscle actin (α-SMA).[1,11] The quiescent HSC indicates the opposite reactions, and the elevation of intracellular cyclic adenosine 5'-monophosphate (cAMP) has been reported to be an important factor in the anti-proliferative effect in HSC.[12] A cyclic nucleotide phosphodiesterase inhibitor which increases the cytoplasmic cAMP concentration inhibits the transdifferentiation to the activated form of HSC.[13] These previous reports suggest that the elevation of cAMP should be requisite to quiescent HSC.

Platelets have critical roles in hemostasis, and at the same time also contain many kinds of substances which are not essential for hemostasis.[14] The dense granules within platelets have low molecular materials, such as calcium, serotonin, adenosine 5'-diphosphate (ADP), and adenosine 5'-triphosphate (ATP).[15] They are stored in abundance and are released to close spaces.[15,16] Platelets always go through hepatic

sinusoids and adhere there under certain conditions such as ischemia reperfusion injury or inflammation.[17-19] Moreover, platelets can translocate into Disse's space in mice,[20] or can be directly adjacent to collagen fibrils in hepatitis C virus-induced fibrotic human liver.[21] These reports suggest that platelets and HSC can be located closely in vivo, and that platelets can provide some substances into Disse's space through multiple fenestrae on liver sinusoidal endothelial cell.[22]

In LC patients, platelet counts are lower and ATP contents are less than those of healthy people.[23,24] We have previously reported that thrombocytosis reduces liver fibrosis in rodent models.[25,26] From these reports, we hypothesized that human platelets released their contents into the environment near HSC and suppressed activation of human HSC in normal liver. In this study, we examined the interaction between human HSC and human platelets and investigated their underlying mechanism to apply platelets to treatment for human LC.

Methods

Chemicals or Reagents

ATP and apyrase, which degrades ATP, were purchased from Sigma-Aldrich Co. (St. Louis, MO). Adenosine, Dulbecco's modified Eagle's medium (D-MEM) and phosphate buffered saline (PBS) were purchased from Wako Pure Chemical Industries, Ltd. (Osaka, Japan). Acid citrate dextrose formula A is the anticoagulant product used in this study and was purchased from TERUMO Co. (Tokyo, Japan). Anti-human vascular endothelial growth factor (VEGF) antibody MAB293 was purchased from R&D Systems, Inc. (Minneapolis, MN). Anti-human insulin-like growth factor -1 receptor

(IGF-1R) inhibitor II and platelet-derived growth factor-receptor (PDGF-R) tyrosine kinase inhibitor IV were purchased from Calbiochem, Inc. (San Diego, CA). All chemicals are commercially available.

Cell culture

TWNT-1, which is the immortalized human HSC cell line and is kindly donated from Dr. Kobayashi, Okayama University, and primary human HSC were cultured in D-MEM supplemented with 10% fetal bovine serum.[27] Cell culture chambers (Becton Dickinson Labware, Franklin Lakes, NJ) whose pore sizes are 0.2 μm were used to separate platelets from TWNT-1. Primary human HSCs were obtained from surgical specimens by a two-step collagenase perfusion method, followed by density gradient centrifugation.[28,29] Surgical specimens were collected under written informed consent and approval by the Ethics Committee and the institutional review board of University of Tsukuba hospital. All cultures were maintained at 37°C in a humidified atmosphere containing 5% CO_2.

Platelet preparation

Blood was obtained from healthy volunteers using an anticoagulant after obtaining informed consents, as previously reported.[30] Washed platelets were suspended in PBS and used as platelet group (PLT). To obtain platelet extracts, platelets were disrupted by freezing and thawing for five cycles and centrifuged at 15000 *g*, 4°C for 30 min. The supernatant was used as platelet extracts.

Light microscopy

To examine morphologic changes of TWNT-1 after adding platelets, cultured cells were photographed using light microscopy IX71 (OLYMPUS Corp., Tokyo) and the digital camera DP71 (OLYMPUS Corp.) under the high magnification power (x 200) after washing dishes with PBS and removing apoptotic cells or platelets. We divided cells into two groups according their shapes and counted the number of cells. One group consisted of the spindle shaped cells that have a long axis more than twice that of the short axis. The other consisted of the oval shaped cells that have a long axis less than twice that of the short axis. The spindle one was considered as highly-activated status and the oval one was considered as resting status in this study.[11]

Western blot

Cultured cells were washed with PBS, lysated, subjected to 10% SDS-PAGE, and transferred to a nitrocellulose membrane (Millipore Co., Billerica, MA). Primary antibodies were mouse monoclonal anti-human smooth muscle actin (DAKO Co., Grostrup, Denmark) and rabbit polyclonal anti-G3PDH antibody (TREVIGEN, Inc., Gaithersburg, MD). Secondary antibodies were anti-mouse or anti-rabbit IgG HRP-linked antibody (Cell Signaling Technology, Inc., Danvers, MA). All antibodies were diluted to 1:1000 except for anti-G3PDH (1:5000). Because α-SMA is a well-known marker of HSC activation,[2] we used the anti-human smooth muscle actin antibody. GAPDH was used as the endogenous control.

DNA synthesis assay

The effect of platelets on DNA synthesis was measured using Cell Proliferation ELISA, 5-bromo-2’-deoxyuridine (BrdU) colorimetric kit (Roche Ltd.). TWNT-1 ($5x10^3$ cells)

were plated into each well of 96-well dishes. Platelets were added and cultured for 24 hours. The plate was washed before adding BrdU.

RNA extraction and reverse transcription – polymerase chain reaction (RT-PCR)

RNA extraction was carried out using FastPure RNA Kit (Takara BIO Inc., Otsu, Japan), following the procedure recommended by the manufacturer. The synthesis of complimentary DNA was performed using AMV Reverse Transcriptase (Promega Corp., Madison, WI) and random primer (Takara BIO, Inc.). Briefly, the mixture of 1 mM dNTPs (Fermentas LIFE SCIENCES Corp., Ontario, Canada), 0.025 μg/μl random primer, 0.25 U/μl reverse transcriptase, and 500 ng total RNA were incubated at 30°C for 10 min, 37°C for 60 min, 95°C for 5 min, and 4°C before storage in -80°C.

Quantitative real-time PCR

Primers for real-time PCR were designed by Primer Express Software for Real-Time PCR version 3.0 (Applied Biosystems Corp., Foster, CA) using GenBank sequences. Primers were purchased from Hokkaido System Science Co., Ltd. (Hokkaido, Japan) and listed in Table 1. We examined *ACTA2, COL1A1, MMP-1, TIMP-1, ADORA1, ADORA2A, ADORA2B, ADORA3* and *GAPDH* (encoding alpha 2 helix of α-SMA, pro-alpha 1 chain of type I collagen, matrix metallopeptidase-1, tissue inhibitor of metalloproteinases 1, adenosine A1 receptor, adenosine A2A receptor, adenosine A2B receptor, adenosine A3 receptor, and glyceraldehyde-3-phosphate dehydrogenase, respectively). The real-time PCR was performed using SYBR Green Realtime PCR Master Mix-Plus (TOYOBO Co., Ltd., Osaka, Japan) and Applied Biosystems 7300 Real-time PCR system (Applied Biosystems Corp.), following the procedure

recommended by the manufacturer. *GAPDH* was used as the endogenous control.

Agarose gel-electrophoresis

PCR products were subjected to 1% agarose gel containing 0.005% ethidium bromide (Wako Pure Chemical Industries, Ltd.). After the electrophoresis was performed, the gel was pictured when ultraviolet was radiated using Electronic U.V. Transilluminator, FAS-III (TOYOBO Co., Ltd.).

