

Dlg5 interacts with the TGF- β receptor and promotes its degradation

Takuhito Sezaki¹, Lucia Tomiyama^{1,2}, Yasuhisa Kimura¹, Kazumitsu Ueda^{1,2}, and Noriyuki Kioka¹⁺

¹Division of Applied Life Sciences, Graduate School of Agriculture, Kyoto University, Sakyo, Kyoto 606-8502, Japan,

²Institute for Integrated Cell-Material Sciences (iCeMS), Kyoto University, Sakyo, Kyoto 606-8507, Japan

⁺To whom correspondence should be addressed.

Noriyuki Kioka, Ph.D.,

Division of Applied Life Sciences, Graduate School of Agriculture, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan

E-mail: nkioka@kais.kyoto-u.ac.jp Fax: +81-75-753-6104

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Abbreviations: ALLN, N-Acetyl-L-leucyl-L-leucyl-L-norleucinal; CD, Crohn's disease; Dlg5, Discs large homolog 5; EMT, epithelial to mesenchymal transition; IBD, inflammatory bowel disease; JNK, c-Jun N-terminal kinases; MUGUK, membrane-associated guanylate kinase; p38, 38 mitogen-activated protein; T β RI, TGF- β type I receptor; T β RII, TGF- β type II receptor; TGF- β , Transforming growth factor-beta

Abstract

Discs large homolog 5 (Dlg5) is a member of the membrane-associated guanylate kinase adaptor family of proteins and is involved in epithelial-to-mesenchymal transition via transforming growth factor- β (TGF- β) signaling. However, the mechanism underlying the regulation of TGF- β signaling is unclear. We show here that Dlg5 interacts and colocalizes with both TGF- β type I (T β RI) and type II (T β RII) receptors at plasma membrane. T β RI activation is not required for this interaction. Furthermore, the overexpression of Dlg5 enhances the degradation of T β RI. Proteasome inhibitors inhibited this enhanced degradation. These results suggest that Dlg5 interacts with T β Rs and promotes their degradation.

1. Introduction

Discs large homolog 5 (Dlg5) is a member of the membrane-associated guanylate kinase (MAGUK) adaptor family of proteins. Each MAGUK family member has at least one PDZ (P^SD-95, Dlg, Z^O-1) domain, an SH3 (Src homology 3) domain, and a guanylate kinase domain. Dlg5 was initially proposed to be one of five human homologs of the *Drosophila* Discs large (Dlg) protein, a tumor suppressor gene which is required for tumor suppression in imaginal discs, based on similarities in their sequences and domain structures [1,2]. However, Dlg5 has its own ortholog in other animals including *Drosophila*, thus it does not belong to the DLG MAGUK subfamily but seems to have its own function [2]. We have identified Dlg5 as a binding protein for vinxin [3,4] and shown that Dlg5 associates with β -catenin and that it localizes at cell-cell adhesion sites. Several other Dlg5 binding proteins, including p55 [1], syntaxin 4 [5] and citron kinase [6], have been identified. It has been reported that *Dlg5* polymorphisms are associated with Crohn's disease (CD), which is an inflammatory bowel disease (IBD) [7-11]. *Dlg5* knockout mice showed defects in the kidney and brain [5] as well as abnormal cell polarity. However, these phenotypes cannot explain the pathogenesis of CD.

Recently, we showed that Dlg5 suppresses the epithelial-to-mesenchymal transition (EMT) of renal epithelial cells via the inhibition of TGF- β receptor-dependent signaling [12]. TGF- β stimulation induces intracellular signals via two serine-threonine kinase receptors, type I (T β RI) and type II (T β RII) TGF- β receptors. Both T β RI and T β RII form stable homodimers in the absence of TGF- β . Upon TGF- β binding, T β RI homodimers and T β RII homodimers form a heterotetrameric receptor complex, leading to the activation of two downstream signaling pathways [13-15]. The first pathway is Smad signal, in which TGF- β stimulation results in T β RI-mediated phosphorylation of receptor-regulated Smads (Smad2 and Smad3). Phosphorylated Smad2 and Smad3 bind to the common mediator Smad (Smad4). The Smad2/3/4 complexes then accumulate in

the nucleus and regulate target gene transcription. The other pathway is non-Smad signal. T β RI activates c-Jun N-terminal kinases (JNK) and p38 mitogen-activated protein kinases (p38 MAPK) through MKK4 and MKK3/6, respectively, independent of Smad signals. Dlg5 depletion in LLC-PK1 renal proximal tubule epithelial cells increases the activation of JNK and p38 MAPK, which are necessary to induce the EMT of these cells [12]. Dlg5 seems to affect T β R because specific inhibition of T β RI or overexpression of Smad7, a physiological inhibitor of T β R-dependent signaling, suppresses Dlg5 depletion-induced EMT. However, the mechanism by which Dlg5 regulates T β R is unknown. Here, we show that Dlg5 interacts with T β RI and enhances its degradation.

