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Plasma gelsolin facilitates interaction between β_2 glycoprotein I and $\alpha 5\beta 1$ integrin

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Abstract

Antiphospholipid syndrome (APS) is characterized by thrombosis and the presence of antiphospholipid antibodies (aPL) that directly recognizes plasma β_2 glycoprotein I (β_2 GPI). Tissue factor (TF), the major initiator of the extrinsic coagulation system, is induced on monocytes by aPL *in vitro*, explaining in part the pathophysiology in APS. We previously reported that the mitogen-activated protein kinase (MAPK) pathway plays an important role in aPL-induced TF expression on monocytes. In this study, we identified plasma gelsolin as a protein associated with β_2 GPI by using immunoaffinity chromatography and mass spectrometric analysis. An *in vivo* binding assay showed that endogenous β_2 GPI interacts with plasma gelsolin, which binds to integrin $\alpha_5\beta_1$ through fibronectin. The tethering of β_2 GPI to monoclonal anti- β_2 GPI autoantibody on the cell surface was enhanced in the presence of plasma gelsolin. Immunoblot analysis demonstrated that p38 MAPK protein was phosphorylated by monoclonal anti- β_2 GPI antibody treatment, and its phosphorylation was attenuated in the presence of anti-integrin $\alpha_5\beta_1$ antibody. Furthermore, focal adhesion kinase (FAK), a downstream molecule of the fibronectin-integrin signaling pathway, was phosphorylated by anti- β_2 GPI antibody treatment. These results indicate that molecules including gelsolin and integrin are involved in the anti- β_2 GPI antibody-induced MAPK pathway on monocytes and that integrin is a possible therapeutic target to modify a prothrombotic state in patients with APS.

Key words: β_2 GPI·gelsolin·integrin·TF·APS

Introduction

Antiphospholipid syndrome (APS) is a clinical condition characterized by recurrent thrombotic events and/or pregnancy morbidity associated with the persistence of antiphospholipid antibodies (aPL). Although the original concept of aPL considers that those antibodies were directed against anionic phospholipids (PL), evidence shows that PL-binding plasma proteins such as β_2 -glycoprotein I (β_2 GPI) [1-3] and prothrombin [4] are the dominant antigenic targets recognized by aPL in patients with APS.

Among the aPL found in patients with APS, antibodies directing to cardiolipin- β_2 GPI complex (aCL/ β_2 GPI), also called anticardiolipin antibodies or anti- β_2 GPI antibodies, have been the best studied in their clinical or biological properties in the last two decades [5]. β_2 GPI is a single-chain glycoprotein containing 326 amino acids and contains a high proportion of proline and cysteine residues and is heavily glycosylated [6]. β_2 GPI is a member of the complement control protein repeat or short consensus repeat (SCR) superfamily and is composed of five homologous motifs of approximately 60 amino acids designated as SCR or as sushi domains. Each motif contains four conserved half cysteine residues, related to the formation of two internal disulphide bridges. While the first four domains are typical, the fifth domain of β_2 GPI is a modified form containing 82 amino acid residues and six half cysteines. The tertiary structure of β_2 GPI revealed a highly glycosylated protein with an elongated fishhook-like arrangement of the globular SCR domains [7,8]. β_2 GPI binds to solid phase phospholipids through a major phospholipid binding site located in the fifth

domain, C²⁸¹KNKEKKC²⁸⁸ close to the hydrophobic loop [9].

The aCL/ β_2 GPI recognize the epitopes that appear on β_2 GPI only when β_2 GPI interacts with anionic phospholipids [10]. The location of the exact epitopic sites for aCL/ β_2 GPI on β_2 GPI molecule has been focus of intensive debate. ACL/ β_2 GPI have been shown to recognize different epitopes located in all five domains of β_2 GPI. Domain IV or I were reported as candidates for major epitopic location by using a series of deletion mutant proteins of β_2 GPI [11]. Recently, de Laat et al showed that pathogenic aCL/ β_2 GPI bind a cryptic epitope on domain I of β_2 GPI which is accessible for aCL/ β_2 GPI only after conformational change, and is induced by the binding of β_2 GPI to a negatively charged surface via a positive-charge patch in domain V [12,13]. Moreover, our group demonstrated that epitopic structures recognized by aCL/ β_2 GPI are cryptic and that three electrostatic interactions between domain IV and V (D¹⁹³-K²⁴⁶, D²²²-K³¹⁷ and E²²⁸-K³⁰⁸) are involved in their exposure [14]. This hypothesis is also supported by our previous data showing that replacement of one single amino acid at position 247 of β_2 GPI, which is important for the interaction between domain IV and V, can alter the antigenicity of β_2 GPI for pathogenic autoantibodies [14,15].

Recently, great interest has arisen on the binding of aCL/ β_2 GPI to endothelial cells or other procoagulant cells and how this binding mediates cell dysfunctions that potentially induce the clinical manifestations of the APS. A number of *in vitro* studies have shown that procoagulant cells, treated with aCL/ β_2 GPI, are activated and express procoagulant molecules such as tissue factor (TF) [16,17]. Further research has focused on the signal transduction mechanisms implicated in the increased expression of

pro-coagulants substances in response to aPL. The adapter molecule myeloid differentiation protein (MyD88)-dependent signaling pathway and the nuclear factor kappa B (NF- κ B) have been involved in endothelial cell activation by aPL [18-21]. We [22] and others [23-26] showed clear evidence that the p38 mitogen activated protein kinase (MAPK) pathway of cell activation plays an important role in aPL-mediated cell activation. Such cell activation by aCL/ β_2 GPI might require an interaction between β_2 GPI and a specific cell surface receptor. The Toll-like receptor (TLR) family may mediate a role in the interaction of the β_2 GPI-aCL/ β_2 GPI complex on the endothelial cell surface [18]. Annexin II, also known as Annexin A2, is an endothelial cell receptor for tPA and plasminogen, and suggested to interact with the β_2 GPI-aCL/ β_2 GPI complex on the endothelial cell surface mediating cell activation [27,28]. Some members of low-density lipoprotein receptor family, such as LDL-R related protein, megalin, the very-low density lipoprotein receptor, were shown to bind to β_2 GPI [29]. However, no evidence has shown a direct interaction between β_2 GPI and Toll-like receptors. Annexin II does not span the cell membrane thus cannot induce cell activation unless the presence of an unknown “adaptor” is present. β_2 GPI was required to be chemically dimerized to bind to any of LDL receptors [29]. In addition, no information has been available regarding β_2 GPI on monocytes. In fact, monocytes are more potent to produce TF compared with endothelium, therefore the investigation of β_2 GPI-aCL/ β_2 GPI interaction on monocytes are essential to explore the pathophysiology of APS.

