Shroom2, a myosin-VIIa- and actin-binding protein, directly interacts with ZO-1 at tight junctions

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Summary

Defects in myosin VIIa lead to developmental anomalies of the auditory and visual sensory cells. We sought proteins interacting with the myosin VIIa tail by using the yeast two-hybrid system. Here, we report on shroom2, a submembranous PDZ domain-containing protein that is associated with the tight junctions in multiple embryonic and adult epithelia. Shroom2 directly interacts with the C-terminal MyTH4-FERM domain of myosin VIIa and with F-actin. In addition, a shroom2 fragment containing the region of interaction with F-actin was able to protect actin filaments from cytochalasin-D-induced disruption in MDCK cells. Transfection experiments in MDCK and LE (L fibroblasts that express E-cadherin) cells led us to conclude that shroom2 is targeted to the cell-cell junctions in the presence of tight junctions only. In Ca2+-switch experiments on MDCK cells, ZO-1 (also known as TJP1) preceded GFP-tagged shroom2 at the differentiating tight junctions. ZO-1 directly interacts with the serine- and proline-rich region of shroom2 in vitro. Moreover, the two proteins colocalize in vivo at mature tight junctions, and could be coimmunoprecipitated from brain and cochlear extracts. We suggest that shroom2 and ZO-1 form a tight-junction-associated scaffolding complex, possibly linked to myosin VIIa, that bridges the junctional membrane to the underlying cytoskeleton, thereby contributing to the stabilization of these junctions.

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Key words: Myosin VIIa, Shroom2, F-actin, ZO-1, Tight junctions

Introduction

Epithelia have specialized intercellular structures involved in cell-cell contacts. The apical junctional complex (AJC) comprises the tight junction (TJ) and the subjacent adherens junction (AJ). The AJ is involved in initiating and maintaining adhesion between adjacent cells, whereas the TJ controls paracellular permeability and maintains cell polarity. The TJ and AJ are associated with thick bundles of actin microfilaments, which form a characteristic perijunctional actin ring at the apical pole of differentiated epithelial cells (Mooseker, 1985; Madara, 1998; Turner, 2000). Both the TJ and AJ are multiprotein complexes that consist of integral membrane proteins and the cytosolic junctional plaques (Perez-Moreno et al., 2003; Schneeberger and Lynch, 2004; Miyoshi and Takai, 2005). TJ integral membrane proteins include occludin, claudins and junctional adhesion molecules (JAMs), which interact with their counterparts at the plasma membrane of adjacent cells. Among the growing number of proteins identified in the TJ plaque is an array of PDZ-domain-containing proteins, such as members of the ZO family, which act as submembranous scaffolding molecules that bridge TJ complexes to the actin cytoskeleton. Some of these TJ proteins also participate in intracellular signaling pathways that regulate gene expression (Matter and Balda, 2003; Ivanov et al., 2005b).

Both the actin cytoskeleton and myosin II have been involved in the formation and functioning of the AJC. Active cytoskeletal rearrangements, through de novo actin polymerization, have been shown to mediate the formation of both the AJ and TJ (Vasioukhin et al., 2000; Verma et al., 2004; Ivanov et al., 2005a). This tight association to actin filaments is also responsible for the maintenance of the mature AJC (Fanning, 2001; Bershadsky, 2004). Myosin II is involved, through the Rho kinase pathway, in the localization and accumulation of E-cadherin at cell-cell contacts, thereby promoting AJ integrity (Shewan et al., 2005). Myosin II also plays a crucial role in TJ formation (Ivanov et al., 2005a). Along the same line cingulin, a peripheral component of the TJ that interacts with myosin II, has been proposed to transduce the force produced by the contraction of the actomyosin cytoskeleton to TJ proteins (Cordononsi et al., 1999). Moreover, there is increasing evidence that the perijunctional actin ring directly regulates TJ permeability through the cortical tension generated by actomyosin contraction (Turner, 2000).