2. Materials and methods

2.1 Antibodies and reagents

MG132 and N-Acetyl-L-leucyl-L-leucyl-L-norleucinal (ALLN) were purchased from Calbiochem. Bafilomycin and cycloheximide were from WAKO Pure Chemical Industries, Osaka, Japan and Sigma, respectively. The following antibodies were used in this study: anti-Flag (Sigma), anti-GFP (WAKO Pure Chemical Industries), anti-GFP (Santa Cruz Biotechnology), anti-T β RI (Santa Cruz Biotechnology), anti- β -tubulin (Sigma), and anti-vinculin (Sigma) antibodies. The anti-Dlg5 antibody was described previously [3].

2.2 Cell culture, plasmids, and transfection

The 293T and Caco-2 cells (RIKEN BRC through the National Bio-Resource Project of the MEXT, Japan) were maintained in Dulbecco's Modified Eagle Medium containing 10% fetal bovine serum. PC3 cells (obtained from Dr. Yoshiyuki Kakehi of Kagawa University) were maintained in RPMI-1640 medium containing 10% fetal bovine serum. The longest variant of Dlg5 (Dlg5 α , see Fig. 1E), which includes 1,919

amino acids containing CARD (caspase recruitment domain), coiled-coil, SH3, and GUK domains, as well as four PDZ domains, was purchased from Promega (Madison, USA). A shorter variant (Dlg5 β), which lacks the CARD domain, was described previously [3]. Dlg5 Δ CC, which lacks the CARD and coiled-coil domains and corresponds to an open reading frame of KIAA0583 (AB011155), was obtained from the Kazusa DNA Research Institute. Plasmids encoding the TGF- β receptors (T β RI-FLAG and T β RII-HA, both of which are epitope-tagged at C-terminus) were gifts from Dr. S. Aota (RIKEN, Japan). Transfection of plasmid DNA was performed using Lipofectamine LTX (Invitrogen) according to the manufacturer's instructions.

2.3 RNA interference (RNAi)

The stealth siRNAs for Dlg5/lp-dlg (GGAUUCCAUGGAGUGGGAAACGGAA) were designed based on the sequence of the human Dlg5 cDNA (NP_004738) and synthesized by Invitrogen. The transfection of siRNAs (10 nM) was performed using Lipofectamine RNAiMAX (Invitrogen) as previously described [16].

2.4 Immunoprecipitation and immunoblotting

Immunoprecipitation and immunoblotting were performed as previously described [12,17]. Briefly, cells cultured under various conditions were washed with PBS. The cells were then lysed in RIPA buffer without SDS (150 mM NaCl, 1% NP-40, 0.5% sodium deoxycholate, 50 mM Tris-HCl pH 7.5, 0.1 mg/mL *p*-amidinophenyl methanesulfonyl fluoride, 5 μ g/mL leupeptin, and 10 μ g/mL aprotinin) on ice for 30 minutes. Lysates were centrifuged at 18,700 $\times$ g for ten minutes. For immunoprecipitation, equal amounts of cell lysate were incubated with the indicated antibodies for 1 hour and then with Protein G sepharose beads for 1 hour. For immunoblotting, cell lysates or immunoprecipitates were electrophoresed and transferred onto PVDF membranes (Millipore). After blocking with BLOCKING ONE (Nacalai Tesque, Kyoto, Japan), the membranes were incubated with primary antibodies

and then with the appropriate secondary antibodies. Antigen detection was performed with an LAS 3000 image analyzer (FUJIFILM, Tokyo, Japan) using the ImmunoStar LD kit (Wako, Osaka, Japan). Quantification was performed by Multi Gauge (FUJIFILM, Tokyo, Japan).

2.5 Immunostaining

Caco-2 cells were transfected with plasmids encoding GFP-Dlg5 Δ CC, T β RI-Flag and T β RII-HA. The cells were cultured on coverslips coated with type IV collagen for 24 hours. Cells were fixed with methanol for 20 minutes at -20°C and blocked with 10% goat serum in PBS+ for 30 minutes. They were then incubated with anti-Flag antibody and anti-HA antibody for 1 hour at room temperature, followed by incubation with Alexa 633-labeled goat anti-rabbit IgG (Invitrogen) and Alexa 546-labeled goat anti-rat IgG for 1 hour. Fluorescence imaging was performed with a LSM700 confocal microscopy system (Carl Zeiss Co., Ltd.).

2.6 Statistical analysis

The statistical analysis was performed using Student's paired *t*-test.

3. Results

3.1 Dlg5 interacts with T β RI and T β RII

Previously, we showed that Dlg5 suppresses EMT through the inhibition of TGF- β receptor-mediated signaling [12]. Several molecules, including Smad7 and Smurf1/2, attenuate TGF- β signaling via binding to the T β Rs [18]. To examine whether Dlg5 can interact with T β Rs, T β RI-Flag and T β RII-HA were cotransfected with GFP-tagged Dlg5 variant (GFP-Dlg5 Δ CC) into 293T cells, followed by coimmunoprecipitation using an anti-GFP antibody. As shown in Fig. 1A, both T β RI and T β RII were coprecipitated with Dlg5 Δ CC. To check whether Dlg5 could bind T β RI independent of