Assay of type I collagen in the cultured medium of TWNT-1

The amount of type I collagen was measured using anti-human procollagen type I C-peptide ELISA kit (Takara BIO, Inc.). The supernatant of cultured medium was separated, centrifuged at 15000 *g*, 4°C for 30 min to remove the debris, and stored at -80°C until analysis.

Analysis of adenine nucleotide concentration

The concentrations of ATP, ADP, and AMP in platelets were measured by high performance liquid chromatography (HPLC) as previously reported.[31] The HPLC system for adenosine measurement was the GULLIVER HPLC-900 (JASCO Corp., Tokyo, Japan). The column was Wakosil-II 5C18HG (Wako Pure Chemical Industries, Ltd.) and ultraviolet absorbance was measured at 260 nm. The running buffer was 60 mM ammonium phosphate buffer which was adjusted to pH 5.0. In addition, we used Adenosine 5'-triphosphate Bioluminescent Assay kit (Sigma-Aldrich Co.) to assess the ATP concentration on the platelet's surface, referring to the procedure of measuring cellular surface concentration of ATP.[32] Briefly, washed platelets were centrifuged at

1000 *g*, 4°C for 5 min. The pellet was loosened using a large pipette. After the aliquot of 10 μl pellet and the same amount of Assay Mix in the kit were mixed, the chemical luminescence was measured by luminometer, TD 20 / 20 (Promega Corp.). The same volume of ATP solution was used as control.

Measurement of intracellular cAMP

As cAMP is the second messenger of adenosine signaling pathway, we examined cytoplasmic cAMP of TWNT-1.[33] TWNT-1 ($7x10^3$ cells) were plated into each well of 96-well dishes and cultured over night. We added stimulants, incubated them for an hour, and washed the plate with PBS before starting measurements. The intracellular cAMP was investigated using cAMP-Screen Assay kit (Applied Biosystems Corp.), following the procedure recommended by the manufacturer.

Statistical Analysis

Data are expressed as means ± standard deviation. Student *t* test was performed to assess statistical significance. *P* values less than 0.05 were considered statistically significant.

RESULTS

Human platelets suppress the expression of α-SMA

The expression of α-SMA was measured by Western blot analysis at 1, 4, or 7 days after incubating platelets with TWNT-1. While α-SMA expression was increased with or without platelets, platelets reduced their increment (Fig. 1a). We also examined α-SMA expression after adding platelets to cell culture inserts. It was not suppressed (Fig. 1b).

These findings indicate that human platelets suppress activation of TWNT-1, and that platelets can exhibit it more efficiently when being located close to TWNT-1.

Platelets suppress cellular extension of TWNT-1

TWNT-1 co-cultured with platelets were photographed at random on day 1, 4, and 7, and separated into two groups in terms of their shapes. More oval type cells were shown in the PLT group than the control group. The representative pictures are shown on day 4 (Fig. 1c). The ratio of oval type cells in total decreased in a time-dependent manner in both groups. However, the PLT group showed a significant large ratio on day 4 and 7 (Fig. 1d). This result indicates that platelets also have some effects on keeping TWNT-1 quiescent in terms of their shapes.

Platelets do not affect DNA synthesis of TWNT-1

The BrdU uptake was not changed when incubating platelets with TWNT-1 (Fig. 1e).

Platelets decrease the production of type I collagen

The concentration of type I collagen in cultured medium was significantly decreased in the PLT group on day 4 (Fig. 1f).

Platelets have influences on fibrosis-relating gene expressions

Total RNAs were extracted after incubating platelets with TWNT-1 for 24 hours. After performing real-time PCR, each group was compared with the control group. *ACTA2* and *COL1A1* were significantly decreased in the PLT group (Fig. 2a, b, respectively). *MMP-1* and *TIMP-1* were significantly increased in the PLT group (Fig. 2c, d,

respectively). These findings demonstrate that platelets suppress HSC activation and affect the amount of intrahepatic extracellular matrix. Since TWNT-1 express more α-SMA in a time-dependent manner (Fig. 1a), we cultured TWNT-1 for 1, 4, or 7 days to prepare activated TWNT-1, incubated platelets with them for another 24 hours, and extracted total RNAs to investigate changes of *ACTA2* in the activated TWNT-1. On day 2, 5, and 8, all PLT groups suppressed *ACTA2* expression (Fig. 2e). This result means that platelets suppress activation of TWNT-1 which has been activated to some degree.

Platelet extracts suppress *ACTA2* expression more efficiently when incubated with apyrase

To examine what contributes to suppression of *ACTA2* expression, we incubated four kinds of reagents before adding platelet extracts as follows: PDGF-R inhibitor, anti-VEGF antibody, IGF-1R inhibitor, and apyrase which degrades ATP to ADP or AMP. Platelet extracts also suppressed *ACTA2* expression as well as platelets (Fig. 3a). PDGF-R inhibitor, anti-VEGF antibody, and IGF-1R inhibitor had no effect on *ACTA2* expression (Fig. 3b, c, d, respectively). On the other hand, apyrase reduced *ACTA2* expression in a dose-dependent manner (Fig. 3e). This result implies that ATP derivatives made by apyrase have more influence on *ACTA2* expression than ATP in platelet extracts.

Platelets contain and release large amounts of ATP

We studied adenine nucleotide concentrations both in platelets by HPLC and on platelet's surfaces by luciferase-mediated chemical luminescence to explain the effect of

derivatives made by apyrase. Platelets contained ATP, ADP, and AMP (Fig. 4a). The number of chemical luminescent counts at platelet's surfaces without ATP administration was significantly higher than that of 100 μM ATP solution (Fig. 4b). These results demonstrate that platelets contain large amounts of ATP inside or near their surfaces in vitro.

HSC degrades ATP and produces adenosine in vitro

After culturing TWNT-1 or primary HSC with ATP, we studied the total value of ATP, ADP, and AMP in the cultured medium by HPLC. The values of both the TWNT-1 group and the primary HSC group were significantly decreased in 6 and 24 hours after incubation, compared to control which did not contain any cells (Fig. 4c). After culturing TWNT-1 with ATP or adenosine for 24 hours, we investigated adenosine concentrations in the cultured medium by HPLC as well. The adenosine concentrations after incubating with adenosine or ATP for 24 hours were significantly increased comparing to TWNT-1 alone (Fig. 4d). The adenosine concentration in ATP alone was extremely low (figure not shown). These results suggest that TWNT-1 metabolizes adenosine phosphates and produces adenosine in the medium.

Adenosine and platelets increase cytoplasmic cAMP in TWNT-1

As TWNT-1 produced adenosine in vitro (Fig. 4d), we examined expression of adenosine receptors and changes of their intracellular signaling molecule, i.e., cAMP after incubating adenosine or platelets with TWNT-1. We confirmed four types of mRNA of adenosine receptors by agarose gel-electrophoresis (Fig. 4e). The cytoplasmic cAMP was significantly increased when incubating 1000 μM adenosine and platelets

(Fig. 4f). These results suggest that platelets and large amounts of adenosine activate adenosine-cAMP signaling pathway in TWNT-1.

Adenosine and ATP suppress HSC activation

After incubating adenosine with TWNT-1, α-SMA expression was examined by Western blot. It was suppressed after incubating 1 mM adenosine with TWNT-1 during 1, 4, and 7 days (Fig. 5a). The α-SMA expression in primary human HSC was studied as well. It was also suppressed when incubating with 1 mM adenosine, 1 mM ATP, and platelets (Fig. 5b). DNA synthesis was not changed after incubating ATP with TWNT-1 for 24 hours (Fig. 5c). These results indicate that a large amount of ATP or adenosine suppresses HSC activation without affecting DNA synthesis.