In this study, we identified a plasma gelsolin as a novel protein associated with β_2 GPI by using affinity purification and liquid chromatography with mass spectrometry

(LC-MS) analysis, and we showed functional interaction of plasma gelsolin with β_2 GPI.

Materials and methods

Cell culture

RAW264.7 and HEK293T cell lines were cultured under an atmosphere of 5% CO₂ at 37°C in Dulbecco's modified Eagle's medium (DMEM; Sigma Chemical Co., St. Louis, MO, USA) supplemented with 10% fetal bovine serum (FBS) (Gibco BRL, Paisley, UK). To remove β_2 GPI, the culture medium was changed to serum-free DMEM for 16 hrs before the assay.

Cloning of cDNAs and plasmid construction

The signal sequence region and other region of human β_2 GPI cDNA lacking the signal sequence (β_2 GPI(ss-)) were amplified by PCR from human B cell cDNA (CLONTECH Laboratories, Inc. Mountain View, CA). The resulting fragment containing β_2 GPI(ss-) was ligated into the EcoR I and Sal I sites of p3xFLAG CMV7.1 vector (Sigma). The fragment containing the human β_2 GPI signal sequence was ligated into the BamH I and Pst I sites of pBluescript II SK⁺ vector (pBS-Sig) (Stratagene, La Jolla, CA). The β_2 GPI(ss-) cDNA fragment with 3xFLAG was ligated into the Pst I and Sal I sites of pBS-Sig. The Sig-3xFLAG- β_2 GPI fragment was then ligated into pcDNA3 (Invitrogen, Carlsbad, CA) (pcDNA3-Sig-3xFLAG- β_2 GPI) or into pCAG-puro vector which contains a puromycin-resistant gene in pCAGGS vector provided by Dr. J. Miyazaki

(Osaka University). The gelsolin cDNA was obtained from ATCC (#MGC-39262, Manassas, VA) and ligated into pcDNA3.

Proteins and antibodies

Recombinant human β_2 GPI was purified as described previously [11]. FLAG- β_2 GPI was collected from the culture supernatant of HEK293T cells transiently transfected with pcDNA3-Sig-3xFLAG- β_2 GPI using FuGENE6 (Roche, Branchburg, NJ). Expression of all constructs was performed in conditioned serum-free Opti-MEM (GIBCO, BRL, Paisley, UK). Furthermore, a stable cell line expressing FLAG- β_2 GPI was generated by transfection with pCAG-I-puro vector encoding FLAG-tagged- β_2 GPI cDNA. The culture supernatant of FLAG- β_2 GPI-expressing cells was collected after 4 days of culture and then filtered (0.22 μ m). The antibodies used in this study were as follows: mouse monoclonal anti- β_2 GPI antibody (WBCAL1; aCL/ β_2 GPI [30], and MAB1066, Chemicon International Inc., Temecula, CA), mouse monoclonal anti-gelsolin antibody (clone 2, BD Transduction Laboratories, San Jose, CA), rat monoclonal anti-integrin $\alpha_5\beta_1$ antibody (MAB1984, Chemicon), mouse monoclonal anti-integrin β_1 antibody (Ha2/5, BD), rabbit polyclonal anti-p38 MAP kinase antibody (#9212, Cell Signaling Technology, Inc., Beverly, MA, USA), rabbit polyclonal anti-phospho-p38 MAP kinase antibody (#9211, Cell Signaling), mouse monoclonal anti-FAK antibody (clone 77, BD), mouse monoclonal anti-FAK(pY397)-phospho-specific antibody (clone 18, BD), mouse anti- β -actin (AC15,

Sigma) and mouse monoclonal anti-FLAG (M2) (Sigma). EZ-Link Sulfo-NHS-Biotin Reagent was used as a biotinylation reagent. IgG with aPL activity was purified from sera of six patients with APS diagnosed by Sapporo criteria. Control IgG was isolated from normal human serum. Protein concentrations were determined by Bradford method. Consent forms for this study were signed by all of the patients and healthy donors.

Purification of the β_2 GPI-related proteome

NHS-activated Sepharose 4 Fast Flow (0.5 ml) (Amersham Biosciences AB, Sweden) washed with 100 mM HCl was mixed with 250 μ g of anti-FLAG (M2) mAb (250 μ g) in coupling buffer (0.2M NaHCO₃-NaCl, pH 8.3), and the mixture was rotated for 2 hrs at room temperature for conjugation. The unconjugated antibody was removed from the resin by washing with 500 mM ethanolamine (pH 8.3) and 0.1 M CH₃COOH (pH 4.0), and the resin was then equilibrated with PBS. RAW264.7 cells were cultured under an atmosphere of 5% CO₂ at 37°C in serum-free DMEM for 16 hrs. After incubation, 5 x 10⁷ cells were collected, suspended with 1 ml of PBS, and incubated for 2 hrs at 4°C with 0.5 ml of culture supernatant (FLAG- β_2 GPI) after transfection with pcDNA3-Sig-3xFLAG- β_2 GPI. The cells were then washed twice with 1 ml of PBS, suspended with 1 ml of PBS, and incubated for 2 hrs at 4°C after addition of the membrane-impermeable cross-linker 3,3'-Dithiobis(sulfosuccinimidylpropionate) (DTSSP) (Pierce) was added to a final concentration of 1 mM. Then Tris-HCl (pH 7.5)

was added as a stop solution to a final concentration of 10 mM. The cells were then harvested, washed with PBS, lysed in 10 ml of a solution containing 50 mM Tris-HCl (pH 7.4), 150 mM NaCl, 0.5% Triton X-100, aprotinin (10 mg/ml), leupeptin (10 mg/ml), 1 mM PMSF, 400 mM Na₃VO₄, 400 mM EDTA, 10 mM NaF, and 10 mM sodium pyrophosphate (buffer A), and centrifuged at 16,000 x g for 10 min at 4°C. The resulting supernatant was applied to the M2 column of 100 µl bed volume and the column was then washed with buffer A. HA-peptide (Roche) was loaded to the column to remove non-specific binding and then bound proteins were eluted with two volumes of FLAG peptide (Sigma). The eluents from the column were concentrated by precipitation with TCA and subjected to in-solution digestion for LC-MS/MS analysis.

In-solution digestion of purified proteins

Proteins were precipitated with 10% TFA and washed with acetone twice. Precipitated proteins were dissolved in 100 mM Tris-HCl and 7 M guanidium hydroxide (pH 8.0), diluted with 100 mM Tris-HCl (pH 8.0) to 1 M guanidium hydroxide, and then digested with Lys-C endopeptidase (500 ng) for 16 hrs at 37°C. The resulting peptides were desalted with a C18 disc settled microtip, dried, and dissolved in 0.1% TFA/2% acetonitrile.