The myosin superfamily comprises myosin II (conventional myosin) and 17 classes of unconventional myosins (Krendel and Mooseker, 2005). Myosin II forms bipolar filaments that are crucial for contractile properties. By contrast, unconventional myosins do not assemble into filaments. The binding of their tails to specific proteins and/or lipids is thought.
to position these motors at certain intracellular locations. The motor activity of their head is then harnessed to exert a tension on the molecules. Unconventional myosins either move along actin filaments and convey tethered vesicles and/or proteins, or anchor vesicles or proteins to actin filaments and exert a tension force on these components (Krendel and Mooseker, 2005). These motors have been implicated in a variety of cellular functions including membrane trafficking, cell movements and signal transduction (Krendel and Mooseker, 2005). Among the unconventional myosins, myosin VIIa has been proposed to be involved in cell adhesion processes. Indeed, myosin VIIa is abundant at cell-cell junctions and binds to vezatin, a putative transmembrane protein of the AJ, associated with the cadherin-catenin complex (Kussell-Andermann et al., 2000). Moreover, myosin VIIa is associated with Keap1 (a mammalian homologue of the Drosophila ring canal protein Kelch), a submembranous protein present in the ectoplasmic specialization, a dynamic adhesion structure that forms between Sertoli cells in the testis (Velichkova et al., 2002).

Mutations in the gene encoding myosin VIIa are responsible for the most prevalent genetic form of Usher syndrome type I (USH1), a disease characterized by congenital deafness, vestibular dysfunction, and progressive retinitis pigmentosa leading to blindness (Weil et al., 1995; El-Amraoui and Petit, 2005). With the objective of getting a deeper understanding of the role of myosin VIIa in the inner ear and retinal sensory cells, we sought proteins interacting with the tail of this myosin in the yeast two-hybrid system. We thereby identified shroom2, a protein located at the TJs of embryonic and adult epithelia.

**Results**

**Shroom2, a submembranous PDZ-domain-containing protein, binds to myosin VIIa**
The C-terminal fragment of myosin VIIa containing SH3, MyTH4 and FERM domains (aa 1605-2215; Fig. 1A) was used as the bait to screen a yeast two-hybrid mouse inner ear cDNA library (Boeda et al., 2002). Among the potential ligands isolated was a prey composed of 368 aa (aa 350-721) of the murine shroom2 (hereafter referred to as mShrm2; Fig. 1B), a member of the shroom family of proteins. The shroom family consists of four different proteins, shroom1 (Shrm1, also known as Apx) (Staub et al., 1992; Zuckerman et al., 1999), shroom2 (Shrm2, also known as Apxl), shroom3 (Shrm3, also known as KIAA1481), and shroom4 (Shrm4, also known as KIAA1202) (Staub et al., 1992; Zuckerman et al., 1999), defined by the arrangement of at least two out of three conserved sequence motifs (Hagens et al., 2006 and references therein). By using race-PCR on a mouse vestibular cDNA library and sequence comparison with ESTs, we reconstituted a cDNA containing an entire open reading frame of 4461 bp, that displays 74% nucleotide sequence identity with the human shroom2 coding sequence. The deduced shroom2 amino acid sequence predicts a 1487 aa protein (163.5 kDa) with a PDZ domain (aa 27-107), a serine- and proline-rich domain (SPR; aa 123-326, 21% serine and 10% proline residues), the myosin-VIIa-binding region (MBR; aa 350-721), and the two Apx-Shroom domain (ASD) motifs ASD1 (aa 705-807) and ASD2 (aa 1191-1487) (see Fig. 1B).