T β RII and vice versa, we performed immunoprecipitation assays. GFP-Dlg5 Δ CC was transfected into 293T cells with T β RI-Flag and then immunoprecipitated with anti-GFP antibody. T β RI (Fig. 1B) was coprecipitated with Dlg5 Δ CC. The reciprocal coimmunoprecipitation experiment confirmed this interaction (data not shown). We also examined whether the interaction of Dlg5 with T β RII depends on T β RI. GFP-Dlg5 Δ CC was transfected into 293T cells with T β RII-HA and then immunoprecipitated with anti-GFP antibody. T β RII (Fig. 1C) was coprecipitated with Dlg5 Δ CC. These results indicate that Dlg5 can interact with both T β RI and T β RII independently. Dlg5 has splice variants, such as Dlg5 α and β (Fig. 1E, also see Materials and Methods). To determine which Dlg5 splice variants can interact with the T β Rs, coimmunoprecipitation experiments with Dlg5 α , - β , and - Δ CC were performed. T β RI coprecipitated with all these Dlg5 variants (Fig. 1D), suggesting that these variants all contain the T β RI interaction region. Because T β RI coprecipitated the most effectively with Dlg5 Δ CC, possibly because Dlg5 α and Dlg5 β were less soluble in the lysis buffer than Dlg5 Δ CC (Fig. 1D), primarily Dlg5 Δ CC was used in subsequent experiments.

To confirm the interaction between endogenous Dlg5 and the T β Rs, we performed coimmunoprecipitation experiments using PC3 prostate cancer cells in which Dlg5 is expressed at high levels. The PC3 cell lysates were subject to immunoprecipitation with anti-T β RI antibody and examined for coimmunoprecipitation of endogenous Dlg5. As shown in Fig. 2, Dlg5 was detected when anti-T β RI antibody, but not control IgG, was used for the immunoprecipitation. Transfection of Dlg5 siRNA reduced the expression of Dlg5 in lysates as well as in the coprecipitation of Dlg5 with T β RI. We could not detect coimmunoprecipitation of endogenous T β RII with Dlg5 because it could not be immunoprecipitated efficiently (data not shown). These results suggest that Dlg5 binds T β RI under physiological conditions. Thus, we focused on T β RI in subsequent experiments.

3.2 T β RI activation and kinase activity are not necessary for Dlg5 binding

The interactions of T β RI with Smad7, SARA (Smad anchor for receptor activation), and TAK1 (TGF- β activated kinase 1) are regulated by T β RI activation [18-21]. To investigate whether T β RI activation affects its interaction with Dlg5, coimmunoprecipitation experiments using constitutively active (CA-T β RI T204D) and kinase-dead (KD-T β RI D351A) T β RI mutants were performed. As shown in Fig. 3A, CA-T β RI and KD-T β RI were coimmunoprecipitated with Dlg5 similarly to WT-T β RI. Next, we examined the effect of TGF- β stimulation on the Dlg5-T β RI interaction. After cotransfection of T β RI with GFP-Dlg5 Δ CC, the cells were incubated with TGF- β for 30 or 180 minutes before immunoprecipitation was performed (Fig. 3B). T β RI was coimmunoprecipitated with GFP-Dlg5 Δ CC before TGF- β stimulation. Thirty minutes after TGF- β stimulation, phosphorylated Smad2 was detected, thus indicating the activation of T β RI. However, the amount of T β RI coimmunoprecipitated was comparable to that before TGF- β stimulation, even after TGF- β stimulation for 30 or 180 minutes (Fig. 3B). We also examined the effect of TGF- β stimulation on the interaction of endogenous proteins. PC3 cells were treated with or without TGF- β , then cell lysates were immunoprecipitated with anti-T β RI antibody. Coimmunoprecipitated Dlg5 with T β RI in TGF- β treated cells was comparable to that in untreated cells (Fig. 3C). These results suggest that T β RI activation and kinase activity are not necessary for binding to Dlg5.

3.3 Dlg5 colocalizes with T β Rs at the plasma membrane

To test for colocalization of Dlg5 with the T β Rs in cells, Caco-2 colon epithelial cells were used. Caco-2 cells have well-organized cell-cell adhesion structures where Dlg5 localizes (data not shown). GFP-Dlg5 Δ CC, T β RI-Flag, and T β RII-HA were cotransfected into Caco-2 cells. Cells were fixed and immunostained with anti-Flag and anti-HA antibodies. GFP-Dlg5 Δ CC localized to the plasma membrane as well as

diffusely (Fig. 4), which is consistent with a previous report [3]. Both T β RI-Flag and T β RII-HA were also detected at the plasma membrane as well as in the cytosol (Fig. 4). The merged image indicates the colocalization of T β RI, T β RII, and GFP-Dlg5 Δ CC at the plasma membrane. These results suggest that GFP-Dlg5 Δ CC, T β RI-Flag, and T β RII-HA colocalize at the plasma membrane in Caco-2 cells.

