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TspanC8 tetraspanins regulate ADAM10/Kuzbanian trafficking and promote Notch activation in flies and mammals

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Introduction

Cell–cell communication during development and throughout adult life are mediated via secreted and cell surface proteins. Various regulatory mechanisms ensure proper levels of cell–cell interactions and signaling in time and space. One such mechanism involves the regulated processing of cell surface proteins by proteases of the ADAM (a disintegrin and metalloprotease) family. ADAM proteases are type I transmembrane proteins that cleave membrane proteins at sites located close to the membrane, thereby leading to the extracellular release of the ectodomain. This shedding mechanism is essential for cytokine secretion, cell–cell adhesion, and signaling by transmembrane ligands and receptors (Blobel, 2005; Reiss and Saftig, 2009).

ADAM10 is one of the best-characterized members of the ADAM family (Blobel, 2005; Reiss and Saftig, 2009).

ADAM10 has several important targets including the amyloid precursor protein (APP) involved in Alzheimer’s disease, Fas ligand, several EGF receptor ligands, and Notch receptors. Genetic and biochemical studies have shown that ADAM10, known as Kuzbanian (Kuz) in Drosophila, regulates the ligand-dependent processing of Notch at an extracellular site called S2 (Pan and Rubin, 1997; Sotillos et al., 1997; Wen et al., 1997; Brou et al., 2000; Mumm et al., 2000; Hartmann et al., 2002; Lieber et al., 2002; Bozkulak and Weinmaster, 2009; van Tetering et al., 2009). This site is normally protected from ADAM10 cleavage by three Lin12-Notch repeats (LNRs). Upon ligand binding, a ligand-induced conformational change is thought to displace the LNRs, thereby exposing the S2 site to ADAM10 (Gordon et al., 2007; Tiyanont et al., 2011; Meloty-Kapella et al., 2012). S2 cleavage by ADAM10 generates a membrane-tethered form of Notch that is further processed by γ-secretase.

The metalloprotease ADAM10/Kuzbanian catalyzes the ligand-dependent ectodomain shedding of Notch receptors and activates Notch. Here, we show that the human tetraspanins of the evolutionary conserved TspanC8 subfamily (Tspan5, Tspan10, Tspan14, Tspan15, Tspan17, and Tspan33) directly interact with ADAM10, regulate its exit from the endoplasmic reticulum, and that four of them regulate ADAM10 surface expression levels. In an independent RNAi screen in Drosophila, two TspanC8 genes were identified as Notch regulators. Functional analysis of the three Drosophila TspanC8 genes (Tsp3A, Tsp86D, and Tsp26D) indicated that these genes act redundantly to promote Notch signaling. During oogenesis, TspanC8 genes were up-regulated in border cells and regulated Kuzbanian distribution, Notch activity, and cell migration. Furthermore, the human TspanC8 tetraspanins Tspan5 and Tspan14 positively regulated ligand-induced ADAM10-dependent Notch1 signaling. We conclude that TspanC8 tetraspanins have a conserved function in the regulation of ADAM10 trafficking and activity, thereby positively regulating Notch receptor activation.
at an S3 site located within the transmembrane domain of Notch. S3 cleavage results in the release of the Notch intracellular domain (NICD) that acts in the nucleus to regulate the transcription of Notch target genes (Lecourtois and Schweisguth, 1998; Schroeter et al., 1998; Struhl and Adachi, 1998; De Strooper et al., 1999; Kopan and Ilagan, 2009).

ADAM10 was recently shown to associate with several tetraspanins (Arduise et al., 2008; Xu et al., 2009). Tetraspanins are integral membrane proteins with four transmembrane segments, three short intracellular domains, and a specific fold in the largest of the two extracellular domains. They are expressed in many cell types and have been implicated in various biological processes including cell migration, cell fusion, lymphocyte activation, as well as viral and parasitic infections (Hemler, 2005; Charrin et al., 2009). Tetraspanins are believed to play a role in membrane compartmentalization. This hypothesis is based to a large extent on their unique ability to interact with one another and with non-tetraspanin integral proteins to form a dynamic network of interactions (Hemler, 2005; Charrin et al., 2009). Inside this “tetraspanin web” or “tetraspanin-enriched microdomains,” tetraspanins specifically interact with a limited number of partner proteins to form primary complexes. These in turn assemble through tetraspanin–tetraspanin interaction to generate higher order complexes. Primary complexes can be isolated from higher order complexes using detergents such as digitonin, which disrupt tetraspanin–tetraspanin interactions and/or precipitate higher order complexes. Such biochemical approaches have been instrumental to show that the integrins α3β1 and α6β1 form primary complexes with the tetraspanin CD151 and that the Ig domain-containing proteins CD9P-1/EWI-F and EWI-2 are partners of both CD9 and CD81 (Yauch et al., 1998; Serru et al., 1999; Charrin et al., 2001, 2003; Stipp et al., 2001a,b). By contrast, the specific tetraspanins that directly interact with ADAM10 to form primary complexes have not been identified.

In this study, members of a subfamily of tetraspanins that we named TspanC8 were identified as direct and specific partners of ADAM10. In an independent large-scale RNAi screen in Drosophila, we uncovered two TspanC8 genes as positive regulators of Notch. Using a combination of in vitro and in vivo assays, we show that TspanC8 tetraspanins regulate the exit of ADAM10/Kuzbanian from the ER, promote its accumulation at the cell surface, and thereby regulate Notch receptor activation in both flies and mammals.