In transfected HeLa cells expressing the GFP-tagged shroom2 MBR (GFP-mShrm2MBR) only, we observed a punctate staining throughout cell bodies and also peripheral long GFP-labeled structures associated to F-actin (open arrowheads, Fig. 1C). In co-transfected cells that express both GFP-mShrm2MBR and the myosin VIIa tail, the two proteins colocalized in the punctate structures (arrows, Fig. 1D). To further map the myosin-VIIa-binding site in shroom2, we generated a construct encoding the N-terminal part of MBR (aa 350-563), mShrm2MBRΔC. In transfected HeLa cells, GFP-tagged mShrm2MBRΔC (GFP-mShrm2MBRΔC) exhibited a diffuse cytoplasmatic staining (Fig. 1E), whereas addition of the myosin VIIa tail resulted in colocalization of GFP-mShrm2MBRΔC and myosin VIIa tail (arrows, Fig. 1F). This difference in the labeling pattern suggested that this shroom2 fragment is able to interact with the myosin VIIa tail. We then tested the direct interaction between mShrm2MBR and the myosin VIIa tail by in vitro binding assays (Fig. 1G). The 35S-labeled myosin VIIa tail (aa 847-2215), SH3/MyTH4/FERM (aa 1612-2215) and MyTH4/FERM (aa 1752-2215) fragments did bind to GST-mShrm2MBR, whereas a peptide containing the SH3 and MyTH4 domains only (aa 1605-1907) did not (Fig. 1G). None of the myosin VIIa fragments bound to GST alone. These results suggested that the C-terminal FERM domain of myosin VIIa mediates the interaction with shroom2. Similar experiments carried out with either the 35S-labeled MyTH4 domain (aa 1752-1890) or the FERM domain (aa 1896-2215) alone, however, failed to detect any interaction with mShrm2MBR in both cases (not shown). In the reciprocal experiments, immobilized biotin-tagged myosin VIIa MyTH4/FERM or FERM fragments alone were incubated with supernatants containing GST-mShrm2MBR. The GST-tagged mShrm2MBR did bind to myosin VIIa MyTH4/FERM, but not to myosin VIIa FERM (supplementary material Fig. S1A). These results indicate that the entire C-terminal repeat, composed of both the MyTH4 and FERM domains, is necessary for the binding of myosin VIIa to shroom2. To confirm that shroom2 and myosin VIIa can form a complex in a cellular context, we carried out communoprecipitation assays. Since our antibodies against myosin VIIa and shroom2 did not immunoprecipitate the corresponding proteins (supplementary material Fig. S1B-D), we used HEK293 cells expressing both Myc-tagged full-length shroom2 (Myc-mShrm2) and either the myosin VIIa tail or full-length myosin VIIa (Fig. 1H). By using the anti-Myc antibody, both the myosin VIIa tail and full-length myosin VIIa were co-immunoprecipitated with Myc-tagged shroom2 (Myc-mShrm2), but not with the Myc-tag alone (Fig. 1H). Together, these results show that shroom2 directly interacts with myosin VIIa, through the MBRΔC region and C-terminal MyTH4/ FERM repeat.

**Shroom2 is an F-actin-binding protein**
To analyze the distribution of shroom2, we produced polyclonal antibodies against a mixture of two synthetic peptides derived from the shroom2 protein sequence (see Materials and Methods, and supplementary material Fig. S1B). Because immunofluorescence analysis of several epithelial cell lines (MDCK, LLC-PK, Caco-2 cells) showed faint shroom2 immunoreactivity (Fig. 2A), we studied the subcellular distribution of full-length shroom2 or various truncated forms in transfected cells (Fig. 2B; supplementary material Fig. S2). In MDCK cells expressing GFP-tagged full-length shroom2
(GFP-mShrm2), the protein was targeted to the AJC (Fig. 2B), in accordance with the endogenous shroom2 labeling. Both endogenous shroom2 and GFP-mShrm2 were more concentrated at tricellular contacts (arrowheads in Fig. 2A,B).
Truncated GFP-mShrm2 fragments (GFP-mShrm2ΔPDZ, GFP-mShrm2PSP, GFP-mShrm2MBR-ASD1) were detected at cell-cell contacts, whereas GFP-mShrm2MBRΔC and a C-terminal fragment containing ASD2 gave a diffuse labeling (supplementary material Fig. S2 and data not shown). Overexpression of either GFP-mShrm2 or GFP-mShrm2MBR resulted in a significant increase of the F-actin labeling in transfected cells, compared with the non-transfected neighbouring cells (Fig. 2C,E, and supplementary material Fig. S6B). In addition, cells expressing GFP-mShrm2MBR showed many F-actin clumps (Fig. 2E). Transfected cells were treated with cytochalasin D, which binds to the barbed end of actin filaments and alters actin polymerization (Fig. 2D,F). In cells producing GFP-mShrm2, both the cortical actin filaments and the stress fibres were disrupted, and GFP-mShrm2 was detected in the same spots as F-actin (Fig. 2D). By contrast, the large filaments co-labeled for F-actin and mShrm2MBR resisted disassembly in the presence of cytochalasin D (Fig. S2).
Thus, indicating that mShrm2MBR is able to stabilize actin filaments. Dietz et al. have shown that a region of shroom2 composed partly of the MBR and the ASD1 domain (aa 513-880) binds to F-actin (Dietz et al., 2006). By in vitro co-sedimentation assays, we showed that, in the presence of F-actin, the bulk of the GST-tagged mShrm2MBR fusion protein co-sediments with F-actin, whereas in the absence of F-actin, GST-tagged mShrm2MBR is present in the supernatant (Fig. 2H). Also, MDCK cells expressing GFP-mShrm2MBRAC (aa 350-563) exhibited a diffuse cytoplasmic labeling, with no particular colocalization with F-actin (data not shown). Together, these results suggest that the region of shroom2 that binds to F-actin, which will be referred to as ABR (for actin-binding region; aa 563-721), resides in the C-terminal part of MBR (see supplementary material Fig. S7A).