DISCUSSION

Activated HSC produces a lot of extracellular matrix and contributes to deteriorate hepatic fibrogenesis.[1,2] Since we have already found that hepatic fibrosis decreases after inducing thrombocytosis in rodents,[25,26] we hypothesized that human platelets would also have an anti-fibrotic effect. In this study, we indicated that human platelets suppress HSC activation and collagen production in human HSC via an adenosine-cAMP signaling pathway in vitro.

It is likely that HSC is physiologically exposed to high concentration of ATP or its derivatives in the microcirculation because ATP is released from red blood cells or intrahepatic cells and hepatocytes are abundant in ATP.[34-36] On the other hand, adenine nucleotides decrease very rapidly in circulating blood through the degradation by

functional enzymes or the uptake from erythrocytes.[37] It seems to be difficult to examine the exact concentration of adenine nucleotides without degradation in vivo. This is the limitation of this study.

The DNA synthesis was not changed after incubating platelets or ATP with TWNT-1. These results may indicate that the volume of ATP or platelets in this study is not sufficient to stimulate HSC proliferation in vitro.

We clearly indicated that HSC produces adenosine by degrading adenine nucleotides. The nucleotide-hydrolysing pathway mainly comprises four enzymes, ecto-nucleotide triphosphate diphosphohydrolase family (E-NTPDase), ecto-nucleotide pyrophosphatase/phosphodiesterase family (E-NPP), ecto-5'-nucleotidase (CD73), and alkaline phosphatase. HSC has been also reported to show these activities,[38-40] which demonstrates that the extracellular ATP may be easily broken down to adenosine by HSC in vivo. Andrade et al. implied that CD73-dependent adenosine generation might regulate the function of quiescent HSC.[40] Hernández-Muñoz R et al. reported that adenosine administration blocks active hepatic fibrogenesis and increases the collagen degradation in rats.[41,42] These reports together with our results imply that adenosine seems to be important in quiescent HSC and anti-fibrotic effects.

The signal from adenosine is transmitted by four types of adenosine receptors; A_1R, $A_{2A}R$, $A_{2B}R$, and A_3R.[33] They are all G protein-coupled receptors whose effectors are adenylyl cyclase (AC) which produces cAMP. We demonstrated the elevation of cAMP in TWNT-1 because it activates cAMP-dependent protein kinase (PKA) and leads to

phosphorylation of cAMP-response element binding protein (CREB) on Ser133.[43] Houglum et al. reported that phosphorylation of CREB on Ser133 might be indispensable for quiescent HSC.[44] From these reports and results of this study, we hypothesize the mechanism of suppressing HSC activation by platelets via adenosine-cAMP signaling pathway in vitro (Fig. 6).

In conclusion, human platelets contribute to suppression of both HSC activation and type I collagen production in vitro. This is mediated by adenosine-cAMP signaling pathway in HSC. We suggest that the effective transport of a high amount of adenine nucleotide into Disse's space should be a key process in the treatment for human LC.

ACKNOWLEDGEMENTS

The authors thank Dr. Kobayashi, Department of Surgery, Okayama University Graduate School of Medicine and Dentistry, for providing the hepatic stellate cell line, TWNT-1. We also thank Chikako Satoh, Department of Surgery, Tohoku University, for technical assistance in HPLC.

REFERENCES

1 Friedman SL. Liver fibrosis – from bench to bedside. *J Hepatol* 2003; **38**(Suppl 1): S38-53.

2 Moreira RK. Hepatic stellate cells and liver fibrosis. *Arch Pathol Lab Med* 2007; **131**: 1728-34.

3 Amann T, Bataille F, Spruss T, et al. Activated hepatic stellate cells promote tumorigenicity of hepatocellular carcinoma. *Cancer Sci* 2009; **100**: 646-53.

4 Clavien PA, Oberkofler CE. Raptis DA, Lehmann K, Rickenbacher A, El-Badry AM. What is critical for liver surgery and partial liver transplantation: size or quality? *Hepatology* 2010; **52**: 715-29.

5 Friedman SL. Mechanism of hepatic fibrogenesis. *Gastroenterology* 2008; **134**: 1655-69.

6 Sakaida I, Teraji S, Yamamoto N, et al. Transplantation of bone marrow cells reduces CCl_4-induced liver fibrosis in mice. *Hepatology* 2004; **40**: 1304-11.

7 Radaeva S, Sun R, Jaruga B, Nguyen VT, Tian Z, Gao B. Natural killer cells ameliorate liver fibrosis by killing activated stellate cells in NKG2D-dependent and tumor necrosis factor-related apoptosis-inducing ligand-dependent manners. *Gastroenterology* 2006; **130**: 435-52.

8 Kim WH, Matsumoto K, Bessho K, Nakamura T. Growth inhibition and apoptosis in liver myofibroblasts promoted by hepatocyte growth factor leads to resolution from liver cirrhosis. *Am J Pathol* 2005; **166**: 1017-28.

9 Gressner AM, Weiskirchen R. Modern pathogenetic concepts of liver fibrosis suggest stellate cells and TGF-β as major players and therapeutic targets. *J Cell Mol Med* 2006; **10**: 76-99.

10 Paik YH, Kim JK, Lee JI, et al. Celecoxib induces hepatic stellate cell apoptosis through inhibition of Akt activation and suppresses hepatic fibrosis in rats. *Gut* 2009; **58**: 1517-27.

11 Sancho-Bru P, Bataller R, Gasull X, Colmenero J, Khurdayan V, Gual A, et al. Genomic and functional characterization of stellate cells isolated from human cirrhotic livers. *J Hepatol* 2005; **43**: 272-82.

12 Mallat A, Préaux AM, Serradeil-Le Gal C, et a l. Growth inhibitory properties of

endothelin-1 activated human hepatic stellate cells: A cyclic adenosine monophosphate-mediated pathway. *J Clin Invest* 1996; **98**: 2771-8.

13 Shimizu E, Kobayashi Y, Oki Y, Kawasaki T, Yoshimi T, Nakamura H. OPC-13013, a cyclic nucleotide phosphodiesterase type III inhibitor, inhibits cell proliferation and transdifferentiation of cultured rat hepatic stellate cells. *Life Sci* 1999; **64**: 2081-8.

14 Maynard DM, Heijnen HFG, Horne MK, White JG, Gahl WA. Proteomic analysis of platelet α-granules using mass spectrometry. *J Thromb Haemost* 2007; **5**: 1945-55.

15 McNicol A, Israels SJ. Platelet dense granules: structure, function and implications for haemostasis. *Thromb Res* 1999; **95**: 1-18.

16 Oury C, Toth-Zsamboki E, Thys C, Tytgat J, Vermylen J, Hoylaerts MF. The ATP-gated P2X1 ion channel acts as a positive regulator of platelet responses to collagen. *Thromb Haemost* 2001; **86**: 1264-71.

17 Pak S, Kondo T, Nakano Y, et al. Platelet adhesion in the sinusoid caused hepatic injury by neutrophils after hepatic ischemia reperfusion. *Platelets* 2010; **21**: 282-8.

18 Nakano Y, Kondo T, Matsuo R, et al. Platelet dynamics in the early phase of postischemic liver in vivo. *J Surg Res* 2008; **149**: 192-8.

19 Singer G, Houghton J, Rivera CA, Anthoni C, Granger DN. Role of LPS in the hepatic microvascular dysfunction elicited by cecal ligation and puncture in mice. *J Hepatol* 2007; **47**: 799-806.