Results

Biochemical identification of TspanC8 tetraspanins as direct partners of ADAM10

Several tetraspanins were previously shown to interact with the mature form of ADAM10 (~68 kD under nonreducing conditions) but not with the immature one (~100 kD, with its prodomain; Arduise et al., 2008; Xu et al., 2009). These coimmunoprecipitation experiments were however performed using a detergent, Brij 97, that preserved tetraspanin–tetraspanin interactions (Fig. 1A) and therefore did not discriminate between direct and indirect interactions. To reveal specific and direct interactions, coimmunoprecipitations were performed after lysis with digitonin. Using digitonin, ADAM10 did not interact with the classical tetraspanins CD9, CD63, CD81, CD82, and CD151, whereas CD9 still interacted with CD9P-1 (Fig. 1A and unpublished data). We conclude that the previously reported interactions of tetraspanins with ADAM10 were indirect.

The lack of digitonin-resistant interactions between ADAM10 and classical tetraspanins prompted us to investigate whether less well-characterized tetraspanins could be the direct partners of ADAM10. We initially selected a subset of tetraspanins identified through database mining (Serru et al., 2000). Because no antibodies were available, V5- or GFP-tagged tetraspanins were transiently expressed into PC3 cells that express high levels of ADAM10. Tspan5 (NET-4), but not Tspan1 (NET-1) or Tspan9 (NET-5), was found to coimmunoprecipitate ADAM10 after digitonin lysis (Fig. 1B and C). Tspan5 belongs to a subfamily of tetraspanins that are characterized by the presence of eight cysteines in the large extracellular domain (Boucheix and Rubinstein, 2001; Huang et al., 2005). We refer to this family here as TspanC8. This family also includes Tspan10 (oculospanin), Tspan14 (DC-TM4F2), Tspan15 (NET-7), Tspan17, and Tspan33 (penumbra). By contrast with most tetraspanins, TspanC8 family members appeared to be evolutionarily conserved from invertebrates to mammals (Fig. S1). ADAM10 was found to interact in a digitonin-resistant manner with GFP-tagged Tspan14, Tspan15, Tspan33, and, to a lesser extent, with Tspan10 and Tspan17 (Fig. 1C). By contrast, two GFP-tagged non-TspanC8 tetraspanins, CD9 and Tspan12, did not coimmunoprecipitate ADAM10 (Fig. 1C).

A Tspan5 molecule mutated at all four putative palmitoylation sites still interacted with ADAM10 (Fig. 1D). Because interactions between tetraspanins rely to a large extent on their palmitoylation (Berditchevski et al., 2002; Charrin et al., 2002; Yang et al., 2002), this result indicated that ADAM10 interacted directly with Tspan5. Direct interactions of ADAM10 with TspanC8 were further suggested by the detection of complexes containing ADAM10 and Tspan5, Tspan14, Tspan15, and Tspan33 after chemical cross-linking (Fig. 1E). Together, these biochemical data indicate that ADAM10 directly interacts with TspanC8 tetraspanins.

Genetic identification of TspanC8 tetraspanins as Notch regulators

In a parallel approach, two genes of the TspanC8 family, Tsp3A and Tsp86D, were identified in an RNAi screen for Notch regulators in Drosophila. Conditional silencing was achieved using the binary UAS/GAL4 system in combination with the thermosensitive GAL80ts inhibitor. We used the apterous-Gal4 driver (ap-Gal4) to direct dsRNA expression in imaginal tissues giving rise to the adult dorsal thorax. 11,199 UAS-dsRNA transgenic lines targeting 6,020 genes, i.e., 40% of the fly genome, were screened. This primary screen led to the identification of 272 genes with previously unknown function in sensory organ development (unpublished data). The silencing of Tsp3A and Tsp86D in imaginal tissues resulted in a weak increase in the number of adult sensory bristles (Figs. S2 and S3), a phenotype
Mummery-Widmer et al. (2009) were weaker than those used in our screen (not depicted). Thus, this screen identified Tsp3A and Tsp86D as potential regulators of Notch.

The Drosophila TspanC8 family includes a third member, Tsp26A, not tested in our screen. Silencing of Tsp26A did not affect bristle density (Figs. S2 and S3). The weak (or lack of) RNAi phenotypes seen for the TspanC8 genes may be due to the partial nature of the silencing effect by dsRNA (Dietzl et al., 2007) indicative of reduced Notch activity (Hartenstein and Posakony, 1990). A similar effect was observed in secondary screens using dsRNA and miRNA constructs that did not overlap with the dsRNA transgenes used in the screen (Fig. S3), therefore arguing against off-target effects. Of note, the Tsp3A and Tsp86D genes were not found in a previous bristle screen for Notch regulators (Mummery-Widmer et al., 2009). Consistent with this, the Tsp3A and Tsp86D RNAi lines used by Mummery-Widmer et al. (2009) were weaker than those used in our screen (not depicted). Thus, this screen identified Tsp3A and Tsp86D as potential regulators of Notch.