3.4 Dlg5 overexpression promotes T β RI degradation

The degradation of T β RI and T β RII is one of main regulatory mechanisms of TGF- β signaling [18,22-25]. To investigate whether Dlg5 affects T β RI degradation, GFP-Dlg5 Δ CC and T β RI-Flag were cotransfected into 293T cells. Twenty-four hours after transfection, cycloheximide was added to the culture medium to inhibit protein synthesis. After further incubation for 0-8 hours, T β RI expression was examined by immunoblotting with anti-Flag antibody. As shown in Fig. 5A, T β RI levels decreased only slightly over time in control cells. In contrast, T β RI levels decreased significantly faster in Dlg5 Δ CC-expressing cells. A quantitative analysis showed that the amount of T β RI was reduced to 80 % and 50 % in control and Dlg5 Δ CC-expressing cells, respectively, 4 hours after the addition of cycloheximide (Fig. 5B). Consistent with this overexpression experiments, Dlg5 knockdown in PC3 cells significantly increased the T β RI expression both under TGF- β -stimulated and -unstimulated conditions (Fig. 5C, D). T β RII degradation after cycloheximide treatment was also examined in 293T cells, but it was very slow and no decrease in T β RII protein levels was detected, even eight hours after cycloheximide treatment (data not shown). These results suggest that Dlg5 promotes the degradation of T β RI.

Proteasomal and lysosomal degradation pathways mediate T β RI degradation, which is enhanced by its interaction with Smad7 [18,24]. To test which degradation pathway is engaged by Dlg5, cells were cotransfected with GFP-Dlg5 Δ CC and T β RI-Flag and then treated with the proteasome inhibitor MG132 or the lysosome inhibitor bafilomycin for

8 hours. Consistent with Fig. 5, Dlg5 Δ CC overexpression significantly decreased T β RI protein levels (Fig. 6A, D). Treatment with MG132 significantly increased T β RI levels in Dlg5 Δ CC-overexpressing cells but not in control cells (Fig. 6B, E). Quantitative analysis showed that MG132 treatment increased T β RI levels 1.3-fold. Another proteasome inhibitor, ALLN, also increased T β RI levels in GFP-Dlg5 Δ CC expressing cells (data not shown). In contrast, bafilomycin increased T β RI levels in both control and Dlg5 Δ CC-overexpressing cells (Fig. 6C, F). These results suggest that Dlg5 enhances the proteasome-dependent degradation of T β RI.

4. Discussion

Dlg5, a member of the MAGUK family of adaptor proteins, localizes at cell-cell adhesion sites. We previously showed that Dlg5 suppresses T β R-mediated signaling and EMT in renal epithelial cells [12]. However, the mechanism of this suppression is unknown. In this research, we found that both T β RI-Flag and T β RII-HA were clearly coprecipitated with Dlg5 Δ CC. Furthermore, endogenous Dlg5 was also coimmunoprecipitated with endogenous T β RI in PC3 cells. GFP-Dlg5 was colocalized with T β RI-Flag and T β RII-HA at cell-cell adhesion sites in Caco-2 cells. These results indicate that Dlg5 forms a signaling complex with T β Rs at the plasma membrane.

We showed here that treatment with proteasome inhibitors suppressed Dlg5 Δ CC-enhanced T β RI degradation. Lysosome inhibitor increased the T β RI expression in Dlg5 Δ CC-expressing cells but it also increased the expression in control cells, implying that Dlg5 enhanced T β RI degradation via proteasome-dependent mechanisms. In some cases, negative regulators of TGF- β signaling associate with T β Rs and promote T β R degradation *via* proteasome- and lysosome-dependent pathways simultaneously [18,24,25]. In other cases, only proteasomal degradation contributes to the T β R degradation [26]. Cellular context may explain the different pathway for the T β RI degradation.

Expression of the TGF- β -signaling inhibitor Smad7 is enhanced by TGF- β stimulation itself. The interaction of T β RI with Smad7 is stimulated by T β RI activation [18-20]. Thus, Smad7 seems to function in a negative feedback loop regulating TGF- β signaling. In contrast, the interaction of Dlg5 with T β RI was not stimulated by T β RI activation. Both the constitutively active mutant of T β RI (CA-T β RI) and the kinase-dead mutant KD-T β RI bind Dlg5 in a manner comparable to the wild type receptor. TGF- β stimulation for 30 or 180 minutes did not affect these interactions. Furthermore, Dlg5 expression decreases after TGF- β stimulation [12]. Thus, Dlg5 seems to participate in positive feedback (specifically double-negative type feedback [27,28]) loop regulating TGF- β signaling but not in a normal negative feedback loop. Alternatively, Dlg5 may suppress leaky (non-specific) activation of TGF- β signaling by binding T β Rs, in a mechanism similar to FKBP12 [29].

The dysregulation of TGF- β signaling increases the risk of CD. TGF- β 1 knockout mice develop systemic inflammation, including in the gut [30]. High levels of Smad7 are observed in CD patients [31], and its knockdown attenuates experimental colitis in mice [32]. We found that Dlg5 interacts with T β Rs and promotes their degradation. These results may explain how *Dlg5* polymorphisms affect the development of IBD, including CD. Future experiments will be directed towards understanding the relationship between Dlg5 polymorphisms and the regulation of T β R signaling.