MS and database searching

Peptides were analyzed by using a quadrupole time of flight hybrid mass spectrometer (Q-tof2, Waters) equipped with an Agilent HP1100 nanoflow pump with a laboratory-made nano-spray stage and ESI column. C18 beads (L-column, 3 μ m) were packed in the spray tip and used as a nano-ESI column (5 cm in length, 100 μ m in id). The sample was loaded to the ESI column at a flow rate of 800 nl/min with mobile phase A (0.1% formic acid/2% acetonitrile) and eluted with a linear gradient of 5 to 35% B (0.1% formic acid/90% acetonitrile) at a flow rate of 200 nl/min. CID spectra were acquired automatically in the data-dependent scan mode in which the two highest peaks were selected for precursor ions. All MS/MS spectra were processed by a MASCOT distiller for generation of peak list files and were subjected to a database search by the MASCOT algorithm (Matrix Science, London) against the non-redundant National Center for Biotechnology Information (nrNCBI) database. Search parameters were set as follows: Lys-C/P was selected as an enzyme allowing one miscleavage, oxidized methionine and pyroglutamine derived from the amino terminus of glutamine were selected as variable modifications, and the mass tolerance was 0.3 Da for precursor ions and 0.3 Da for MS/MS ions.

Transfection, immunoprecipitation and immunoblot analysis

HEK293T cells were transfected by the calcium phosphate method or lipofection method. After 48 hrs, the cells were lysed in a solution containing 50 mM Tris-HCl (pH 7.4), 150 mM NaCl, 1% Nonidet P-40, leupeptin (10 μ g/ml), 1 mM

phenylmethylsulfonyl fluoride, 400 μ M Na₃VO₄, 400 μ M EDTA, 10 mM NaF, and 10 mM sodium pyrophosphate. The cell lysates were centrifuged at 16,000 x *g* for 10 min at 4°C, and the resulting supernatant was incubated with antibodies for 2 hrs at 4°C. Protein G-Sepharose (Amersham Biosciences AB) that had been equilibrated with the same solution was added to the mixture, which was then rotated for 1 hr at 4°C. The resin was separated by centrifugation, washed four times with ice-cold lysis buffer, and then boiled in SDS sample buffer. Immunoblot analysis was performed with the primary antibodies with horseradish peroxidase-conjugated antibodies to mouse or rabbit immunoglobulin G (1:10,000 dilution, Promega Corporation, Madison, WI) and an enhanced chemiluminescence system (ECL, Amersham Biosciences, UK).

Binding assay

The binding between phospholipid- β_2 GPI complex and gelsolin was confirmed by an enzyme-linked immunosorbent assay (ELISA). Non-irradiated microtiter plates (Sumilon type S, Sumitomo Bakelite, Tokyo, Japan) were coated with 30 μ l of 50 μ g/ml cardiolipin (Sigma) and dried overnight at 4°C. To avoid nonspecific binding of proteins, wells were blocked with 150 μ l of Tris-buffered saline (TBS) containing 1% fatty acid-free bovine serum albumin (BSA, A-6003, Sigma) and CaCl₂ (BSA-Ca). After 3 washes in TBS containing 0.05% Tween 20 (Sigma) and CaCl₂ (TBS-Tween-Ca), 50 μ l of 10 μ g/ml β_2 GPI in BSA-Ca was added to half of the wells in the plates and the same volume of BSA-Ca alone (as a sample blank) was added to the other half of the wells.

After 1-hr incubation at 37°C, plates were washed and 50 µl of gelsolin (0-10 µg/ml) in BSA-Ca was added in duplicate. Plates were incubated for 1 hr at room temperature, followed by incubation with mouse monoclonal anti-gelsolin antibody, alkaline phosphatase (ALP)-conjugated goat anti-mouse IgG and substrate. The optical density (OD) of wells coated with cardiolipin alone was subtracted from that of wells containing cardiolipin-β₂GPI complex. All procedures were done in the presence of 0, 1 or 2 mM CaCl₂.

Flowcytometric analysis

Surface aCL/β₂GPI and gelsolin binding on RAW264.7 cells was analyzed using FACSCalibur (Becton Dickinson Immunocytometry Systems, San Jose, CA, USA) with the CellQuest program. RAW264.7 cells were cultured with serum-free DMEM for 16 hrs. The cultured cells were washed with PBS including 2% BSA and 0.1% NaN₃ and treated with 50 µg/ml of β₂GPI at room temperature for 10 min, followed by exposure to primary antibodies for 30 min on ice. After washing twice, cells were stained with Alexa488-labeled goat anti-mouse IgG antibody (Invitrogen) for 30 min on ice. After washing twice, cells were analysed using FACSCalibur.

Luciferase assay. Stable κB luciferase reporter-expressing RAW264.7 cells were inoculated into a 24-well dish at 1×10^6 cells/500 µl of cell culture medium and stimulated as indicated [31]. After stimulation at 37°C for 4 h, the cells were harvested

and lysed in 50 μ l of cell culture lysis reagent (Promega Corp.), and then luciferase activity was measured using 20 μ l of lysate and 100 μ l of luciferase assay substrate (Promega Corp.). The luminescence was quantified with a luminometer (Berthold Japan, Tokyo, Japan).

Results

Immunoaffinity purification of β_2 GPI-associated proteins

To isolate β_2 GPI-binding proteins, we constructed FLAG-tagged human β_2 GPI (Fig. 1A). Since β_2 GPI binds to anionic phospholipids via a lysine-rich motif on domain V at the carboxy-terminus, we decided to preserve the intact structure at the carboxy-terminus. β_2 GPI is a secretory apolipoprotein that is mainly produced in the liver and secreted to plasma. β_2 GPI cDNA encodes a protein of 345 amino acids including a hydrophobic amino-terminal signal sequence (19 amino acid residues) that is lacking in the mature form of β_2 GPI. Thus, the FLAG-tag sequence was placed between the signal peptide sequence and mature protein (Fig. 1A). An expression vector encoding FLAG- β_2 GPI was transfected into HEK293T cells, and the culture supernatant and whole cell lysate were analyzed by immunoblotting using anti-FLAG or anti- β_2 GPI antibody. Immunoblot analysis showed that FLAG- β_2 GPI was detected by anti-FLAG and anti- β_2 GPI antibody from both the cell lysate and culture supernatant (Fig. 1B).