20 Murata S, Ohkohchi N, Matsuo R, Ikeda O, Myronovych A, Hoshi R. Platelets promote liver regeneration in early period after hepatectomy in mice. *World J Surg* 2007; **31**: 808-16.

21 Zaldivar MM, Pauels K, von Hundelshausen P, et al. CXC chemokine ligand 4

(CXCL4) is a platelet-derived mediator of experimental liver fibrosis. *Hepatology* 2010; **51**: 1345-53.

22 Wisse E, De Zanger RB, Charels K, Van Dar Smissen P, McCuskey RS. The liver sieve: Concerning the structure and function of endothelial fenestrae, the sinusoidal wall and the space of Disse. *Hepatology* 1985; **5**: 683-92.

23 Ingeberg S, Jacobsen P, Fischer E, Bentsen KD. Platelet aggregation and release of ATP in patients with hepatic cirrhosis. *Scand J Gastroenterol* 1985; **20**: 285-8.

24 Laffi G, Marra F, Gresele P, et al. Evidence for a storage pool deficit in platelets from cirrhotic patients with defective aggregation. *Gastroenterology* 1992; **103**: 641-6.

25 Murata S, Hashimoto I, Nakano Y, Myronovych A, Watanabe M, Ohkohchi N. Single administration of thrombopoietin prevents progression of liver fibrosis and promotes liver regeneration after partial hepatectomy in cirrhotic rats. *Ann Surg* 2008; **248**: 821-8.

26 Watanabe M, Murata S, Hashimoto I, et al. Platelets contribute to the reduction of liver fibrosis in mice. *J Gastroenterol Hepatol* 2009; **24**: 78-89.

27 Watanabe T, Shibata N, Westerman KA, et al. Establishment of immortalized human hepatic stellate scavenger cells to develop bioartificial livers. *Transplantation* 2003; **75**: 1873-80.

28 Seglen PO. Preparation of isolated rat liver cells. *Methods Cell Biol* 1976; **13**: 29-83.

29 Nakamura A, Ueno T, Yagi Y, et al. Human primary cultured hepatic stellate cells can be cryopreserved. *Med Mol Morphol* 2010; **43**: 107-15.

30 Matsuo R, Ohkohchi N, Murata S, et al. Platelets strongly induce hepatocyte proliferation with IGF-1 and HGF in vitro. *J Surg Res* 2008; **145**: 279-86.

31 Hoshi R, Murata S, Matsuo R, et al. Freezed-dried platelets promote hepatocyte proliferation in mice. *Cryobiology* 2007; **55**: 255-60.

32 Seminario-Vidal L, Lazarowski ER, Okada SF. Assessment of extracellular ATP concentrations. *Methods Mol Biol* 2009; **574**: 25-36.

33 Fredholm BB, Arslan G, Halldner L, Kull B, Schulte G, Wasserman W. Structure and function of adenosine receptors and their genes. *Naunyn Schmiedebergs Arch Phamakol* 2000; **362**: 364-74.

34 Sprague RS, Stephenson AH, Ellsworth ML. Red not dead: signaling in and from erythrocytes. *Trends Endocrinol Metab* 2007; **18**: 350-5.

35 Gonzales E, Julien B, Serrière-Lanneau V, et al. ATP release after partial hepatectomy regulates liver regeneration in the rat. *J Hepatol* 2010; **52**: 54-62.

36 Feranchak AP, Lewis MA, Kresge C, et al. Initiation of purinergic signaling by exocytosis of ATP-containing vesicles in liver epithelium. *J Bio Chem* 2010; **285**: 8138-47.

37 Agteresch HJ, Dagnelie PC, van den Berg WO, Wilson JHP. Adenosine triphosphate: established and potential clinical applications. *Drugs* 1999; **58**: 211-32.

38 Dranoff JA, Ogawa M, Kruglov EA, et al. Expression of P2Y nucleotide receptors and ectonucleotidases in quiescent and activated rat hepatic stellate cell. *Am J Physiol Gastrointest Liver Physiol* 2004; **287**: G417-24.

39 Andrade CMB, Wink MR, Margis R, Borojevic R, Battastini AMO, Guma FCR. Activity and expression of ecto-nucleotide pyrophosphate / phosphodiesterases in a hepatic stellate cell line. *Mol Cell Biochem* 2009; **325**: 179-85.

40 Andrade CMB, Roesch GC, Wink MR, et al. Activity and expression of ecto-5'-nucleotidase/CD73 are increased during phenotype conversion of a hepatic

stellate cell line. *Life Sci* 2008; **82**: 21-9.

41 Hernández-Muñoz R, Díaz-Muñoz M, Suárez J, De Sánchez VC. Adenosine partially prevents cirrhosis induced by carbon tetrachloride in rats. *Hepatology* 1990; **12**: 242-8.

42 Hernández-Muñoz R, Díaz-Muñoz M, Suárez-Cuenca JA, et al. Adenosine reverses a preestablished CCl_4-induced micronodular cirrhosis through enhancing collagenolytic activity and stimulating hepatocyte cell proliferation in rats. *Hepatology* 2001; **34**: 677-87.

43 Mayr B, Montminy M. Transcriptional regulation by the phosphorylation-dependent factor CREB. *Nat Rev Mol Cell Biol* 2001; **2**: 599-609.

44 Houglum K, Lee KS, Chojkier M. Proliferation of hepatic stellate cells is inhibited by phosphorylation of CREB on serine 133. *J Clin Invest* 1997; **99**: 1322-8.

FIGURE LEGENDS

Figure 1 Platelets suppress activation of hepatic stellate cells (HSC) and collagen production.

The immortalized human HSC, TWNT-1 ($1x10^4$ cells), were plated on 6-well dishes and incubated with platelets ($1x10^8$ cells) for 1, 4, and 7 days. (a) The expression of alpha smooth muscle actin (α-SMA) which is a well-known marker of HSC activation was examined by Western blot (first row, α-SMA; second row, GAPDH; third row, α-SMA in platelets themselves). (b) After incubating platelets with TWNT-1 separately using chambers, α-SMA expression was examined as well. (c) TWNT-1 incubated with PBS (control) or platelets (PLT) for 1, 4 and 7 days were photographed and separated into two groups (n = 10). We determined that the oval shaped cell had a long axis less than twice that of the short axis and was not as activated as the spindle one.[11] The representative figures at day 4 are shown (arrow; oval shaped cell). (d) The ratios of oval shaped cells in total were counted at day 1, 4, and 7. (e) DNA synthesis in TWNT-1 was examined by 5-bromo-2'-deoxyuridine (BrdU) uptake assay after incubating platelets (PLT) for 24 hours (n = 8). (f) The supernatant of co-cultured medium with platelets for 1 or 4 days was examined by ELISA for type I collagen (n = 6). All results are representative of three independent experiments (mean ± SD). * $P <$ 0.01.

Figure 2 Platelets affect fibrosis-relating gene expressions.

TWNT-1 ($1x10^6$ cells) were plated on 6 cm dishes and incubated with PBS (control) and platelets ($2x10^8$ cells, PLT) for 24 hours. Total RNAs were extracted and real-time PCR was performed (n = 3). (a-d) *ACTA2*, *COL1A1*, *MMP-1*, and *TIMP-1* were

examined, respectively. (e) In *ACTA2*, after TWNT-1 (1x 10^6, 5x10^5, and 1x10^5 cells) were cultured for 1, 4, and 7 days to obtain subconfluent dishes at the same time, respectively, TWNT-1 were incubated with platelets for another 24 hours and real-time PCR was performed as well. All results are representative of three independent experiments (mean ± SD). * $P < 0.01$, ** $P < 0.05$ versus control. ACTA2, alpha 2 helix of α-SMA; COL1A1, pro-alpha 1 chain of type I collagen; MMP-1, matrix metallopeptidase-1; TIMP-1, tissue inhibitor of metalloproteinases-1; GAPDH, glyceraldehyde-3-phosphate dehydrogenase.