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Figure 1. Several TspanC8 tetraspanins interact with ADAM10 in a digitonin-resistant manner. [A] HCT116 cells were lysed in the presence of Brij 97 or digitonin before immunoprecipitation with the indicated mAb. The composition of the complexes was analyzed by Western blot. This experiment is representative of several experiments performed with various cell lines. Int-a2: integrin a2. [B] PC3 cells were transiently transfected with V5-tagged Tspan1, Tspan5, or Tspan9 and interaction with ADAM10 was analyzed by coimmunoprecipitation after digitonin lysis and Western blot using mAb to ADAM10 (top) or GFP (bottom). A10: ADAM10. [C] PC3 cells were transiently transfected with the indicated GFP-tagged tetraspanins and interaction with ADAM10 was analyzed by coimmunoprecipitation after digitonin lysis and Western blot using mAb to ADAM10 (top) or GFP (bottom). [D] Analysis of ADAM10 interaction with nonpalmitoylatable Tspan5 (Tspan5-plm) after digitonin lysis. [E] HEK 293 cells were transfected with HA-tagged ADAM10 and plasmids encoding either GFP or the indicated GFP-tagged tetraspanins. After cross-linking with DSP, the different tetraspanins were immunoprecipitated using the anti-GFP antibody. The samples were electrophoresed under reducing conditions to break the cross-linker, and the presence of ADAM10 cross-linked to the tetraspanins was detected by Western blot using an anti-HA antibody (top). The efficient immunoprecipitation of the different tetraspanins is controlled by immunoblotting the samples using an anti-GFP antibody (bottom). [F] S2 cells were transiently transfected with plasmids encoding Kuz-myc and GFP-Tsp3A, alone or in combination, and lysed using digitonin. The interaction between Kuz and Tsp3A was analyzed by immunoprecipitation and Western blotting using anti-Myc (Kuz) and anti-GFP (Tsp3A) antibodies. All experiments were performed at least twice.
Figure 2. *Drosophila TspanC8* genes are required for Notch receptor signaling. (A–F) Wild-type pattern of sensory organs in adult flies (A) and of SOPs in 16 h after puparium formation (APF) pupae (B; positive for nuclear Senseless in white in B and E). At 22 h APF, each sense organ is composed of four cells (C and F; Cut in green). One of these four cells is a neuron (C and F; Elav in red). TspanC8 flies exhibited a bristle loss phenotype (D) associated with the specification of too many SOPs (E) and the transformation of external cells into internal cells, including neurons (F). TspanC8 corresponds here to the silencing of Tsp3A and Tsp26A by ap-GAL4 in a Tsp86D heterozygous background (see Table S1 for complete genotype). (G) Clones of cells silenced for Tsp3A were marked by nuclear GFP (green) in the notum of developing pupae. Competition for the SOP fate was studied by scoring the genotype (i.e., GFP) of SOPs (Senseless [Sens] in red) along clone borders. (H) Histogram showing the percentage of GFP-positive SOPs along clone borders for various genotypes (n is the number of scored SOPs). Control wild-type clones were also studied [wt]. For each genotype, the distribution was significantly different.
or to genetic redundancy. To test this possibility, different silencing combinations were tested. All yielded stronger phenotypes than individual silencing (Fig. S3). Strikingly, silencing all three genes or silencing Tsp3A and Tsp26A in heterozygous Tsp86D flies was associated with an increase in the number of sensory organ precursor cells (SOPs; Fig. 2, B and E), a transformation of external sensory cells into internal cells (Fig. 2, C and F), and thereby led to a dramatic bristle loss phenotype (Fig. 2, A and D; and Fig. S3). These three phenotypes are indicative of a strong decrease of Notch activity (Hartenstein and Posakony, 1990). We therefore conclude that these genes act redundantly to regulate the activity of Notch. Notch-like phenotypes were also observed in adult wings (Fig. S3) and in ovaries (see following paragraphs). Thus, the Tsp3A, Tsp26A, and Tsp86D genes are required to regulate Notch activity in several developmental contexts.

We next asked whether these TspanC8 genes act in signal-sending cells to promote ligand activity or in signal-receiving cells to promote receptor activity. To distinguish between these two possibilities, we used a clone border assay that measures the relative ability of cells of different genotypes to compete for the adoption of the SOP fate along mosaic clone borders (Heitzler and Simpson, 1991). In this assay, cells receiving a weaker inhibitory signal are more likely to become SOPs, whereas cells sending a weaker inhibitory signal are more likely to adopt a non-SOP fate. We therefore scored the genotype of SOPs located along the clone borders and found that cells with reduced levels of Tsp3A, Tsp26A, or Tsp86D were more likely to become SOPs (Fig. 2, G and H). This indicated that the TspanC8 genes act in signal-receiving cells to promote Notch activity. Because the silencing of TspanC8 had no significant effect on the levels and distribution of Notch and Delta (Fig. 2, I–J’’), we wondered whether TspanC8 might regulate Notch indirectly via Kuz, the fly homologue of ADAM10, which also acts in signal-receiving cells to promote the S2 cleavage of Notch (Klein, 2002; Lieber et al., 2002). Consistent with this hypothesis, a Myc-tagged version of Kuz was found to interact in a digitonin-resistant manner with GFP-Tsp3A in Drosophila S2 cells (Fig. 1 F). Thus, the molecular interaction between ADAM10/Kuz and TspanC8 is evolutionarily conserved.

Surface accumulation of ADAM10 correlates with high TspanC8 levels

Our identification of TspanC8 tetraspanins as direct partners of ADAM10 and positive regulators of Notch suggested that these proteins may have an essential and conserved function in the regulation of ADAM10/Kuz. To test whether human TspanC8 tetraspanins regulate ADAM10, we screened various carcinoma cell lines for surface expression of ADAM10 and selected three cell lines with high (HCT116 and PC3) and low (HeLa) surface expression of ADAM10 for further analysis (Fig. 3 A). Although HeLa cells expressed slightly less ADAM10 at the mRNA level (Fig. 3 B), we examined whether the observed differences in surface levels reflected differences in subcellular distribution. Consistent with our FACS results, ADAM10 was detected at the surface of nonpermeabilized HCT116 and PC3 cells but was barely detectable at the surface of HeLa cells (Fig. 3 C). However, a perinuclear pool of ADAM10 was detected in HeLa cells upon permeabilization (Fig. 3 C). This intracellular pool colocalized with PDI, an ER marker (Fig. 3 D), suggesting that ADAM10 may be retained in the ER of HeLa cells. Additionally, RT-qPCR analysis showed that HeLa cells expressed low levels of TspanC8, whereas HCT116 and PC3 cells expressed high levels of Tspan14 and Tspan15, respectively (Fig. 3 E). Thus, accumulation of ADAM10 in the ER correlated with low levels of TspanC8, suggesting that TspanC8 tetraspanins may regulate the ER exit of ADAM10.