To confirm that β_2 GPI binding proteins exist on the cell surface of RAW264.7 cells, we performed a pull-down assay using biotinylated cell surface proteins from RAW264.7 cells and FLAG-tagged β_2 GPI. The cell surface proteins of RAW264.7 cells were biotinylated, incubated with FLAG- β_2 GPI, and then biotinylated cell surface membrane proteins were chemically cross-linked with FLAG- β_2 GPI. Cells were lysed, and the lysates were immunoprecipitated with anti-FLAG antibody to purify

biotinylated proteins cross-linked to FLAG- β_2 GPI and visualized with HRP-conjugated streptavidin. Smear proteins other than FLAG- β_2 GPI were reproducibly found (Fig. 1C). Next, we performed large-scale immunoaffinity chromatography with an anti-FLAG pull down assay. RAW264.7 cells were cultured with FLAG- β_2 GPI and then the lysate of RAW264.7 cells was used for affinity chromatography with anti-FLAG antibody-conjugated Sepharose beads. The purified fraction eluted using FLAG-peptides was subject to SDS-PAGE and detected with silver staining. Silver staining indicated that a large number of smear proteins interact with β_2 GPI (Fig. 1D).

Identification of β_2 GPI-associated proteins by LC-MS

Proteins immunopurified with anti-FLAG (M2)-conjugated Sepharose were directly digested with Lys-C endopeptidase and analyzed by an online-nanoLC-ESI-quadrupole time of flight hybrid mass spectrometer. Obtained MS/MS data were searched against the non-redundant National Center for Biotechnology Information (nrNCBI) database MASCOT algorithm. Many proteins with a significant MASCOT score were identified, but most of them were intracellular proteins such as molecular chaperones and ribosomal proteins that were abundant and seem to be contaminants (Supplementary Table 1). These proteins were omitted from the list of identified protein, and proteins expressed on the membrane and/or cell surface were approved as candidates for β_2 GPI-binding protein. Eventually, we found five peptides corresponding to gelsolin,

and two of the five peptides had reliable MASCOT scores (more than 31, $p < 0.05$,) (Fig. 2A). The MS/MS data of the peptide (127-142 amino acid residue) with the highest MASCOT score are shown in Fig. 2B and C. Gelsolin has two types of localization pattern: one isoform localizes in the cytosol to regulate formation of actin fiber, whereas the other isoform, which has a signal peptide, localizes outside the cell or on the cell surface. We focused on plasma gelsolin as a β_2 GPI-binding protein because gelsolin interacts with fibronectin and integrin, which can transduce intracellular signaling in collaboration with several types of kinase such as MAPK and FAK.

Interaction of β_2 GPI with plasma gelsolin

To confirm the binding between β_2 GPI and gelsolin, we examined the interaction between β_2 GPI and gelsolin using HEK293T cells. HEK293T cells were transfected with expression plasmids encoding FLAG-tagged β_2 GPI and gelsolin. The cell lysates were immunoprecipitated with anti- β_2 GPI (WBCAL1; monoclonal aCL/ β_2 GPI) or FLAG antibodies and then immunoblotted with anti-gelsolin or β_2 GPI antibodies (MAB1066). Immunoprecipitation and immunoblot analysis revealed that FLAG-tagged β_2 GPI specifically interacted with gelsolin (Fig. 3A). To further verify the interaction between recombinant β_2 GPI and endogenous gelsolin, we examined the interaction with endogenous gelsolin. The supernatant including endogenous plasma gelsolin secreted from cultured RAW264.7 cells was mixed with human recombinant β_2 GPI and subjected to immunoprecipitation with antibodies as indicated (WBCAL1 or

Mock), and the resulting precipitates were subjected to immunoblot analysis with anti-gelsolin or anti- β_2 GPI antibody (MAB1066). An *in vitro* pull-down assay showed that plasma gelsolin directly binds to β_2 GPI (Fig. 3B). Direct binding of gelsolin to cardiolipin- β_2 GPI complex was confirmed by ELISA in a calcium-dependent fashion (Fig. 3C).

Plasma gelsolin enhances the localization of β_2 GPI on the cell surface

It has been reported that plasma gelsolin binds to fibronectin, which belongs to the family of extracellular matrix proteins and plays important roles in cellular adhesion, proliferation, differentiation and migration [32]. First, we confirmed the expression of β_2 GPI (recombinant human β_2 GPIs or FLAG-tagged β_2 GPIs) on the cell surface by flowcytometric analysis. When RAW264.7 cells were incubated with β_2 GPI at 37°C for 1 h, interaction of β_2 GPI on the cell surface was observed (Fig. 4A and B). To determine whether gelsolin affects the expression of β_2 GPI on the cell surface, we examined the expression level of β_2 GPI on the cell surface. The expression level of β_2 GPI on the cell surface was enhanced in the presence of gelsolin compared to that in the absence of gelsolin (Fig. 4C). It has been shown that fibronectin, which binds to gelsolin, associates with the extracellular domain of the integrin family. To determine whether the cell surface expression of β_2 GPI depends on integrin, we examined the expression level of β_2 GPI with anti-integrin $\alpha_5\beta_1$ antibody as an inhibitory antibody. Anti-integrin $\alpha_5\beta_1$ antibody inhibited the expression of β_2 GPI on the surface of RAW264.7 cells (Fig. 4D

and E). These findings indicate that gelsolin enhanced the cell surface expression of β_2 GPI and that the interaction is mediated by integrin on the cell surface.

Intracellular signaling via aCL/ β_2 GPI antibody is dependent on integrin $\alpha_5\beta_1$

We previously reported that p38-MAPK was phosphorylated in RAW264.7 cells stimulated by human monoclonal aCL/ β_2 GPI [22]. To determine whether a cell surface complex including gelsolin activates RAW264.7 cells, we investigated the phosphorylation of p38-MAPK. Stimulation to RAW264.7 cells by aCL (WBCAL1) showed that p38-MAPK phosphorylation was not induced by plasma gelsolin alone but was induced by aCL/ β_2 GPI stimulation and was further enhanced by plasma gelsolin plus aCL/ β_2 GPI stimulation (Fig. 5A). However, anti-integrin $\alpha_5\beta_1$ antibody attenuated phosphorylation of p38-MAPK by plasma gelsolin plus aCL/ β_2 GPI stimulation (Fig. 5A). These findings indicate that aCL/ β_2 GPI caused phosphorylation of p38-MAPK in collaboration with gelsolin and integrin on the cell surface. Furthermore, to determine the effect on downstream molecules such as focal adhesion kinase FAK, the phosphorylation of FAK by aCL/ β_2 GPI was investigated. Stimulation of aCL/ β_2 GPI and plasma gelsolin resulted in an increased level of phosphorylation of FAK, whereas anti-integrin $\alpha_5\beta_1$ antibody attenuated the phosphorylation of FAK (Fig. 5B). Taken together, the results suggest that anti- β_2 GPI antibody affects the integrin signaling including its downstream signal molecule FAK, followed by activation of p38-MAPK.