**Shroom2, a TJ protein of embryonic and adult epithelia**

To explore the relevance of shroom2 association with the actin cytoskeleton, we analyzed subcellular distribution of shroom2 in vivo. In agreement with the results obtained by Dietz et al. (Dietz et al., 2006), shroom2 was detected at the AJC of mouse embryonic epithelial and endothelial cells (Figs 3, 4, 5). We further explored shroom2 distribution in adult mouse epithelium. Shroom2 labeling was detected at the most apical border of cell-cell contacts in all tested epithelia, i.e. in the nasal cavity, brain, inner ear, retina, submandibular gland, lung, liver, pancreas, stomach, intestine, kidney and testis (Figs 3, 4, 5, supplementary material Fig. S3, and data not shown). Expression of mShrm2 in neuronal processes may be associated with the TJ-like structures that form between the myelin sheath lamellae (Dermietzel and Kroczek, 1980). Because some of the retinal and inner ear anomalies in myosin VIIa-defective mice (Liu et al., 1998; Self et al., 1998; Liu et al., 1999) might result from a disruption of the interaction between myosin VIIa and shroom2, we focused on the distribution of shroom2 in these sensory organs. In the retina, shroom2 was first detected at embryonic day 12 (E12) in the differentiating pigment epithelium, and the labeling then increased from E14 onwards (Fig. 4A-C). Analysis at 3 weeks and at 3 months of age showed that the bulk of shroom2
immunoreactivity is in retinal pigment epithelium (RPE) cells (Fig. 4C,D, supplementary material Fig. S4), and also in some neuronal extensions in the inner plexiform layer of the neuroretina, where bipolar cells and interneurons of the inner nuclear layer synapse with ganglion cells (Fig. 4C). In the inner ear, the shroom2 labeling progresses differently during the morphogenesis period and maturation steps of the auditory organ (Fig. 5). Intense staining of shroom2 showed that it was equally distributed at the apical part of all epithelial cells facing the luminal space of the early developing cochlear and vestibular organs (Fig. 5A and data not shown). At late embryonic and postnatal stages in the cochlea, strong shroom2 labeling was detected at the tightly joined apical surfaces of sensory cells (hair cells) and supporting cells, that form the reticular lamina (Fig. 5B-D; supplementary material Fig. S5B), and in the apical region of the stria vascularis marginal cells (Fig. 5E, supplementary material Fig. S5A). Notably, the labeling was even more intense at tricellular contacts (arrowheads in Fig. 5E). Labeling of Shroom2 and myosin VIIa defective shaker-1B4626SB mice, did not show any significant alteration in the distribution of shroom2 (Fig. 5G), suggesting that myosin VIIa is not required for targeting of shroom2 to the TJ in hair cells.

Double immuno-labeling experiments with TJ and AJ markers were carried out in various epithelia to define the precise shroom2 distribution within the AJC. In all the analyzed epithelia, i.e. olfactory epithelium (Fig. 3A), choroid plexus (Fig. 3B), gastric glands (Fig. 3C,D), intestinal cells (Fig. 3E,F), retinal pigment epithelial cells (Fig. 4D, supplementary material Fig. S4) and inner ear epithelial cells (Fig. 5A-D, supplementary material Fig. S5B), we found that...
shroom2 colocalized with occludin (not shown), and ZO-1 (also known as TJP1) at the apical most border. By contrast, no significant colocalization was observed between shroom2 and the AJ proteins β-catenin and E-cadherin (Fig. 3D,F; and supplementary material Fig. S3D). We conclude that shroom2 is preferentially targeted to the TJs, in embryonic and adult epithelia.