TspanC8 tetraspanins promote the ER exit and increase cell surface expression of ADAM10

As a first test to determine whether TspanC8 tetraspanins regulate the ER exit of ADAM10, we examined whether the cell surface accumulation of ADAM10 could be restored in HeLa cells by expressing GFP-tagged versions of TspanC8 tetraspanins. Surface levels of ADAM10 were increased up to fivefold upon transient transfection of Tspan5, Tspan14, Tspan15, and Tspan33 (Fig. 4 A), and this was associated with an accumulation of mature ADAM10 (Fig. 4 B). Maximal levels of ADAM10 expression at the cell surface were reached with moderate levels of these tetraspanins. This regulation of ADAM10 appeared to be independent from tetraspanin–tetraspanin interactions because expression of Tspan5-plm, i.e., mutated at predicted palmitoylation sites, similarly increased ADAM10 surface levels. Additionally, this regulation was specific of TspanC8 because transfection of CD9 or Tspan12 had no effect. Conversely, expression of TspanC8 proteins did not affect the expression level of ADAM17 (Fig. S4).

Confocal microscopy analysis shows that expression of Tspan5, Tspan14, Tspan15, or Tspan33 led to the redistribution of ADAM10 from the ER to the cell surface of HeLa cells, where it colocalized with the transfected TspanC8 (Fig. 5 A). To test whether ADAM10 interacts with TspanC8 at the cell surface, cell surface proteins of HeLa cells stably expressing or not Tspan5, Tspan14, or Tspan15 were biotinylated and lysates were subjected to immunoprecipitation using anti-ADAM10 or anti-GFP antibodies (Fig. 4 C). In transfected cells, but not in control cells, anti-GFP precipitated a biotin-labeled protein that co-migrated with ADAM10 (Fig. 4 C) and that was revealed with the anti-ADAM10 mAb in dual-color Western blots. Importantly, in these experiments the level of association of ADAM10 with the transfected TspanC8 was higher than in the

from wild-type (x<sup>2</sup> test, P < 0.0001). (I–J’’’) Wing imaginal discs stained for Notch (I–J’’) and Delta (J’–J’’’), from third instar larvae silenced for Tsp3A, Tsp26A, and Tsp86D using ap-Gal4 that directs transgene expression in dorsal cells [D; V is ventral]; the DV boundary is indicated by a dashed line). l’, l”, j’, and j” (l’ and j’: surface views; l” and j’’: –7 µm from the surface) show high magnification views of the area boxed in l and j, respectively. The silencing of the TspanC8 genes in D cells did not change the levels or distribution of Notch and Delta (compare with control V cells). Bars: (B and E) 100 µm; (C, F, G, l, and j) 25 µm; (l’ and j’’) 5 µm.
Tspan14, and Tspan15 could also be coimmunoprecipitated with ADAM10 (Fig. 4 C). This stronger association may be due in part to the absence of competition with endogenous TspanC8 in HeLa cells. We therefore conclude that the interaction of ADAM10 with these TspanC8 tetraspanins is quantitatively important and occurs at the cell surface.

In these experiments, Tspan10 and Tspan17 appeared to behave differently than the other TspanC8: Tspan17 had only a moderate effect on ADAM10 surface expression and Tspan10 did not change ADAM10 surface expression or maturation (Fig. 4, A and B). Nevertheless, Tspan10 and Tspan17 appeared to relocalize ADAM10 into a Tspan10- and Tspan17-positive intracellular compartment marked by CD63, a marker of late endosomes (Fig. 5 A and Fig. S4 B), suggesting that Tspan10 and Tspan17 might also promote the ER exit of ADAM10. Together, these results indicated that TspanC8 tetraspanins promote the ER exit and, with the exception of Tspan10 and Tspan17, cell surface accumulation of ADAM10.

We next examined the effect of TspanC8 tetraspanins on the distribution of Kuz in transfected S2 Drosophila cells. Expression of GFP-tagged Tsp86D and Tsp3A led to a significant change in the distribution of Myc-tagged Kuz. In control cells, only 4 ± 1% of the Kuz-expressing cells exhibited a clear plasma membrane localization of Kuz. Expression of Tsp86D and Tsp3A increased the percentage of cells with Kuz localizing predominantly at the plasma membrane to 9 ± 3 and 22 ± 2%, respectively (Fig. 5, B–B’). We therefore propose that the regulation of Kuz/ADAM10 distribution by TspanC8 is conserved across species.

Endogenous TspanC8 tetraspanins are required for the ER exit of ADAM10

We next investigated whether endogenous TspanC8 are required for the surface accumulation of ADAM10. The Tspan14 and Tspan15 genes were silenced using siRNAs in HCT116 cells and PC3 cells, respectively. Silencing was strong and specific, as determined by RT-qPCR (Fig. 6 A). In both cases, silencing led to decreased levels of ADAM10 at the cell surface (Fig. 6 B) and to the accumulation of ADAM10 in an intracellular compartment identified as the ER using PDI as a marker (Fig. 6 C). This indicates that endogenous TspanC8 tetraspanins are required to promote the exit of ADAM10 from the ER.