It has been reported that the p38-MAPK pathway is linked to the NF- κ B pathway

[33]. To determine whether aCL/ β_2 GPI antibody functions with gelsolin, we examined its effect on relative luciferase activity by NF- κ B. The transcriptional activity of NF- κ B was further increased by stimulation with the combination of gelsolin and one of the aCL/ β_2 GPI antibodies, WBCAL1, whereas it was inhibited by anti-integrin $\alpha_5\beta_1$ antibody (Fig. 5C). These findings indicate that aCL/ β_2 GPI causes the engagement of integrin with gelsolin, resulting in activation of the p38-MAPK pathway and NF- κ B pathway.

Discussion

We identified plasma gelsolin as a novel β_2 GPI-binding protein on the cell surface of monocytes. Affinity purification using an anti-FLAG- β_2 GPI-conjugated column clarified that β_2 GPI interacts with gelsolin on monocytes, and then the binding of β_2 GPI with gelsolin was confirmed by immunoprecipitation. Moreover, flowcytometric analysis demonstrated that gelsolin enhances the affinity of β_2 GPI on the cell surface. Gelsolin is expressed as two isoforms, cytoplasmic gelsolin and plasma gelsolin, which are encoded by a single gene and produced by alternative translation [34]. Both gene products of gelsolin have six homologous repeats (S1~S6), each of which contains 120-130 amino acid residues, and plasma gelsolin has an extra 23 amino acid residues at the amino-terminus [35,36]. Cytoplasmic gelsolin is known as an actin-depolymerizing factor and plays a crucial role in removal of actin released by tissue injury. Plasma gelsolin has another function as a carrier protein for bioactive mediators such as lysophosphatidic acid (LPA), lipopolysaccharide (LPS), amyloid β protein ($A\beta$) and platelet-activating factor (PAF) to protect cells from exposure to excess stimulation [37-41]. Plasma gelsolin also interacts with fibronectin and especially colocalizes at a region where inflammation arises [32]. Fibronectin forms a dimeric glycoprotein in plasma and a dimeric or multimeric form that interacts with integrin $\alpha_5\beta_1$ on the cell surface. Fibronectin is involved in cell adhesion, morphological change and migration processes, including wound healing, blood coagulation, host defense and metastasis.

Integrins are heterodimeric membrane proteins composed of an α chain and a β

chain. Each specific integrin induces a variety of responses in different cell types. Integrin $\alpha 5$ chain undergoes post-translational cleavage to yield disulfide-linked light and heavy chains that join with the $\beta 1$ chain to form a fibronectin receptor [42]. Integrins provide dynamic, physical links between the extracellular matrix (ECM) such as fibronectin and cytoskeletons. In addition to adhesion, integrins are known to participate in cell surface-mediated signaling in concert with other cell surface receptors, including growth factor receptors such as EGF, LPA or thrombin, and are involved in proliferation, survival, morphological change, migration and gene expression. Ligation of ECM to integrins triggers assembly of cytoskeleton proteins (such as tallin, actin and paxillin) and intracellular tyrosine kinase FAK and results in a large variety of signal transduction events. Integrin-mediated signals is likely to be necessary in normal cells, such as human umbilical vein endothelial cells or mammary epithelial cells, to block apoptosis via the Akt pathway and activate cells via the MAPK pathway [43-45]. In Ntera2 neuronal cells, $\alpha 5\beta 1$ -mediated adhesion to fibronectin decreased apoptosis. Previous studies have shown that expression of $\alpha 5\beta 1$ promotes apoptosis of human hematopoietic cell lines, monocyte-differentiated HL-60 cell lines and mouse macrophage RAW264.7 cell lines [46-48]. However, it has been reported that fibronectin could not mediate the binding of β_2 GPI to the cell surface in endothelial cells [27,49]. We confirmed direct interaction of phospholipid-bound β_2 GPI and gelsolin by ELISA, and the binding was found only in the presence of calcium. The interaction of β_2 GPI with gelsolin in our study suggests that engagement of β_2 GPI by anti- β_2 GPI antibody caused the complex formation including gelsolin, fibronectin and

integrin $\alpha 5\beta 1$, followed by activation of the p38-MAPK pathway and NF- κ B pathway.

Zeisel et al. reported that FAK and myeloid differentiation protein 88 (MyD88) pathways were inter-linked and initiate a proinflammatory response through NF- κ B activation [50]. In a previous study, we demonstrated that the p38 MAPK-dependent signaling pathway participates in aPL-mediated TF expression. A specific inhibitor of p38 MAPK decreased TF mRNA expression induced by aCL/ β_2 GPI stimulation, indicating a crucial role of the p38 MAPK pathway in APS. Raschi et al. reported that a dominant-negative form of TNF-receptor-associated factor 6 (TRAF6) and MyD88 abrogated NF- κ B activation induced by monoclonal aCL/ β_2 GPI, suggesting that aCL/ β_2 GPI reacts to β_2 GPI associated with a member of the toll-like receptor (TLR) or interleukin-1 receptor family. The present study demonstrated that gelsolin is a scaffolding protein that links β_2 GPI and integrin/fibronectin and that integrin is also important for activation of the p38 MAPK and NF- κ B pathways by aCL/ β_2 GPI.

Several inhibitors for integrins have been developed and investigated in animal models of inflammatory diseases, and some of these inhibitors (e.g., anti-integrin α IIB β 3, anti-integrin α 4 β 7) are used clinically as anti-platelet agents or anti-inflammatory bowel disease agents [51]. Recently, RGD peptides that bind to integrin α v β 3, α v β 5 or α 5 β 1 have become available for the treatment of inflammatory arthritis [52]. This is a first report to prove how the β_2 GPI-aCL/ β_2 GPI interaction on monocyte surface occurs with its partner molecule, gelsolin. Despite the fact that we could not show direct procoagulant alteration of cells by aCL/ β_2 GPI with integrin α 5 β 1 blockade in this study, neither on monocytes nor on endothelial cells, our findings

provide a clue for establishing specific treatments by down-regulating the p38 MAPK pathway via integrin $\alpha 5\beta 1$ and therapeutic benefits for patients with autoimmune diseases, including APS.

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Figure legends

Fig. 1 Immunoaffinity purification of the β_2 GPI-related proteome. **(A)** Schematic representation of β_2 GPI. Gray box: signal peptide, black box: FLAG-tag. **(B)** Expression of secretory β_2 GPI and intracellular β_2 GPI. HEK293T cells were transfected with expression plasmids encoding FLAG-tagged β_2 GPI. Cells were lysed and subjected to immunoblot (IB) analysis with anti-FLAG or anti- β_2 GPI antibody. **(C)** Pull-down analysis of biotinylated cell surface proteins binding to FLAG- β_2 GPI. RAW264.7 cell surface proteins were biotinylated using EZ-Link Sulfo-NHS-Biotin Reagent and then the cells were cross-linked with FLAG- β_2 GPI using 3,3'-Dithiobis(sulfosuccinimidylpropionate). The cells were lysed and subjected to immunoprecipitation (IP) with anti-FLAG antibody. The resulting precipitates were subjected to SDS-PAGE and visualized with HRP-conjugated streptavidin **(D)** Silver staining of β_2 GPI-associated proteins. The β_2 GPI-associated proteins purified by the procedure indicated in C were detected by silver staining.