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Figure legends

Figure 1. GFP-Dlg5 is coimmunoprecipitated with T β RI-Flag and T β RII-HA. A-C: GFP or GFP-Dlg5 Δ CC were cotransfected into 293T cells together with Flag-tagged T β RI and HA-tagged T β RII (A), Flag-tagged T β RI (B) or HA-tagged T β RII (C). Cell lysates were subject to immunoprecipitation (IP) with an anti-GFP antibody. Immune complexes were examined using the antibodies indicated. Arrows mean differentially glycosylated forms of T β RII. **D:** T β RI-Flag, as well as either GFP, GFP-Dlg5 α , GFP-Dlg5 β or GFP-Dlg5 Δ CC, was transfected into 293T cells. Cell lysates were immunoprecipitated with anti-GFP antibody, and immunoblotting was performed with the antibodies indicated. **E:** Schematic diagram showing the protein domains of Dlg5 α , - β , and - Δ CC. Dlg5 α contains CARD, coiled-coil, SH3, and GUK domains, as well as four PDZ domains. Dlg5 α and β are splice variants. Dlg5 Δ CC is a deletion mutant that lacks the CARD and coiled-coil domains.

Figure 2. Endogenous Dlg5 is coimmunoprecipitated with T β RI in PC3 cells. PC3 cells were transfected with Dlg5 siRNA and incubated for three days. The cells were then lysed and immunoprecipitated with anti-T β RI antibody or control IgG. The immune complexes were examined with the antibodies indicated.

Figure 3. T β RI activation and kinase activity are not necessary for binding to Dlg5. **A:** GFP-Dlg5 Δ CC, together with Flag-tagged wild type (WT), constitutively active (CA) or kinase-dead (KD) T β RI, was transfected into 293T cells. Cell lysates were immunoprecipitated (IP) with anti-GFP antibody and immunoblotted with the antibodies indicated. The expression levels of KD-T β RI were low for unknown reasons. **B:** 293T cells were transfected with Flag-tagged T β RI and GFP-tagged Dlg5 Δ CC. The cells were then treated with TGF- β for 30 or 180 minutes, followed by immunoprecipitation and immunoblotting with the antibodies indicated. **C:** PC3 cells were treated with or without TGF- β for 30 minutes, followed by immunoprecipitation and immunoblotting with the antibodies indicated.

Figure 4. Dlg5 colocalizes with T β RI and T β RII. Caco-2 cells were cotransfected with T β RI-Flag, T β RII-HA and GFP-Dlg5 Δ CC. The cells were fixed and immunostained with anti-Flag and anti-HA antibodies. Dlg5 was visualized by GFP fluorescence.

Figure 5. Dlg5 promotes T β RI degradation. **A:** GFP-Dlg5 Δ CC and T β RI-Flag were cotransfected into 293T cells. Twenty-four hours after transfection, 100 μ g/ml cycloheximide was added to the culture medium to inhibit protein synthesis. After further incubation for 0-8 hours, T β RI expression was determined by immunoblotting with an anti-Flag antibody. **B:** The relative T β RI expression in A was quantified. The values represent the mean $\pm$ S.E. from three independent experiments. **C:** PC3 cells were transfected with Dlg5 siRNA and incubated for three days. The cells were then treated with TGF- β for 30 minutes, followed by immunoblotting with the indicated antibodies. Vinculin was used as a loading control. **D:** T β RI expression in C was quantified. The values represent the mean $\pm$ S.E. from three independent experiments.

Figure 6. Dlg5-enhanced T β RI degradation involves proteasome. **A-C:** Cells were cotransfected with GFP-Dlg5 Δ CC and T β RI-Flag, then treated without (A) or with MG132 (B) or bafilomycin (C). After incubation for eight hours, T β RI levels were determined by immunoblotting with the antibodies indicated. Vinculin was used as a loading control. **D-F:** T β RI expression in A-C was quantified. The values represent the mean $\pm$ S.E. from three independent experiments.