TspanC8 tetraspanins regulate Kuzbanian localization and Notch activity in vivo

To test whether TspanC8 regulate the subcellular distribution of ADAM10/Kuz in vivo, we turned to Drosophila. Because no anti-Kuz antibodies are available, we generated a GFP tagged-version of Kuz (Fig. S3). Starting from a 96-kb genomic BAC covering the kuz locus (Venken et al., 2006), we used recombineering to generate a Kuz-GFP BAC transgene (Fig. S2; Venken et al., 2009). A single copy of this transgene rescued the lethality of kuz mutant flies, indicating that Kuz-GFP is functional and expressed like wild-type Kuz. A very low level of GFP was detected in most larval and imaginal tissues, indicating that Kuz is expressed at low levels, preventing us from studying the distribution of Kuz in these tissues. Previous studies had, however,
indicated that the *kuz* gene is expressed at higher levels in a group of migrating cells known as the polar/border cells in ovaries (Wang et al., 2006; Fig. 7 A). Consistent with this, Kuz-GFP was detected in migrating polar/border cells (Fig. 7, D–D‴). In this context, the activity of *kuz* is required for both Notch signaling and collective cell migration (Wang et al., 2006). Early silencing of the TspanC8 genes in border cells using the c306 and slow border (slbo) GAL4 drivers resulted in fewer border cells (Fig. 7 B) and delayed migration (Fig. 7 C). Both phenotypes were also observed upon silencing of *kuz* (Fig. 7, B and C). We therefore used this model system to study the in vivo regulation of Kuz distribution by TspanC8.

First, we observed that Kuz-GFP distributed differently in polar and border cells. Kuz localized into intracellular dots in the two centrally located polar cells, whereas it localized more diffusely at the cell periphery and in the cytoplasm in the 6–8 border cells surrounding the two polar cells. The nature of these Kuz-GFP dots is unclear. In particular, the ER or Golgi markers Sec16, Liquid facet Related, GMAP, and Ofut1 did not mark these dots (not depicted). Despite this, we wondered whether different levels of TspanC8 in polar vs. border cells might account for this difference in distribution. Because transcriptome analysis has suggested that the *Tsp86D* gene is expressed in these migrating cells (Wang et al., 2007), we investigated the expression of *Tsp86D* using a 21-kb genomic BAC encoding a GFP-Tsp86D transgene (Venken et al., 2009). GFP-Tsp86D was expressed at high levels in border cells, whereas polar cells had low levels of GFP-Tsp86D (Fig. 7, E–E‴). Similarly, we generated a BAC-encoded GFP-Tsp3A and observed that GFP-Tsp3A was also specifically expressed in border cells (Fig. S2). Thus, the intracellular Kuz-GFP dots in polar cells correlated with low levels of Tsp3A and Tsp86D. Furthermore, the silencing of Tsp3A and Tsp26A in *Tsp86D* heterozygous flies in border cells led to a redistribution of Kuz-GFP into intracellular dots (Fig. 7, F–H; silencing was found to be both efficient and specific in this tissue, as determined using GFP-Tsp3A and GFP-Tsp86D as read-outs: silencing was 80% [Tsp3A] and 97% [Tsp86D] efficient; see Fig. S5). We conclude that TspanC8 tetraspanins regulate the subcellular distribution of Kuz in border cells.

A previous study has shown that Kuz regulates Notch in border cells (Wang et al., 2007). To test whether TspanC8 regulates Kuz-dependent Notch signaling in border cells, we used a Notch transcriptional reporter, Gbe-GFP (Housden et al., 2012), expressed in both border and polar cells (Fig. 7, I and I‴). The silencing of Tsp3A and Tsp26A in *Tsp86D* heterozygous flies led to a significant decrease in Gbe-GFP expression in border but not polar cells (Fig. 7, I–L). Together, our data indicated that TspanC8 tetraspanins regulate the subcellular distribution of Kuz and the activity of Notch in border cells.

Figure 4. Expression of TspanC8 in HeLa cells increases the expression of surface and mature ADAM10. (A) Flow cytometry analysis of the surface expression of ADAM10 in HeLa cells transiently transfected with the indicated GFP-tagged tetraspanins. (B) Western blot analysis of mature ADAM10 and GFP-tagged tetraspanins in transfected HeLa cells. A nonspecific band is indicated by an asterisk. (C) After biotin labeling of surface proteins, HeLa cells stably expressing or not GFP-tagged Tspan5, Tspan14, and Tspan15 were lysed and the interaction of ADAM10 with the transfected tetraspanins was analyzed by coimmunoprecipitation and Western blot. The major 68-kD band revealed by the anti-ADAM10 mAb perfectly overlapped with the band labeled ADAM10 in the top panel. A nonspecific band is indicated by an asterisk. All experiments were performed at least twice with similar outcome.
was regulated by ADAM10 because the silencing of ADAM10 decreased OP9-DLL1-induced Notch1 activity (Fig. 8, B and C). Tspan5 and Tspan14 were the major TspanC8 tetraspanins expressed by U2OS cells (unpublished data). Double silencing of these TspanC8 tetraspanins led to a ~60% reduction in Notch reporter activity, whereas single silencing of Tspan5 or Tspan14 led to a ~45% and ~35% reduction, respectively (Fig. 8 B). This effect correlated with a significant decrease in the surface expression levels of ADAM10 (Fig. 8 C), but not of Notch1 (Fig. 8 D). As a control, the silencing of CD81 had no effect.

These results indicated that Tspan5 and Tspan14 promote Notch receptor activity in signal-receiving cells.

To determine the step at which TspanC8 tetraspanins act, we measured the effect of Tspan5 and Tspan14 silencing on two constitutively activated versions of Notch1. The first one, NICD,
regulate Notch receptor activity at a pre-γ-secretase step in signal-receiving cells, which is fully consistent with a regulation of the ADAM10-dependent S2 cleavage of Notch.