Shroom2 targeting requires pre-existing TJs
To get insight of the role shroom2 plays in the formation and/or the maintenance of TJs, we studied the distribution of GFP-mShrm2 during the establishment of cell-cell contacts in MDCK cells. The cells were analyzed at various times during the formation of contacts between cells. In isolated and non-confluent cells, GFP-mShrm2 displayed a cytoplasmic staining and colocalized with F-actin (Fig. 6A). In islands of differentiating MDCK cells, we observed shroom2 associated with the plasma membrane exclusively at the sites of initial cell-cell contacts (arrowheads Fig. 6B). However, shroom2 was not recruited to all cell-cell contacts, visualized by the ZO-1 staining (arrows, Fig. 6B; and supplementary material Fig. S6A). As cells became confluent and cell-cell junctions more differentiated, both GFP-mShrm2 and ZO-1 were broadly distributed along the junctional sites (Fig. 6C, and

**Fig. 5.** Spatiotemporal shroom2 distribution in the mouse auditory epithelia. (A–D) At E12, shroom2 colocalizes with ZO-1 at the apical surface of all the epithelial cells delineating the cochlear duct (cd) (A). As development proceeds, the shroom2 labeling becomes more intense in the sensory epithelium (organ of Corti) (B). At birth, a transient diffuse labeling is observed throughout the cytoplasm of the sensory inner (IHC), and outer (OHC) hair cells (* over cell bodies), and pillar (p) cells (C). This cell body labeling decreases at later stages, and is not detected from P10 onwards (D). The bulk of shroom2 labeling is associated with the tightly joined apical domains of the hair cells and their adjacent supporting cells, forming the reticular lamina (D), and also at the apical cell-cell junctions of the marginal cells in the stria vascularis (arrowheads in E). The stria vascularis is a bilayer epithelium of the cochlear duct lateral wall, which secretes K⁺ in the endolymph (the fluid filling the cochlear duct) and produces the endocochlear potential. (F) Whole-mount preparation of a mouse organ of Corti at P2, illustrating the codistribution of shroom2 and myosin VIIa. (G) The absence of myosin VIIa in shaker-1 mutant mice does not alter the normal targeting of shroom2 in the hair cells. Stronger shroom2 labeling is observed in the reticular lamina, whereas weaker labeling is seen in other supporting cells (arrows). Bars, 10 μm.
In such confluent cells, GFP-mShrm2 was colocalized with the TJ proteins ZO-1 and occludin, whereas only limited colocalization was observed with $\beta$-catenin (Fig. 6C). We then analyzed the kinetics of the junctional targeting of shroom2 in stably transfected MDCK cells producing either GFP-mShrm2 or GFP alone (Fig. 7, and supplementary material Fig. S6C). MDCK cells were pre-treated with trypsin-EDTA to break all the junctions and individualize cells, as described (Nigam et al., 1992; Riesen et al., 2002). Cells were submitted to long-term Ca\textsuperscript{2+} depletion (20 hours in low-Ca\textsuperscript{2+}medium), which resulted in GFP-mShrm2 and ZO-1 localizing in a diffuse pattern or in dot-like cytoplasmic structures ($t=0$ hours in Fig. 7). After restoration of the normal Ca\textsuperscript{2+} concentration, cell-cell contacts were progressively restored. Within 1 hour after addition of Ca\textsuperscript{2+}, MDCK cells producing GFP-mShrm2 or GFP alone displayed the same kinetics of ZO-1 recruitment to the cell-cell junctions ($t=1$ hour in Fig. 7, and supplementary material Fig. S6C). ZO-1 fluorescence intensity displayed a heterogeneous distribution at cell-cell junctions, whereas GFP-mShrm2 was still diffuse in the cytoplasm. Within 2 hours ($t=2$ hours in Fig. 7), GFP-mShrm2 reached the plasma membrane only in cells where ZO-1 was present at cell-cell contacts. Moreover, there was a strong correlation between the GFP-mShrm2 and ZO-1 fluorescent signal intensities at cell-cell junctions (Fig. 7, $t=2$ hours). Within 4, 7 and 24 hours in the presence of Ca\textsuperscript{2+}, ZO-1 and GFP-mShrm2 were homogeneously distributed along the cell-cell contacts, and were especially abundant at tricellular junctions ($t=7$ hours in Fig. 7, and data not shown).