Fig. 2 Identification of β_2 GPI-binding protein. **(A)** Identified peptide sequences of gelsolin by MS analysis. Five peptides corresponding to mouse gelsolin were identified. **(B)** Assigned b- or y- ions from amino acid sequence of 127 to 142 of mouse gelsolin are represented. **(C)** MS/MS spectrum of peptide 127 to 142 of mouse gelsolin. Fragment ions corresponding to b- and y- ions from identified sequence (124 to 142) are indicated.

Fig. 3 Biochemical interaction between β_2 GPI and plasma gelsolin. **(A)** Interaction between gelsolin and FLAG- β_2 GPI. HEK293T cells were transfected with expression plasmids encoding FLAG-tagged β_2 GPI and gelsolin. Proteins secreted from transfected cells were subjected to immunoprecipitation (IP) with an antibody as indicated, and the resulting precipitates were subjected to immunoblot analysis with anti-gelsolin or anti-FLAG antibody. **(B)** Interaction between endogenous gelsolin and recombinant human β_2 GPI. HEK293T cells were transfected with expression plasmids encoding gelsolin. Gelsolin secreted from transfected cells was mixed with human recombinant β_2 GPI and subjected to immunoprecipitation with an antibody as indicated, and the resulting precipitates were subjected to immunoblot analysis with anti-gelsolin or anti- β_2 GPI antibody. **(C)** The binding between phospholipid-bound β_2 GPI and gelsolin was confirmed by ELISA as described in the Methods section.

Fig. 4 Interaction of β_2 GPI and plasma gelsolin on cell surface. **(A and B)** β_2 GPI binding to the cell surface. RAW264.7 cells cultured with serum-free medium were incubated with or without recombinant human β_2 GPI or FLAG- β_2 GPI, and then binding of β_2 GPI to the cell surface was detected by aCL/ β_2 GPI (WBCAL1). Mock has no primary antibody. Binding to the cell surface by recombinant human β_2 GPI (A) showed almost the same intensity as that by secreted FLAG- β_2 GPI (B). **(C)** Gelsolin affects the binding of β_2 GPI to the cell surface. RAW264.7 cells were incubated with or without recombinant FLAG- β_2 GPI and gelsolin, and then binding of β_2 GPI to the cell surface

was detected by aCL/ β_2 GPI. **(D and E)** Binding of β_2 GPI to the cell surface was inhibited by anti-integrin $\alpha 5\beta 1$ antibody. RAW264.7 cells were incubated with or without recombinant FLAG- β_2 GPI, gelsolin and anti-integrin $\alpha 5\beta 1$ antibody, and then binding of β_2 GPI to the cell surface was detected by aCL/ β_2 GPI.

Fig. 5 Change in intracellular signaling by gelsolin and aCL/ β_2 GPI. **(A)** Gelsolin and integrin affect phosphorylation of p38 MAPK by anti- β_2 GPI antibody. RAW264.7 cells were incubated for 2 h as indicated after serum-free culture for 16 h and then stimulated with aCL/ β_2 GPI (WBCAL1) for 30 min, and then phosphorylation of p38 MAPK was determined by immunoblot analysis using specific antibodies against total-p38 and phospho-p38. **(B)** Anti-integrin $\alpha 5\beta 1$ antibody inhibits phosphorylation of FAK by aCL/ β_2 GPI. RAW264.7 cells were stimulated with aCL/ β_2 GPI for 10 min and then phosphorylation of FAK was determined by immunoblot analysis. **(C)** aCL/ β_2 GPI increases NF- κ B activity. RAW264.7 cells stably expressing κ B luciferase reporter were inoculated into a 24-well dish and stimulated as indicated. After stimulation at 37°C for 4 h, κ B luciferase activity was measured.