**Discussion**

This study identifies a conserved subfamily of tetraspanins, named here TspanC8, which regulate the localization and activity of ADAM10/Kuz and thereby modulate Notch receptor activation. This conclusion is supported by several key findings:
Figure 7. Regulation of Kuz distribution and Notch signaling in Drosophila oocytes. (A) Schematic representation of egg chambers at stages 8, 9, and 10a (oo, oocyte; nc, nurse cell). Border and polar cells are color coded in green and red, respectively (bc, border cells; fc, follicular cells). (B) In wild-type ovaries, migrating clusters contain 7.8 ± 0.1 border cells. The early silencing of Tsp3A, Tsp26A, and Tsp86D in border cells using slbo-Gal4 and c306
(i) ADAM10 interacts with several TspanC8 tetraspanins in both flies and mammals. (ii) ADAM10 surface expression levels are controlled by TspanC8 both in human cells and in *Drosophila*. (iii) TspanC8 tetraspanins act in signal-receiving cells for the ligand-induced and ADAM10/Kuz-dependent activation of Notch.

This study shows that ADAM10 is a specific and direct partner of all six human TspanC8 tetraspanins. In addition, Tspan5, Tspan14, Tspan15, and Tspan33 increased the expression of ADAM10 at the cell surface and promoted its maturation. A similar finding was recently reported for Tspan15 (Prox et al., 2012). Tspan12 was proposed earlier to interact closely with ADAM10 and to promote its maturation (Xu et al., 2009). However, it did not interact with ADAM10 after digitonin lysis, and did not increase ADAM10 surface expression level and maturation when transfected in HeLa cells. These data, together with the observation that the interaction of ADAM10 with Tspan12 required its palmitoylation (Xu et al., 2009), strongly suggest that Tspan12 interacts only indirectly with ADAM10. Additionally, Tspan10 and Tspan17 behaved differently from other TspanC8 tetraspanins because their expression induced the intracellular redistribution of ADAM10 in HeLa cells. We therefore suggest that different TspanC8 may provide ADAM10 with different trafficking properties.

How do Tspan5, Tspan14, Tspan15, and Tspan33 regulate the expression level of mature ADAM10? A possibility, consistent with their interaction at the cell surface, is that these tetraspanins act by stabilizing ADAM10 at the plasma membrane. This increase in mature ADAM10 expression is also probably, to some extent, a direct consequence of the ability of TspanC8 to mediate the ER exit of ADAM10. ADAM10 is retained in the ER through a mechanism involving an arginine-based motif (Marcello et al., 2010) that may function as an ER retention signal. Such arginine-based motifs are often found in subunits of multi-molecular complexes and are masked upon complex assembly, thereby allowing ER exit of the properly assembled complexes (Michelsen et al., 2005). We therefore suggest that TspanC8 tetraspanins allow for the ER exit of ADAM10 by masking its arginine-based motif. A role of tetraspanins in the ER exit of their molecular partner is probably not restricted to TspanC8 tetraspanins, as suggested by the differential expression and/or maturation of CD19 and EWI-2 in the presence or not of their partner tetraspanins (Shoham et al., 2003; Stipp et al., 2003; He et al., 2009). Although an ER retention motif has yet to be defined in EWI-2 or CD19, both proteins contain a putative arginine-based motif (unpublished data).

Our results indicating that several human TspanC8 family members have a similar molecular activity on the regulation of ADAM10 are consistent with our RNAi analysis showing that the fly TspanC8 genes act redundantly to regulate Notch. However, one limitation of this RNAi approach is that silencing is often incomplete (Dietzl et al., 2007), so that residual activity might hinder some aspects of the null mutant phenotype. Despite this limitation, our data clearly established that TspanC8 tetraspanins play an essential role for proper Notch activity in various developmental settings. Kuz is likely to be the main target of TspanC8 in *Drosophila*. First, our clone border analysis indicated that the activity of TspanC8, like that of Kuz, is required in signal-receiving cells. Second, the distribution of Kuz, but not those of Notch and Delta, appeared to be regulated by TspanC8. Third, Kuz appeared to interact with Tsp3A (interaction with Tsp26A and Tsp86D was not tested). Our data further indicated that the relevant target of Kuz is Notch, rather than its ligand Delta. Although Kuz can down-regulate Delta (Qi et al., 1999; Mishra-Gorur et al., 2002), hence potentially interfering with its cis-inhibitory activity (del Álamo et al., 2011), Delta levels remained unchanged upon TspanC8 silencing. Moreover, human Tspan5 and Tspan14 positively regulated ligand-induced ADAM10-dependent Notch1 signaling at a pre-γ-secretase step in an assay where ligands act in trans. Together, our data support the view that TspanC8 tetraspanins regulate Notch activity via the regulation of the ADAM10/Kuz-mediated S2 cleavage. Also consistent with this view are the synergistic interactions observed between the *C. elegans* TspanC8 family member tsp-12 and sup-17, the ADAM10 orthologue. tsp-12 was identified as a suppressor of a mutation causing constitutive or elevated activity of GLP-1, one of two Notch-like receptors in *C. elegans* (Dunn et al., 2010). However, Tsp-12 was proposed to act by facilitating the S3 (rather than the S2) cleavage of GLP-1. This interpretation relied to a large extent on the observation that Tspan33 silencing in HeLa cells reduced the activity of Notch1-ΔE but had no effect on NICD. Whether Tspan33 regulates γ-secretase activity indirectly via the
transfection on Notch activity in HeLa cells. This new link has potential implications for the interpretation of phenotypes associated with defective TspanC8 activity, and further work should determine whether the defect in erythropoiesis of Tspan33 (penumbra) mutant mice is linked to a defect of ADAM10 and/or Notch function (Heikens et al., 2007). Finally, because ADAM10 is a promising therapeutic target in various pathologies (Saftig and Reiss, 2011) and because mouse TspanC8 genes display tissue-specific expression (Wu et al., 2009), it might be envisaged to inhibit ADAM10 activity in a tissue-specific manner by interfering with the activity of specific TspanC8.