Since the experiments in MDCK cells showed that ZO-1 recruitment at the TJ precedes that of shroom2, we asked whether ZO-1 is sufficient to target shroom2 to the TJ. GFP-mShrm2 was expressed in stably transfected L fibroblasts producing human E-cadherin. These cells (LE cells) form E-cadherin-mediated AJ that contain ZO-1 but lack TJ (Itoh et al., 1993). In non-confluent LE cell cultures, GFP-mShrm2 was found in the cytoplasm, associated with F-actin-rich structures (Fig. 8A), reminiscent of the labeling in non-confluent MDCK cells (Fig. 6A). At cell confluence, GFP-mShrm2 became more diffuse in the cytoplasm, and could not be detected at the cell-cell junctions (Fig. 8B-D). This result indicates that ZO-1 is not sufficient to target shroom2 to cell-cell contacts.

**Shroom2 directly interacts with ZO-1**

Transfection experiments showed that the PDZ and SPR domains (PSP) of shroom2 are sufficient to target the protein to the cell-cell contacts (supplementary material Fig. S2). To identify putative shroom2-binding partners at the TJ, we thus used a shroom2 fragment that contained the PDZ and SPR domains as the bait (mShrm2PSP; aa 1-356) to screen the inner ear cDNA library in the yeast two-hybrid system (Fig. 9A). We identified two independent clones encoding a ZO-1 fragment.
that contains part of the third PDZ domain, SH3 and guanylate kinase (GuK) domains, and the acid rich region (Fig. 9A). The direct interaction between shroom2 and ZO-1 was confirmed by in vitro binding assays. Either the GST-tagged ZO-1 prey or GST alone was incubated with 35S-labeled shroom2 fragments (Fig. 9B). The GST-tagged ZO-1 prey bound to full-length shroom2 and to mShrm2PDZ (aa 214-1487), but not to mShrm2ASD2 (aa 931-1487; used as an internal control) (Fig. 9B) or MyRIP/Slac2c (used as an unrelated control) (not shown). This result indicates that the shroom2-PDZ domain does not mediate the interaction with ZO-1. Using 35S-labeled shroom2 fragments containing both the PDZ domain and SPR region (mShrm2SP; aa 1-356), the PDZ domain alone (mShrm2PDZ; aa 1-118) or the SPR region alone (mShrm2SPR; aa 119-356) (Fig. 9B), we found that the SPR region is sufficient for the binding of shroom2 to ZO-1.

Fig. 7. Shroom2 recruitment at the forming TJ after calcium switch in MDCK cells. The lines were used to calculate the fluorescence intensity in line scan. In micrographs, dots with numbers indicate fluorescence intensity at cell edges. Blue asterisks indicate nontransfected cells that do not express GFP-mShrm2. In the fluorescence intensity profiles, vertical blue lines delineate the emplacement of these cells that were used as an internal control for fluorescence quantification. After 20 hours of incubation in low-Ca^{2+} medium (t=0), cells were fixed and analyzed 1 hour (t=1 hour), 2 hours (t=2 hours) and 7 hours (t=7 hours) after Ca^{2+} repletion. At t=0, the fluorescence intensity profiles of transfected cells indicate that both ZO-1 (red) and GFP-mShrm2 (green) are distributed throughout the cytoplasm. At t=1 hour, ZO-1 is recruited at cell-cell junctions in a discontinuous pattern, whereas GFP-mShrm2 is not yet present at the junctions. At t=2 hours, GFP-mShrm2 is mainly detected at cell-cell junctions and the intensity of the labeling at the junctions correlates with that of ZO-1. At t=7 hours, ZO-1 and GFP-mShrm2 display continuous fluorescence patterns along the junctions, and both protein labelings are more intense at tricellular junctions. Bars, 20 μm.
To determine the site at which ZO-1 binds to shroom2, different ZO-1 fragments fused to GST were produced and incubated with 35S-labeled full-length shroom2 or 35S-labeled SPR domain (mShrm2-SPR) only (Fig. 9C). Shroom2 bound to the SH3/GuK domains of ZO-1 (aa 513-812), whereas a binding was not observed with two ZO-1-truncated fragments containing either the N-terminal PDZ3 and SH3 domains (aa 444-649) or the GuK domain alone (aa 644-812) (Fig. 9C). Shroom2 also failed to bind to ZO-1 fragments encompassing the GuK domain followed by the acid rich region (aa 644-891), or by the entire C-terminal part of the prey (aa 644-1015) (data not shown). We conclude that shroom2, through its SPR domain, binds to ZO-1 within the SH3/GuK domains. In pull-down experiments, overexpressed shroom2 bound to the GST-tagged ZO-1 prey but not to GST alone (supplementary material Fig. S1E). Finally, we were able to coimmunoprecipitate endogenous shroom2 and ZO-1, by using the anti-ZO-1 antibody on auditory organ and brain extracts (Fig. 9D). We conclude that shroom2 and ZO-1 can also interact in vivo.