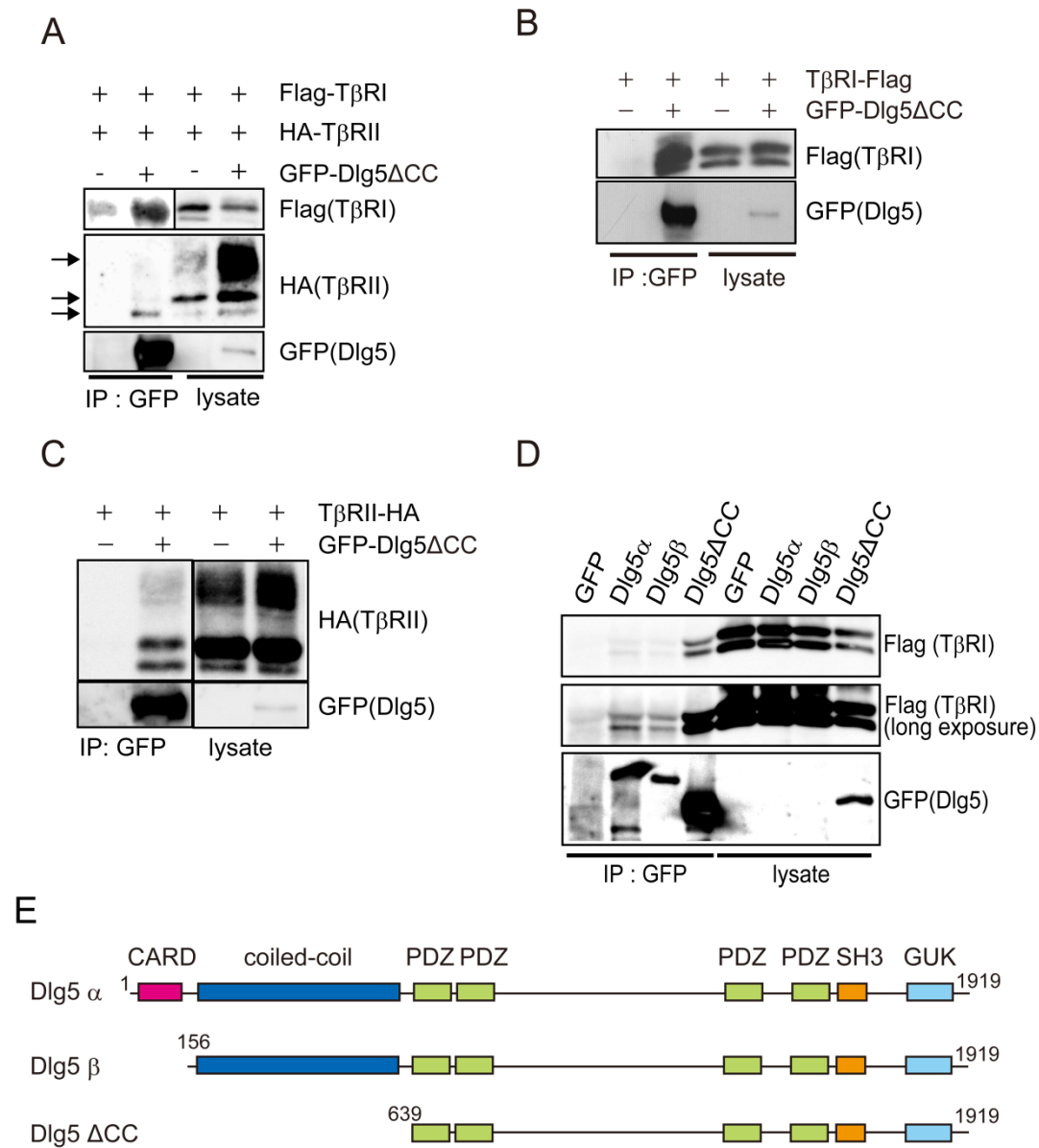


Fig. 1 Sezaki et al.

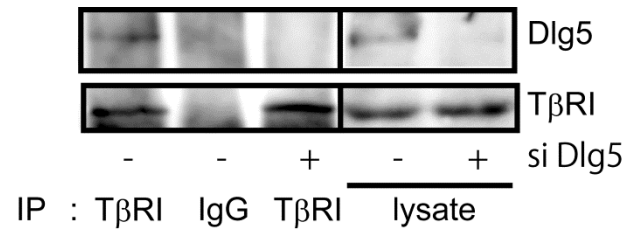


Fig. 2 Sezaki et al.

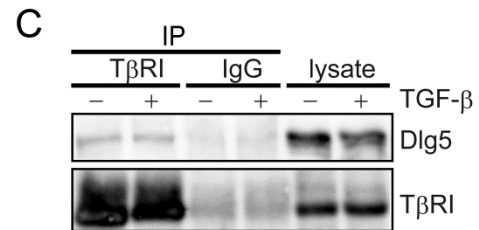
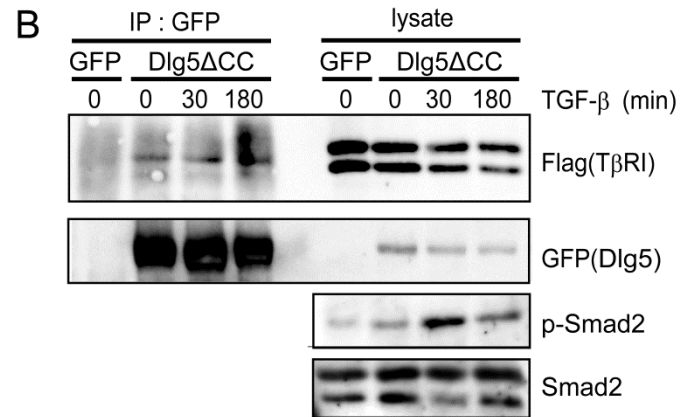
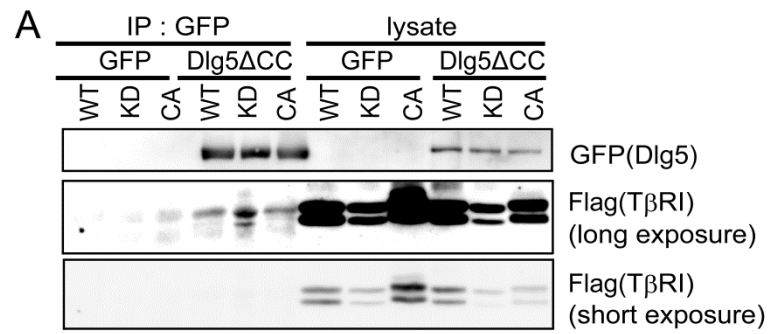


Fig 3. Sezaki et al.