Materials and methods

Reagents for in vitro studies

The mouse mAb anti-human ADAM10 11G2 was described in Arduise et al. (2008); the mouse mAb anti-human Notch1 and anti-human ADAM17 were from R&D Systems and the anti-human PDI from Abcam. The anti-tag non-TspanC8 tetraspanins that were found associated with γ-secretase (Wakabayashi et al., 2009) remains to be determined. Whatever the molecular basis, this result contrasts with our data showing that the silencing of both Tspan5 and Tspan14 significantly decreased ligand-mediated Notch activation but had no effect on the activity of Notch1-ΔE. Unfortunately, we could not investigate the role of Tspan33 in the S2 and S3 processing of Notch1 because none of the cell lines tested here, including HeLa, expressed Tspan33 at a significant level.

In conclusion, this study establishes that the trafficking and activity of ADAM10 are regulated by tetraspanins of the TspanC8 family and that this regulation has important consequences in terms of Notch signaling. Further work should determine why ADAM10 associates with so many tetraspanin partners. We hypothesize that these different tetraspanins may provide ADAM10 with different trafficking properties (Tspan10 and Tspan17) or differentially restrict the range of its substrates, as suggested by the lack of effect of Tspan15 transfection on Notch activity in HeLa cells.

Figure 8. Tspan5 and Tspan14 regulate ligand-induced Notch activation. (A) Notch activity measured using a CSL reporter luciferase assay, of HeLa cells stably expressing or not Tspan5, Tspan14, or Tspan15. Notch was activated by incubation with OP9-DLL1 cells. The figure shows the mean ± SD of four independent experiments in duplicate. (B) U2OS-N1 cells were treated with the indicated siRNA before analysis of Notch activity produced by incubation with OP9 or OP9-DLL1 cells. The figure shows the mean ± SD of three independent experiments performed in duplicate. (C) Flow cytometric analysis of the surface expression of ADAM10 in U2OS-N1 cells treated with the indicated siRNA. The figure shows the mean ± SD of three independent experiments. (D) Flow cytometric analysis of the surface expression of Notch1 in U2OS-N1 cells treated with a control siRNA or siRNAs directed to both Tspan5 and Tspan14. The figure shows the mean ± SD of three independent experiments. (E) U2OS-N1 cells were treated with the indicated siRNA and transfected with NICD and Notch1-ΔE constructs. Notch activity was determined using the luciferase assay. The figure shows the mean ± SD of three independent experiments performed in duplicate. **, P < 0.01; *, P < 0.05 as compared with control cells.
antibodies used in this study were anti-GFP (a mouse mAb from Roche Diagnostics), anti-HA (HA11 mouse mAb from Covance), and anti-V5 (a mouse mAb and a rabbit polyclonal from Sigma-Aldrich). The following siRNAs were obtained from Invitrogen and Eurogentec: control siRNA; Stealth RNAi Negative Control Medium GC, Tspan5: AUGUCAUCGUUGACUGCAGUAU; Tspan14: CGGCAUCUGUUCGAAGAGUAUAU; Tspan15: AACAUCGUUGCUCGUGUAU; CD1: CGACCUAUCAUCAUGUAAU; GC2: GGCGCAUCGAGAAUUCU. All V5- or GFP-tagged tetrascin cDNAs were of human origin. Coding regions were amplified by PCR from previously described plasmids (Tspan1, Tspan5, Tspan9, Tspan12, and Tspan15; Serru et al., 2000), from plasmids obtained from Open Biosystems (Tspan10 and Tspan33), or from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14). PCR products were subcloned into pEGFP-N1, pEGFP-N3, or pcDNA 3.1 Plus载体 by TOPO法 from a reverse-transcription performed on HCT116 RNA (Tspan14).
SPE confocal microscope (Leica) using 20x (HCX PL APO CS, NA 0.6), 40x (HCX PL APO CS, NA 1.4), and 63x (HCX PL APO CS, NA 1.3) objectives. Adult flies were imaged using a Discovery V20 stereomicroscope (Carl Zeiss) using a 1.0x objective (PlanApo SR FWD 60 mm).

Images were processed using ImageJ (National Institutes of Health) and Adobe Photoshop software. Categorization of the plasma membrane vs. cytoplasmic accumulation of Kuzu-Myc in 52 cells, using the cell outline and the cytoplasm as landmarks, was performed blind after running the objects. To identify the Gbe-GFP signal at stage 9–10a, the GFP signal was measured in each polar and border cell on a single confocal section running across the nucleus using ImageJ. Values were corrected by subtracting the background signal measured outside the egg chamber. For each egg chamber, mean values were calculated for the 2 polar and for the 6–10 border cells. The extent of border cell migration was measured as the percentage of migration within individual stage 10a egg chambers. To characterize the distribution of Kuzu-GFP in border and polar cells, 512 × 512 images acquired at 63x (zoom 6) were thresholded and the number of “objects” >8 the distribution of Kuz-GFP in border and polar cells, 512 × 512 images ratio. The extent of border cell migration was measured as the percentage the 6–10 border cells. These two mean values defined a border/polar each egg chamber, mean values were calculated for the 2 polar and for

The CH321-04I18 BAC covering the 6,996 nt 5′ to the transcription start site to 3,040 nt downstream of the 3′FN_3A: CTCAAAGGTCAGTGCCGAAACGA; 5′ TCCTGCTACCATCCTCGCCGTTTATCTGTA; 3′ TGGCTCACCAT. The extent of border cell migration was measured as the percentage of migration within individual stage 10a egg chambers. To characterize the distribution of Kuzu-GFP in border and polar cells, 512 × 512 images acquired at 63x (zoom 6) were thresholded and the number of “objects” >8 pixels in size were counted.