Discussion

We identified shroom2, a submembranous PDZ-domain-containing protein, as a new binding partner of myosin VIIa, and showed that shroom2 is a TJ protein that also directly interacts with F-actin and ZO-1. Consistent with the results obtained by Dietz et al. (Dietz et al., 2006), we found that shroom2 is present at the AJC in embryonic epithelia. In addition, we show that, in adult mouse epithelia, shroom2 is still present at the AJC and localizes preferentially at the TJs. In transfected epithelial cells expressing shroom2, the protein was not detected in nascent TJs that already contained ZO-1, which indicates that shroom2 is not involved in the early stages of junction formation. Rather, the kinetics of shroom2 recruitment at the forming TJs in the Ca2+-switch experiment suggest that the protein plays a role in TJ stabilization. Indeed, shroom2 contains a PDZ domain and is thus expected to exert a scaffolding function by stabilizing submembranous molecular complexes. Notably, numerous TJ proteins, including the two submembranous proteins ZO-2 and ZO-3, the two groups of integral membrane proteins, JAMs and claudins, possess a typical C-terminal PDZ-binding motif (Schneeberger and Lynch, 2004) and are therefore likely candidates to interact with shroom2. Moreover, because shroom2 can bind to F-actin, it may provide a link between the plasma membrane and the cortical cytoskeleton at the TJ. Our results further suggest that the shroom2 MBR subdomain stabilizes actin filaments because it was able to protect F-actin from cytochalasin-D-induced disruption in transfected MDCK cells. Finally, the abundance of shroom2 at TJs in mature epithelia, which are very tight (e.g. marginal cell layer of the cochlear stria vascularis) (Jahnke, 1975) or are continuously submitted to shearing forces (e.g. reticular lamina of the organ of Corti) (Nowotny and Gummer, 2006), further supports the idea that shroom2 is involved in the strengthening of the TJs.

There is increasing evidence that the TJ, on its cytoplasmic side, acts as a platform where the trafficking of proteins to the apical versus basolateral zone is controlled (Kohler and Zahraoui, 2005). In the AJC region, structural proteins (actin, microtubules, spectrin) and regulatory proteins (actin-binding proteins, GTPases, kinases) are juxtaposed with transmembrane proteins (Matter and Balda, 2003; Schneeberger and Lynch, 2004; Köhler and Zahraoui, 2005). The clustering of Rabs, their effectors and the Sec6-Sec8 complex close to the TJ has been proposed to provide the machinery required for docking and fusion of transport vesicles.
Shroom2 displays a wider tissue distribution compared with that of myosin VIIa, but both proteins are present in a variety of epithelial cells, including hair cells, retinal pigment epithelial cells, choroid plexus cells, enterocytes and kidney tubular cells (Sahly et al., 1997; Wolfrum et al., 1998). In these cells, myosin VIIa can be detected throughout the cell body, and electron microscopy analyses have shown that this myosin is especially abundant in ciliary and microvillar structures (Sahly et al., 1997; Wolfrum et al., 1998). In hair cells, myosin VIIa – like shroom2 – is especially abundant in the vesicle-rich region at the immediate vicinity of the AJC (Hasson et al., 1997). How then, does myosin VIIa act in conjunction with shroom2? It has been shown in vitro that dimerized myosin VIIa can move processively on actin filaments, and myosin VIIa requires high ATP concentrations for its motile activity (Inoue and Ikebe, 2003; Yang et al., 2006). By contrast, ADP increases the F-actin-binding affinity of myosin VIIa to actin filaments, suggesting that in subcellular compartments with a high ADP concentration, myosin VIIa is exerting a tension force (Inoue and Ikebe, 2003) rather than having a transport function. Collectively, its kinetic parameters would allow myosin VIIa to exert and hold tension on actin filaments and, when dimerized, to function as a processive cargo transporter. Therefore, depending on the ATP context in situ, myosin VIIa, in conjunction with shroom2, could be involved in the targeting of a certain set of proteins and/or vesicles at the TJ.