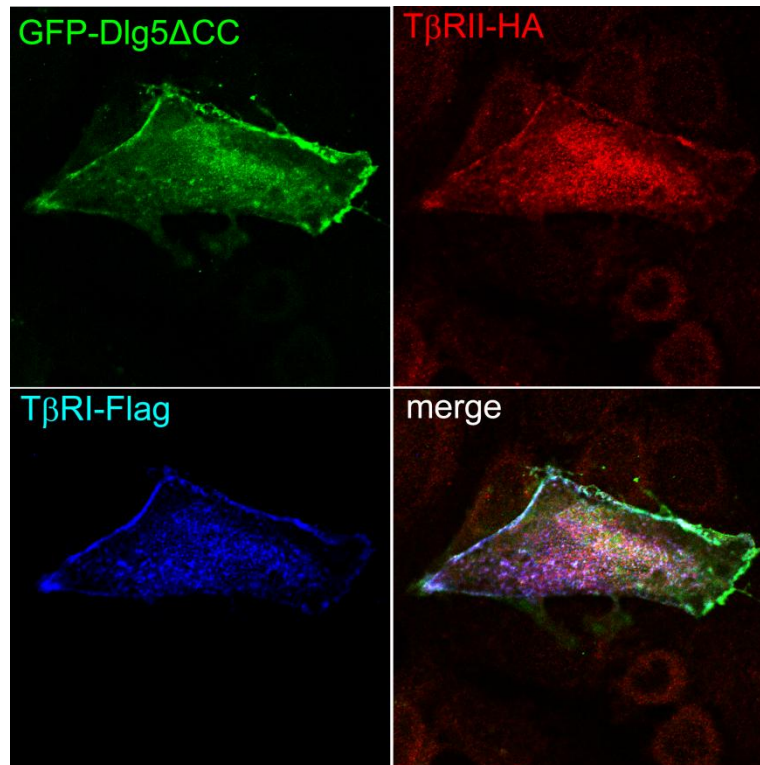


Fig. 4 Sezaki et al.