Figure 3 Platelet extracts suppress *ACTA2* expression more efficiently when incubated with apyrase.

(a) TWNT-1 (1x10^6 cells) were plated on 6 cm dishes and incubated with PBS (control) and platelet extracts (equivalent to 2x10^8 cells) for 24 hours. Total RNAs were extracted and real-time PCR for *ACTA2* was performed (n = 3,* $P < 0.01$ versus control). (b-e) TWNT-1 (1x10^6 cells) were incubated with platelet-derived growth factor receptor (PDGF-R) inhibitor, anti-vascular endothelial growth factor (VEGF) antibody, insulin-like growth factor-1 receptor (IGF-1R) inhibitor, or apyrase which degrades adenosine 5'-triphosphate (ATP) for 30 minutes, respectively. Then, platelet extracts (equivalent to 2x10^8 cells) were incubated for 24 hours. Real-time PCR for *ACTA2* was performed as well (n = 3, * $P < 0.01$, ** $P < 0.05$ versus 0 U / ml). All results are representative of three independent experiments (mean ± SD).

Figure 4 HSC dephosphorylates platelet-derived ATP and produces adenosine which activates adenosine-cyclic adenosine 5'-monophosphate (cAMP) signaling pathway.

(a) Adenine nucleotide concentrations of platelets were measured by high performance liquid chromatography (HPLC) (n = 5). (b) The ATP concentration of platelet's surfaces was examined by luciferase reaction (n = 5, *P < 0.01 versus 100 μM). (c) After TWNT-1 or primary human HSC ($3x10^4$ cells) were incubated with 1 mM ATP, the total amount of ATP, adenosine 5'-diphosphate (ADP), and AMP in the medium was measured at 0, 6, and 24 hours by HPLC (n = 5, * P < 0.01). (d) After culturing TWNT-1 with 1 mM adenosine or 1 mM ATP for 24 hours, the adenosine concentration in the medium was investigated by HPLC (n = 5, * P < 0.01). (e) After PCR for four types of adenosine receptors in TWNT-1, we examined their expressions by agarose gel-electrophoresis. (f) TWNT-1 ($7x10^3$ cells) were plated on 96-well dishes and incubated with adenosine or platelets ($1x10^7$ cells) for an hour. After washing, the intracellular cAMP was measured (n = 8, ** P < 0.05 versus 0 μM). All results are representative of three independent experiments (mean ± SD). A1-R, adenosine A1 receptor; A2A-R, adenosine A2A receptor; A2B-R, adenosine A2B receptor; A3-R, adenosine A3 receptor.

Figure 5 Much amount of adenine nucleotides suppresses activation of HSC.
(a) TWNT-1 ($1x10^4$ cells) were plated on 6-well dishes and incubated with adenosine for 1, 4, and 7 days. The α-SMA expression was examined by Western blot. (b) Primary human HSC ($5x10^3$ cells) were plated and incubated with PBS (control), platelets ($1x10^8$ cells, PLT), 1 mM ATP, or 1 mM adenosine during 1, 4, and 7 days. The α-SMA expression was investigated as well. (c) After incubating TWNT-1 ($5x10^3$ cells) with ATP for 24 hours, the BrdU uptake was measured (n = 8). All results are representative of three independent experiments (mean ± SD).

Figure 6 Scheme for inactivation of human HSC by human platelets. Platelets contact with HSC. Platelets release adenine nucleotides into a close environment. They are hydrolyzed by ecto-nucleotide triphosphate diphosphohydrolase (E-NTPDase), ecto-nucleotide pyrophosphatase/phosphodiesterase (E-NPP), or ecto-5'-nucleotidase (CD73) on HSC plasma membrane, which produces large amounts of adenosine around HSC. Adenosine receptors transmit signals into cytoplasm by activating adenylyl cyclase (AC). AC increases intracellular cAMP. The elevation of cAMP activates cAMP-dependent protein kinase (PKA). The cAMP-response element binding protein (CREB) is phosphorylated by PKA. This phosphorylation is an important factor in quiescent HSC that expresses less α-SMA and produces less extracellular matrix.

Table 1

The list of primers used in PCR

Gene name	GenBank accession number	forward (5’ to 3’)	reverse (5’ to 3’)
ACTA2	NM_001613	CAGGGCTGTTTTCCCATCCA	CCTCTTTTGCTCTGTGCTTCGT
COL1A1	Z74615	GGGCTTGCCTTCCATTCCT	GGAAGTAGAAAGGTTTGCGGTATAA
MMP1	NM_002421	CACAGCTTCCCAGCGACTCT	GCCACTATTTCTCCGCTTTTCA
TIMP1	NM_003254	ACTGTTGGCTGTGAGGAATGC	GGTCCGTCCACAAGCAATG
ADORA1	NM_000674	CCTCACGCACGGCAACTC	TGGCAGCGGAAATGGTCAT
ADORA2A	NM_000675	CTGCTGGCTGCCCCTACAC	GAAGGGATTCACAACCGAATTG
ADORA2B	M97759	GCTCTTCGCCATCCCCTTT	CACGAAGCAGGCGAGGAA
ADORA3	NM_000677	GTCAGCCTGGGCATCACAAT	CACAGCGATGGCCAGCAA
GAPDH	NM_002046	GGAGTCCACTGGCGTCTTCA	TTCACACCCATGACGAACATG