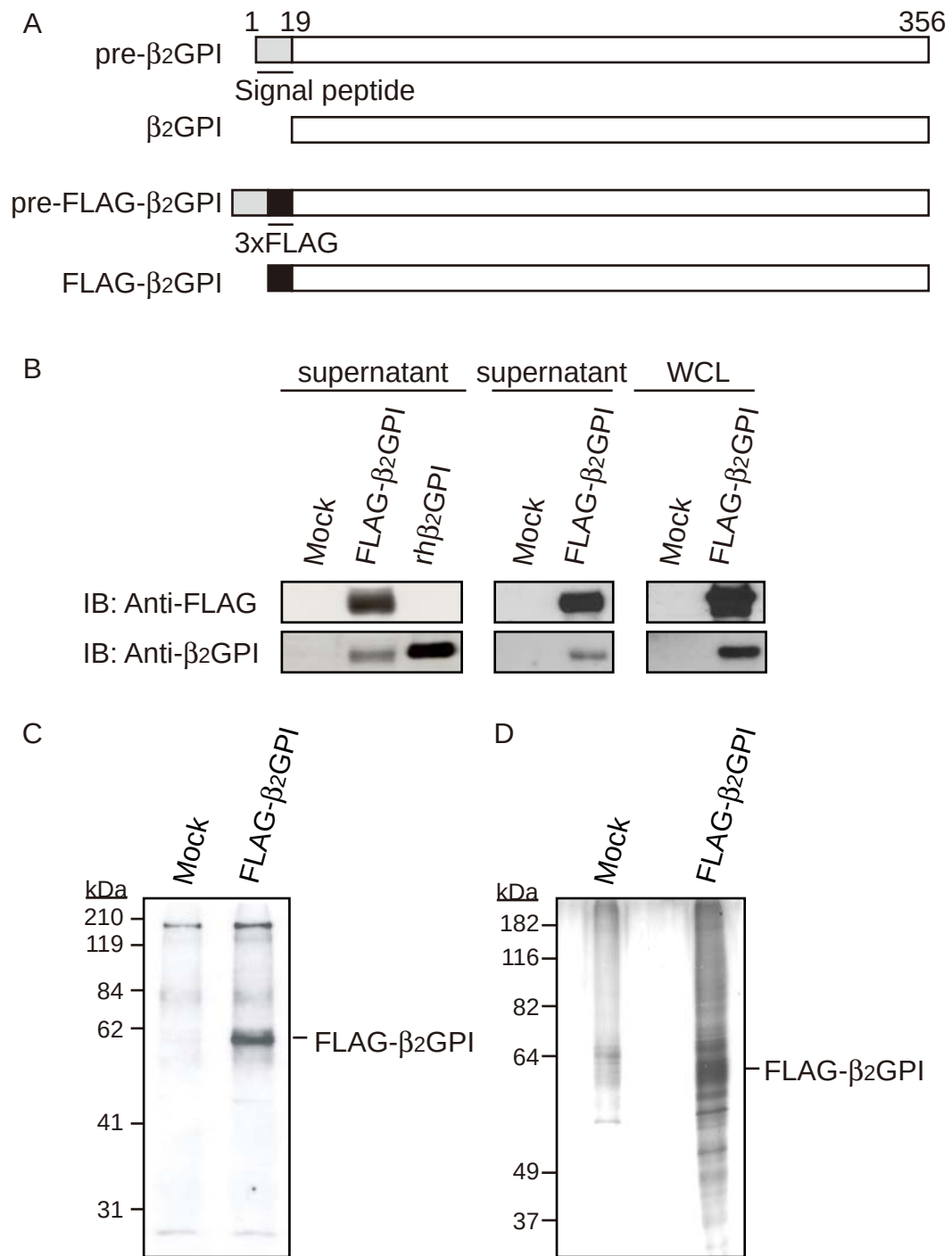


Fig. 1 Bohgaki

A

Start-stop	Charge	Sequence	Delta mass	Mascot score
2-10	2	VVEHPEFLK	-0.05	26
11-24	3	AGKEPGLQIWRVEK	-0.08	22
127 - 142	3	HVVPNEVVVQRLFQVK	-0.10	55
534 - 546	2	SGALNSNDAFVLK.	-0.06	58
547 - 564	2	TPSAAYLWVGAGASEAEK	-0.06	20