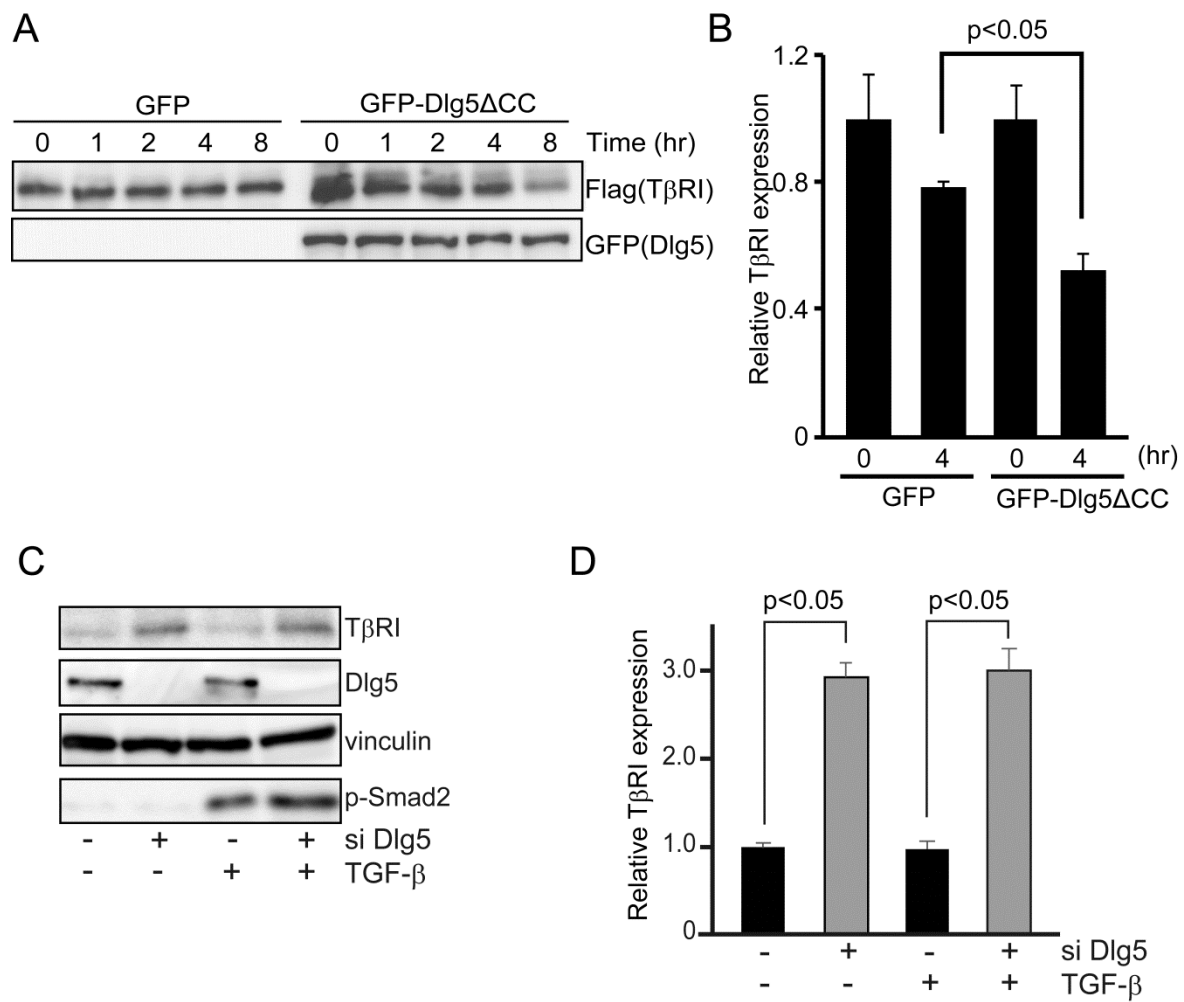


Fig. 5 Sezaki et al.

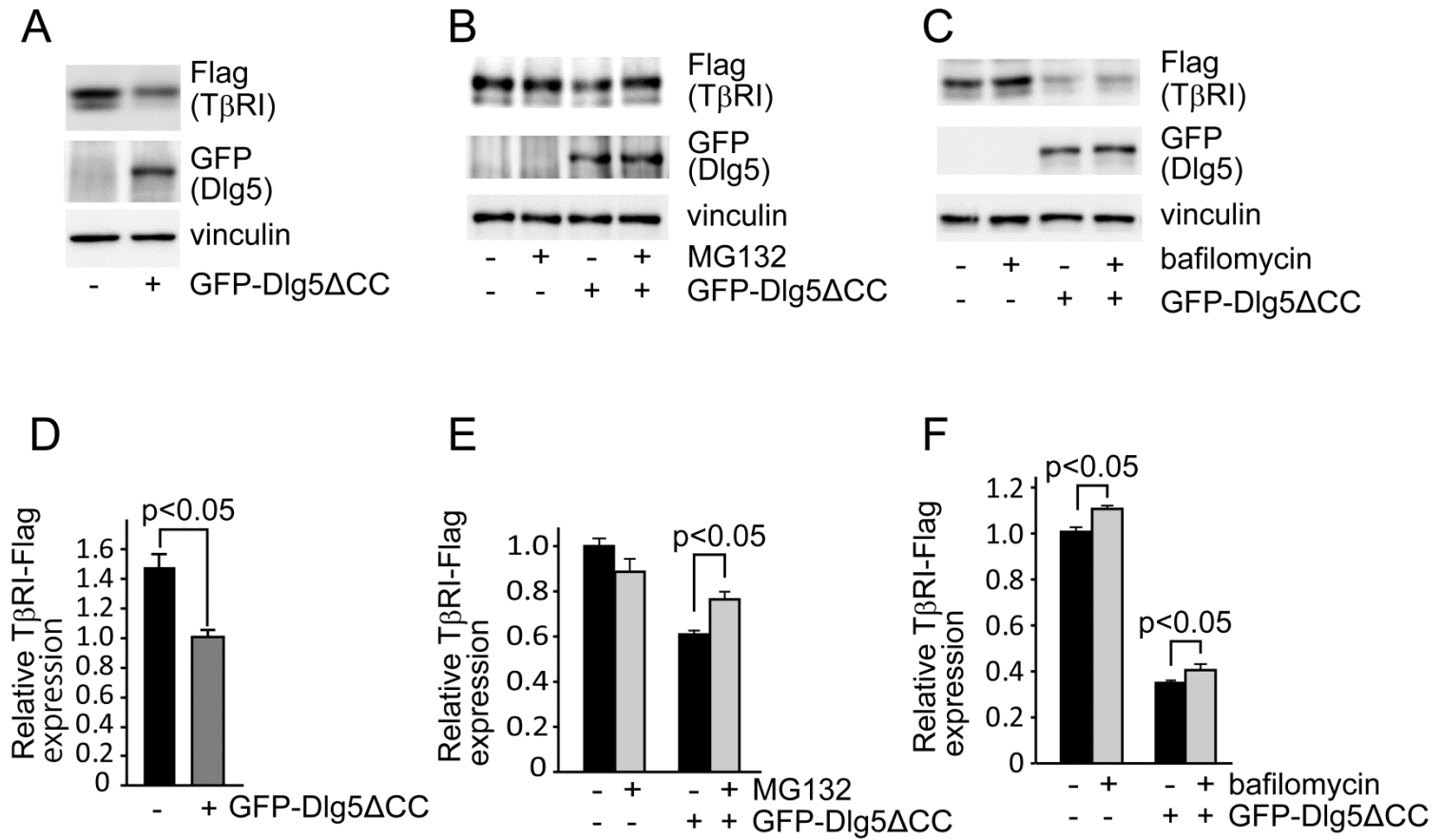


Fig. 6 Sezaki et al.