Figure 1

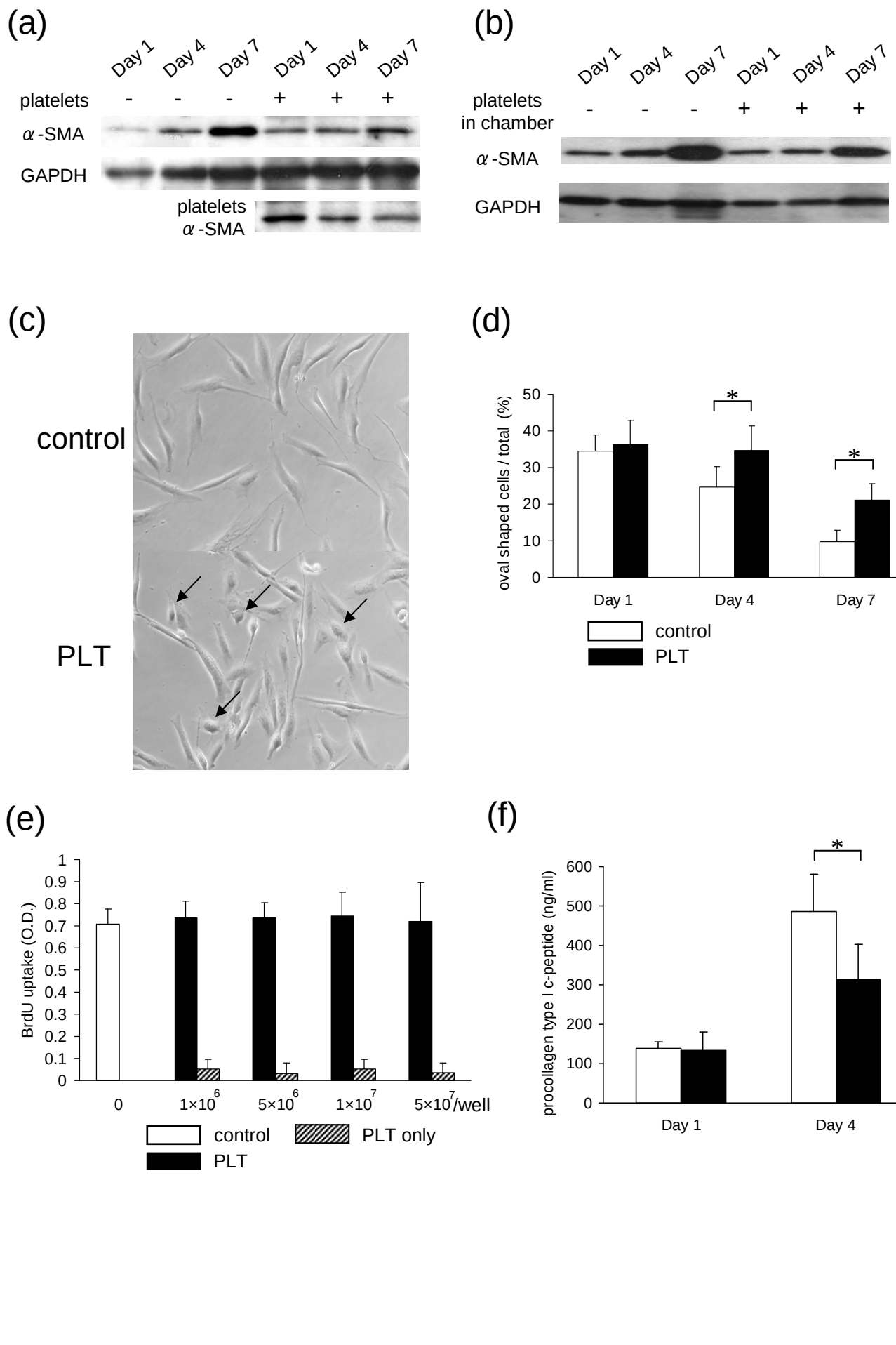

(a)
Day 1
Day 4
Day 7
Day 1
Day 4
Day 7
platelets
- - - + + +
α-SMA
GAPDH
platelets
α-SMA
(b)
Day 1
Day 4
Day 7
Day 1
Day 4
Day 7
platelets
in chamber
- - - + + +
α-SMA
GAPDH
(c)
control
PLT
(d)
oval shaped cells / total (%)
50
40
30
20
10
0
*
*
Day 1
Day 4
Day 7
control
PLT
(e)
BrdU uptake (O.D.)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
1×10^6
5×10^6
1×10^7
5×10^7/well
control
PLT only
PLT
(f)
procollagen type I c-peptide (ng/ml)
600
500
400
300
200
100
0
*
Day 1
Day 4

Figure 2

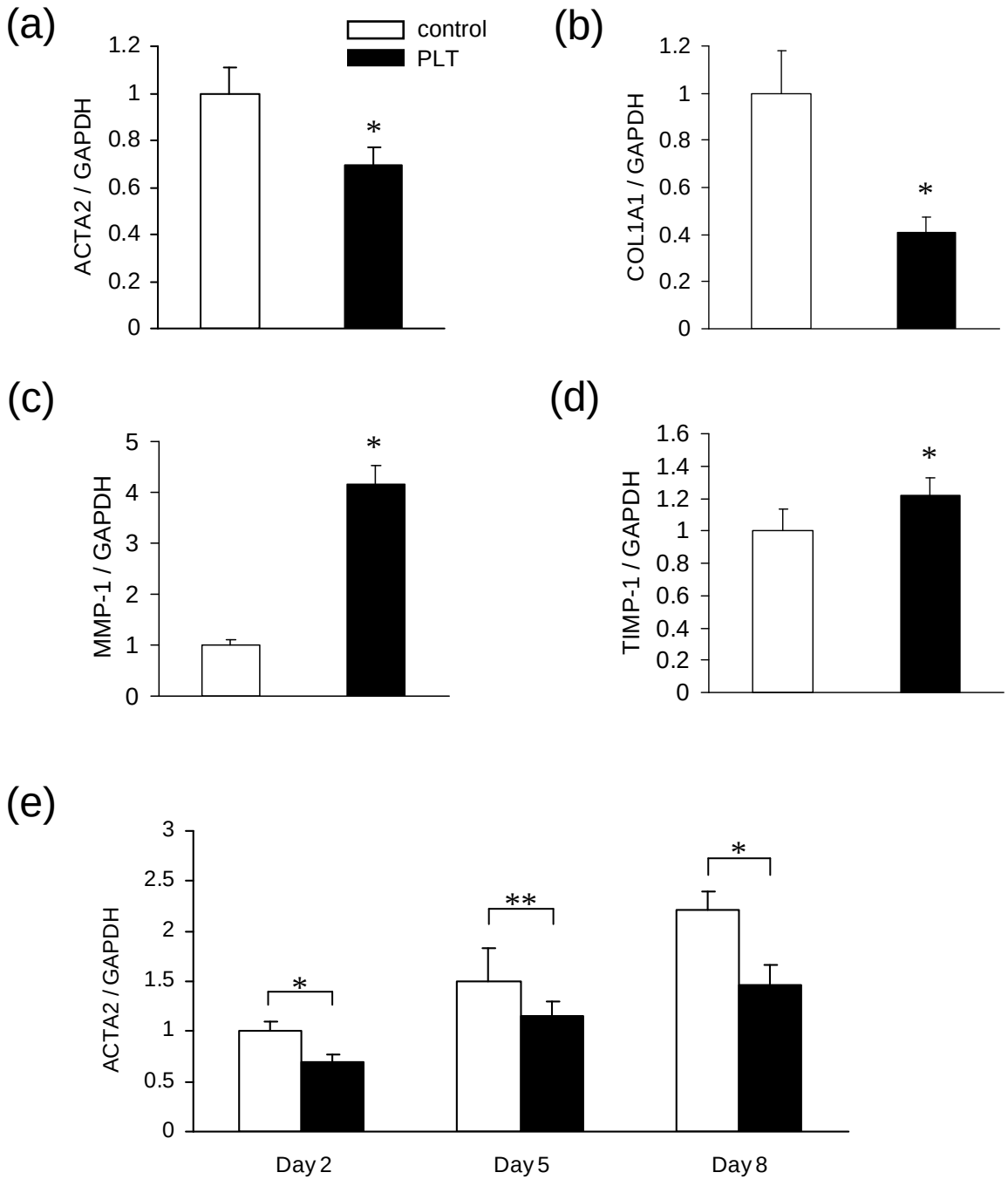

(a)
control
PLT
ACTA2 / GAPDH
1.2
1
0.8
0.6
0.4
0.2
0
*
(b)
COL1A1 / GAPDH
1.2
1
0.8
0.6
0.4
0.2
0
*
(c)
MMP-1 / GAPDH
5
4
3
2
1
0
*
(d)
TIMP-1 / GAPDH
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
*
(e)
ACTA2 / GAPDH
3
2.5
2
1.5
1
0.5
0
*
**
*
Day 2
Day 5
Day 8