**Online supplemental material**

Fig. S1 shows that Tspan8B tetraspanins represent an evolutionary conserved subfamily of tetraspanins. Fig. S2 shows genetic tools used in Droso phila studies. Fig. S3 shows functional redundancy between Drosophila Tspan8B, Tspan6A, and Tspan3A. Fig. S4 shows the effect of Tspan8C tetraspanins on PAM surface expression and codistribution of Tspan1 and Tspan17 with CD63. Fig. S5 shows efficient and specific silencing of Tspan3A and Tspan86D in border cells. Table S1 provides a description of Droso phila genotypes.

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**References**


An evolutionary conserved subfamily of tetraspanins. (A) Amino acid identity levels between *H. sapiens* (Tspan5, 17, 14, 33, 15, 10), *D. melanogaster* (Tsp26A, 86D, 3A), and *C. elegans* (Tsp12) TspanC8 tetraspanins. The prototypal tetraspanin CD151 is also included for comparison. Human tetraspanins have most often less than 30% identity with each other. (B) Sequence alignment of the second extracellular domain of CD151 and the different *H. sapiens*, *D. melanogaster*, and *C. elegans* TspanC8 tetraspanins. This domain is highly divergent within the tetraspanin superfamily with the exception of a few residues that probably maintain the tetraspanin fold (pink). In contrast, TspanC8 tetraspanins share many conserved residues (red, >80% conservation; blue, >60% conservation; green, conservative substitutions) within this domain. The two additional cysteines that are the hallmark of TspanC8 are in yellow. Note that although Tsp12 has only six cysteines in the large extracellular domain, it shares many residues characteristic of TspanC8. The three conserved helices of this domain are shown on top of the sequences.
Figure S2. **Genetic tools.** (A–C) Schematic representation of the *kuz* (A), *Tsp86D* (B), and *Tsp3A* (C) genomic regions. The *kuz*, *Tsp86D*, and *Tsp3A* open reading frame (ORF) are in blue. 5′ and 3′ UTRs are in black. Exons from neighboring genes are in white. The BACs used in this study are indicated in red. GFP [green] was inserted at the 3′ and 5′ ends of *kuz* and *Tsp86D*/*Tsp3A* ORFs, respectively. The *Tsp86D* deficiency is indicated in gray. Bars: (A) 10 kb; (B and C) 1 kb. (D and E) Domain structure of GFP-3A and Kuz-GFP (transmembrane segment, blue; prodomain of Kuz, red; metalloprotease domain, purple; disintegrin domain, yellow; GFP, green). Bars: (D) 20 aa; (E) 200 aa. (F) Sequence targeted by the dsRNAi and shmiR constructs used in this study (NIG-Fly, red; VDRC, green; shmiR, purple). The *Tsp86D*, *Tsp26A*, and *Tsp3A* transcripts are represented as in B. Bar, 200 nt. (G–G′′′) GFP-3A was detected in migrating border cells (b) and in follicular cells. Polar cells (p) exhibited lower levels of GFP-3A. GFP-3A appears to be expressed similarly as GFP-3D and complementary to Kuz-GFP (see Fig. 6). Bars: (G) 40 μm; (G′ and G′′) 5 μm.
Figure S3. **Functional redundancy between Drosophila Tsp86D, Tsp26A, and Tsp3A.** (A–F) Pattern of sensory organs in adult flies silenced for Tsp3A (A), Tsp26A (B), Tsp86D (C), Tsp3A and Tsp26A (D), Tsp3A in a Tsp86D heterozygous background (E), and Tsp26A in a Tsp86D heterozygous background (F). Silencing was achieved using ap-GAL4. See Fig. 2 for a wild-type control and Table S1 for complete genotypes. (G) Histogram showing the number of bristles located in dorsal-central rows 1–5 of the notum (n is the number of scored flies for each genotype). The genotypes are indicated by letters corresponding to the other panels of this figure. For each genotype (except B), the distribution was significantly different from wild type (wt; $\chi^2$ test, $P < 0.01$). (I–K) Wing margin and vein pattern in adult flies silenced for kuz (J) and Tsp3A, Tsp26A, and Tsp86D (K). Silencing was performed using sd-GAL4. A wild-type control is shown in I. Loss of TspanC8 activity in the wing results in wing nicks and vein-thickening Notch-like phenotypes that are milder than those seen upon the silencing of kuz.
Figure S4. Effect of TspanC8 tetraspanins on ADAM17 surface expression and codistribution of Tspan10 and Tspan17 with CD63. (A) Flow cytometry analysis of the surface expression of ADAM17 in HeLa cells transiently transfected with different GFP-tagged tetraspanins. (B) Confocal microscopy analysis of GFP-tagged Tspan10 and Tspan17 (green) and CD63 (red) localization in permeabilized HeLa cells. Bar, 10 µm. These experiments were performed at least twice.
Figure S5. Efficient and specific silencing of Tsp3A and Tsp86D in border cells. (A–D) The expression of GFP-Tsp86D (green) was efficiently and specifically silenced in border cells (marked by the expression of RFP under the control of slbo-GAL4) by dsRNA directed against Tsp86D (C–C'). In the absence of dsRNA (A–A') or in the presence of dsRNA directed against Tsp3A (B–B'), GFP-Tsp86D was detected in border cells. The GFP fluorescence signal was measured to estimate the relative levels of GFP-Tsp86D (D; a.u.: arbitrary units). (E–G') Conversely, the expression of GFP-Tsp3A (green; no dsRNA in E–E') was efficiently silenced by dsRNA directed against Tsp3A (G–G') expressed but not by Tsp86D dsRNA (F–F'). Unfortunately, the expression of GFP-Tsp3A and GFP-Tsp86D was too low in imaginal tissues to evaluate the efficiency of silencing in these tissues. (H) Quantification of the GFP-Tsp3A signal as in D.
Table S1. Genotypes

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