B



C

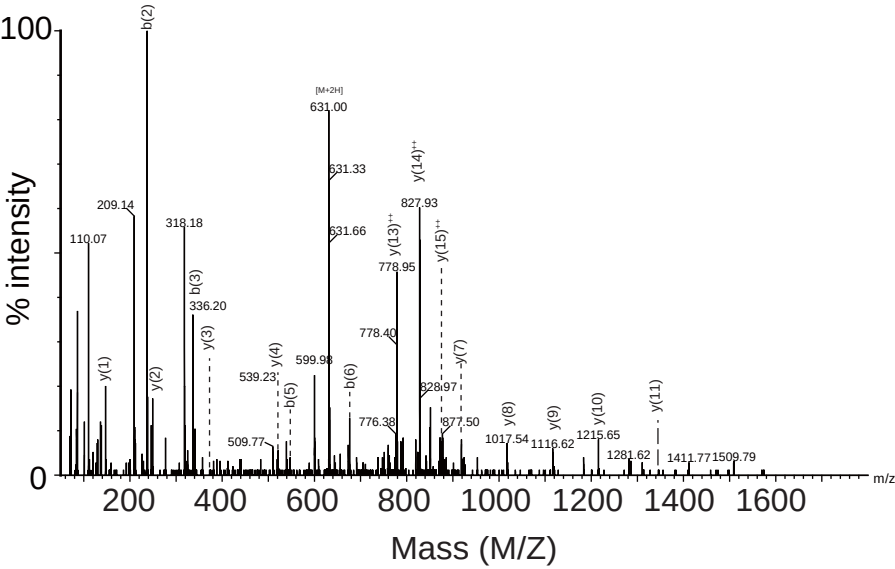


Fig. 2 Bohgaki

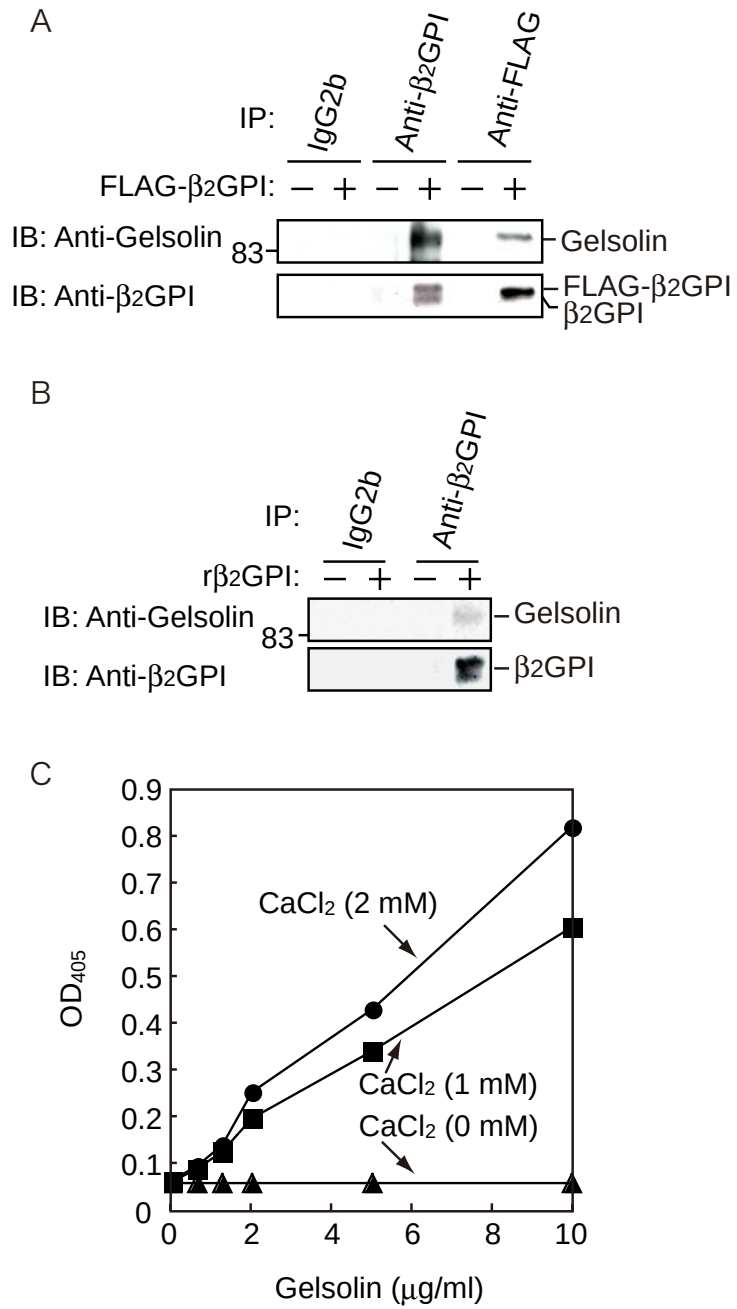


Fig. 3 Bohgaki

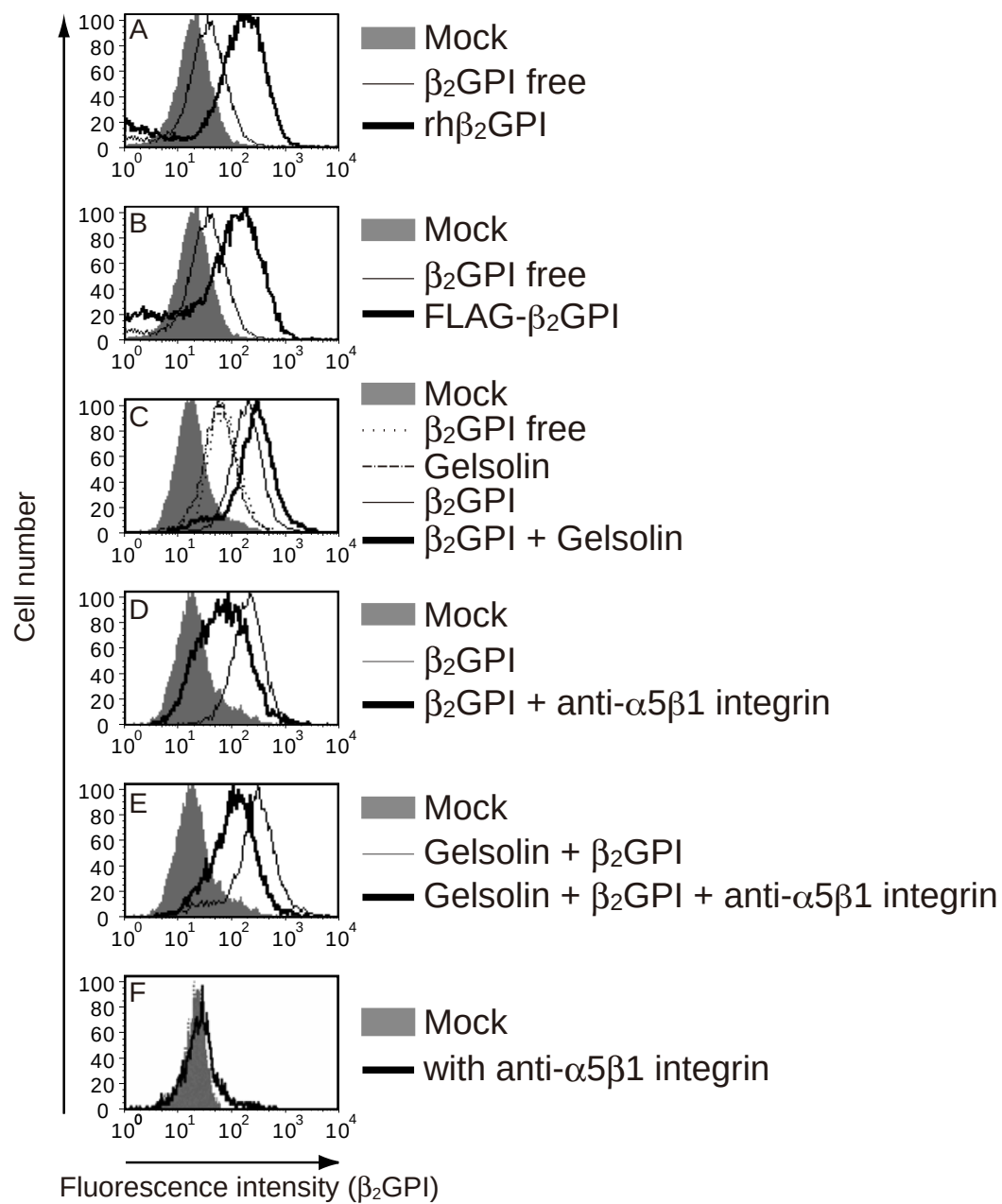


Fig. 4 Bohgaki

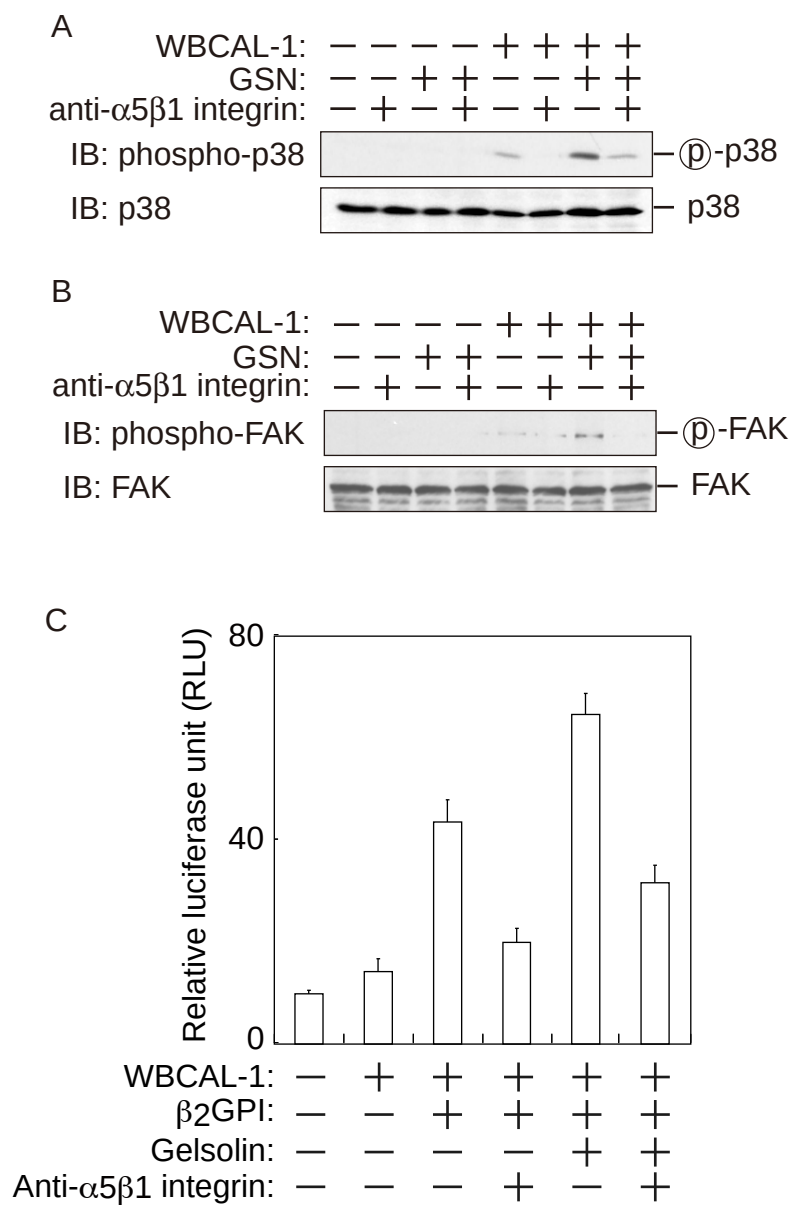


Fig. 5 Bohgaki