Figure 3

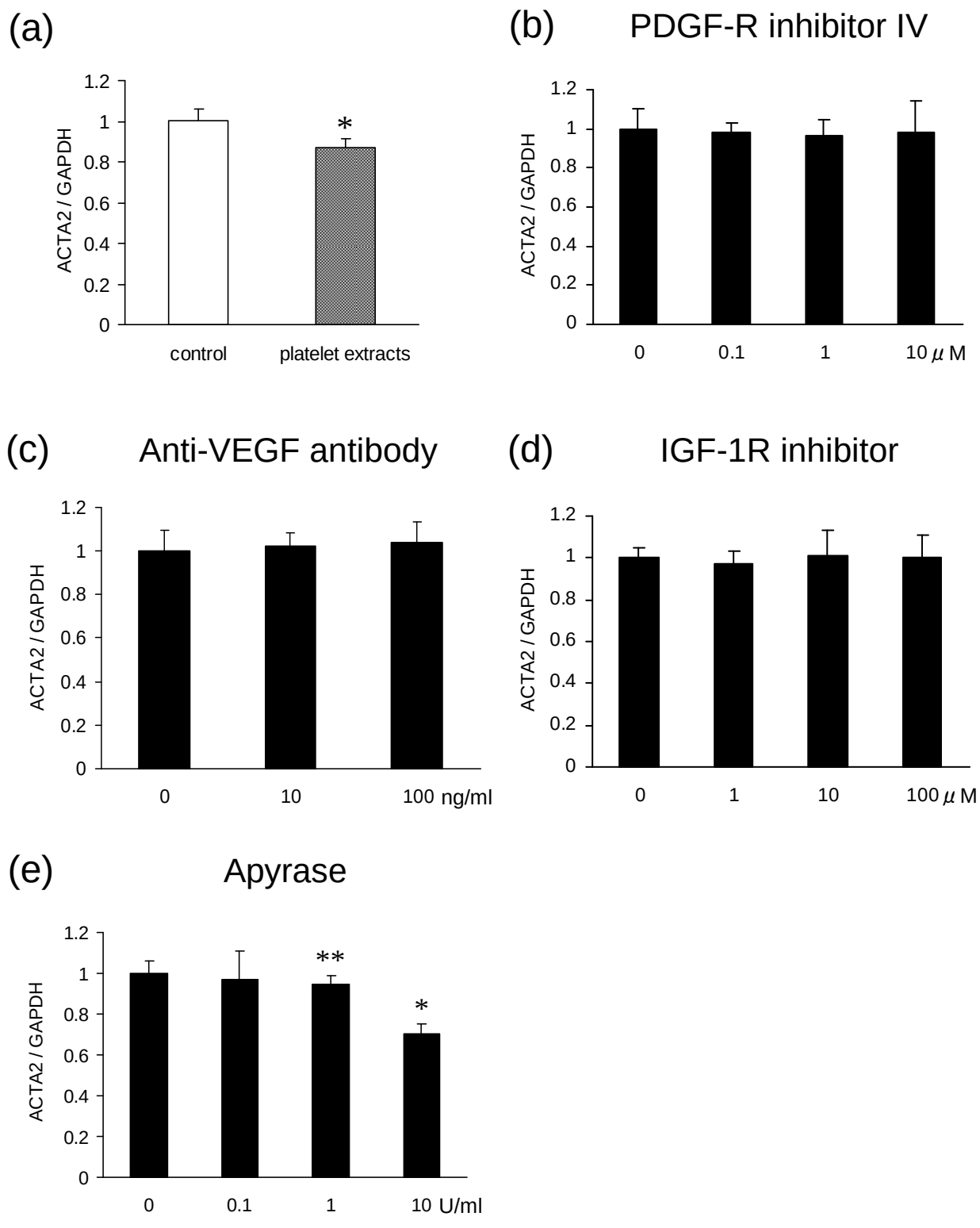

(a)
ACTA2 / GAPDH
1.2
1
0.8
0.6
0.4
0.2
0
*
control
platelet extracts
(b)
PDGF-R inhibitor IV
ACTA2 / GAPDH
0
0.1
1
10 μ M
(c)
Anti-VEGF antibody
ACTA2 / GAPDH
0
10
100 ng/ml
(d)
IGF-1R inhibitor
ACTA2 / GAPDH
0
1
10
100 μ M
(e)
Apyrase
ACTA2 / GAPDH
**
*
0
0.1
1
10 U/ml

Figure 4

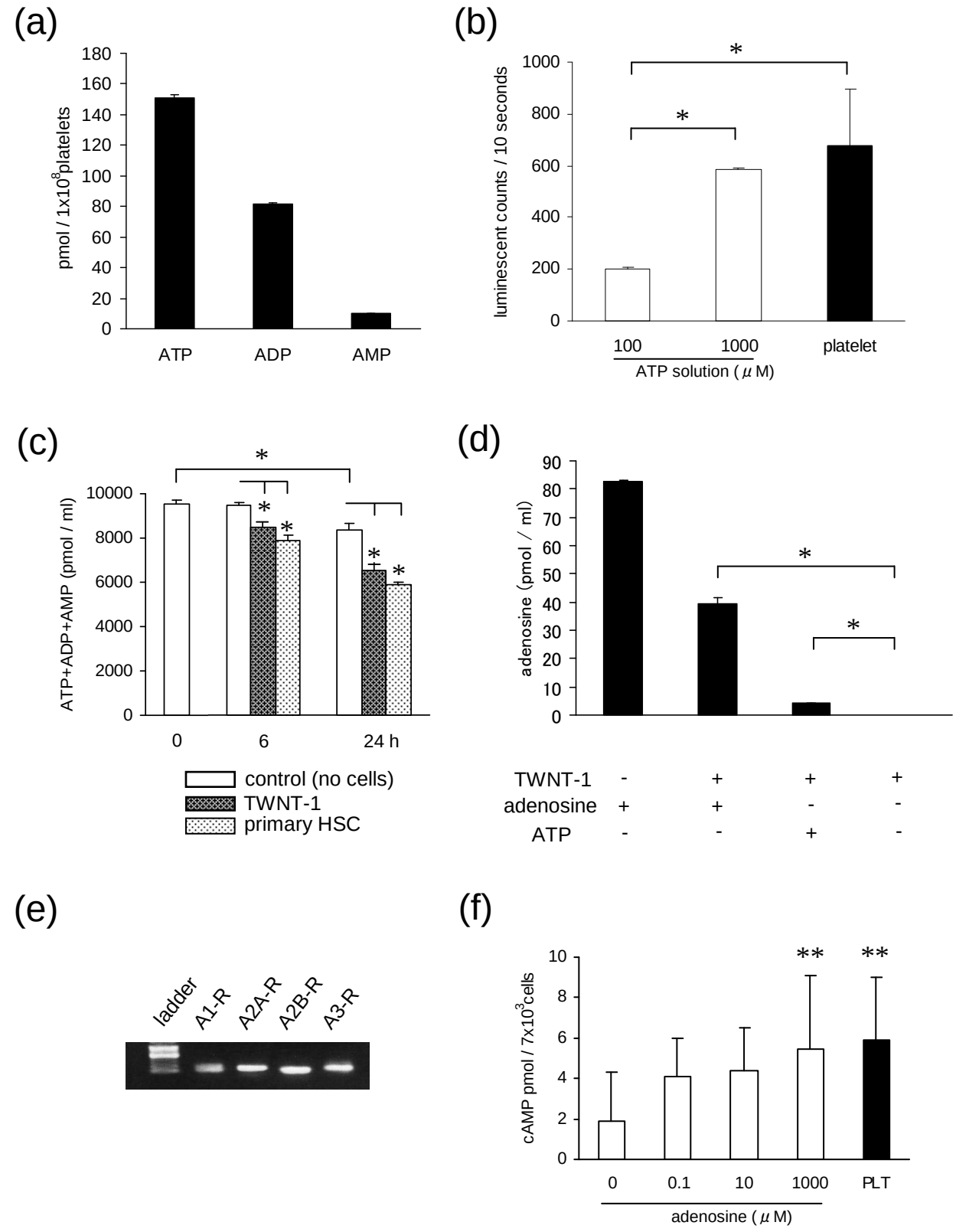
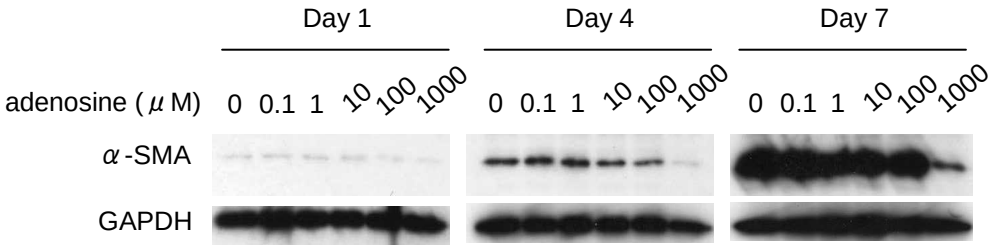
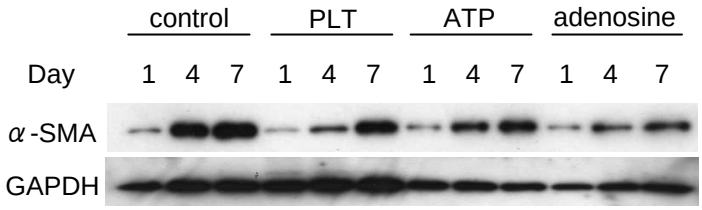

(a)
pmol / 1x10^8 platelets
180
160
140
120
100
80
60
40
20
0
ATP
ADP
AMP
(b)
luminescent counts / 10 seconds
1000
800
600
400
200
0
*
*
100
1000
platelet
ATP solution (μM)
(c)
ATP+ADP+AMP (pmol / ml)
10000
8000
6000
4000
2000
0
*
*
*
*
*
0
6
24 h
control (no cells)
TWNT-1
primary HSC
(d)
adenosine (pmol / ml)
90
80
70
60
50
40
30
20
10
0
*
*
TWNT-1 - + + +
adenosine + + - -
ATP - - + -
(e)
ladder
A1-R
A2A-R
A2B-R
A3-R
(f)
cAMP pmol / 7x10^3 cells
10
8
6
4
2
0
**
**
0
0.1
10
1000
PLT
adenosine (μM)

Figure 5

(a)


Day 1
Day 4
Day 7
adenosine (μM)
0 0.1 1 10 100 1000
0 0.1 1 10 100 1000
0 0.1 1 10 100 1000
α-SMA
GAPDH

(b)


control
PLT
ATP
adenosine
Day
1 4 7 1 4 7 1 4 7 1 4 7
α-SMA
GAPDH

(c)

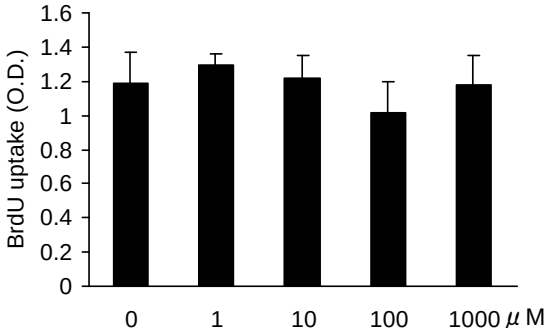
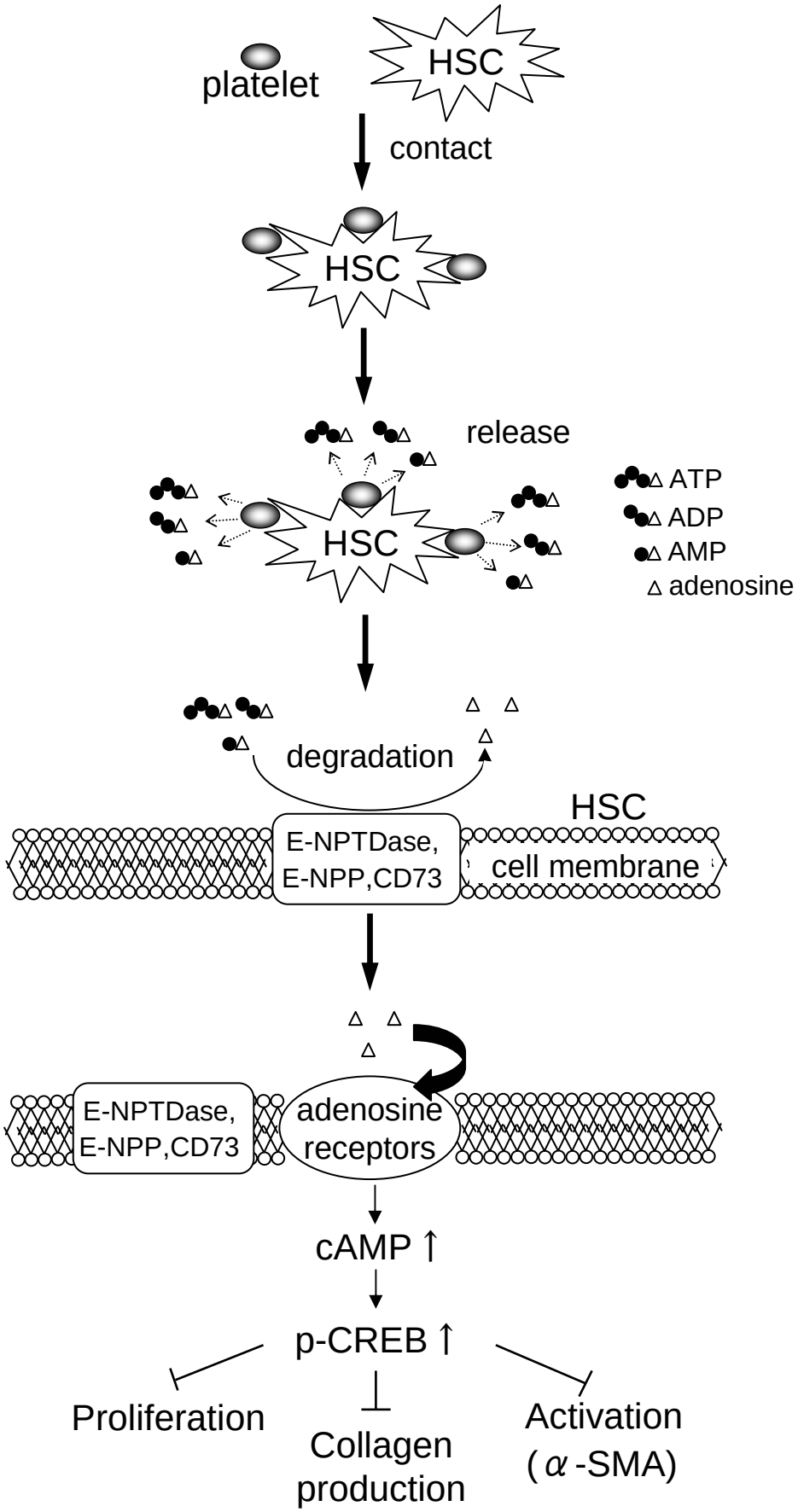

BrdU uptake (O.D.)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
1
10
100
1000 μM

Figure 6


platelet
HSC
contact
HSC
release
HSC
ATP
ADP
AMP
adenosine
degradation
HSC
E-NPTDase,
E-NPP,CD73
cell membrane
E-NPTDase,
E-NPP,CD73
adenosine
receptors
cAMP ↑
p-CREB ↑
Proliferation
Collagen
production
Activation
(α-SMA)