Fairbank et al. have reported that a loss of shroom2 activity results in defects in both the biogenesis and the apical localization of retinal melanosomes in *Xenopus* (Fairbank et al., 2006). It is worthy of note that also in myosin-VIIa-defective mice, melanosomes do not enter the apical processes in retinal pigment epithelial cells (Liu et al., 1998). Myosin VIIa and shroom2 codistribute at the level of the TJ zone, whereas myosin VIIa and its binding partner MyRIP are especially abundant in the apical microvilli (El-Amraoui et al., 2002). Therefore, in the retinal pigment epithelium cells, the putative interaction between shroom2 and myosin VIIa could be essential to transfer melanosomes from microtubules to the apical actin cytoskeleton in the TJ zone. Once in the microvilli,
a tripartite complex of myosin VIIa, MyRIP/Slac2c and Rab27a would mediate the recruitment and movement of melanosomes along the peripheral actin filaments (El-Amraoui et al., 2002; Fukuda and Kuroda, 2002). This scenario is in agreement with the recent results showing that, in addition to their link to F-actin, proteins of the shroom family regulate γ-tubulin distribution and may thus coordinate the assembly of both microtubule and actin cytoskeletons (Fairbank et al., 2006; Lee et al., 2007).

Among the shroom family members, shroom2 displays the same modular organization as shroom3a, namely a N-terminal PDZ domain and two C-terminal ASD domains (see supplementary material Fig. S7A). In primary neural tube cells from mouse embryos, shroom3a is located at the AJ-s (Hildebrand and Soriano, 1999). Shroom3 regulates the formation of a contractile actomyosin network associated with the AJC, and it has been proposed that shroom3 regulates the distribution of myosin II at the AJC (Hildebrand, 2005). Therefore, we propose that through interactions between shroom2 and myosin VIIa, and shroom3a and myosin II, similar interaction networks between the plasma membrane and subcortical actin cytoskeleton takes place at the TJ and AJ, respectively (see supplementary material Fig. S7B).

Materials and Methods

Yeast two-hybrid screenings and expression constructs

Yeast two-hybrid screenings were performed as described previously (Rain et al., 2001) using different baits, namely the C-terminal SH3/MyTH4/FERM fragment of myosin VIIa (aa 1605-2215), and the N-terminal PDZ and SPR domains of shroom2 (mShrm2PSp, aa 1-356).

The full-length mouse cDNA encoding shroom2 (GenBank accession number EF071946) was reconstituted by using race-PCR on a mouse inner ear cDNA library (mShrm2PSP, aa 1-356).

Among the shroom family members, shroom2 displays the critical reading of the manuscript. This work was supported by grants from Fondation Raymonde et Guy Strittmatter, the European Commission FP6 Integrated Project EuroHear LSHG-CT-2004-512063, ANR-05-MRAR-015-01, Ernst-Jung Stiftung für Medizin, Preis, and A & M Suchert-Retina Kontra Blindheit. The confocal microscope was purchased with a donation from Marcel and Liliane Pollack. E.Z. and R.E. received a fellowship from Fondation pour la Recherche Médicale (France).

a solution of 50 µM G-actin (Molecular Probes) was polymerized by incubation for 30 minutes at 37°C in a high-salt buffer containing 50 mM KCl and 2 mM MgCl2. Co-sedimentation assays were done by incubating 2 µg of either GST-mShrm2MBR or GST, with 20 µl of a 16.5 µM F-actin solution for 30 minutes, followed by ultracentrifugation (100,000 g, 1 hour). The same amount of supernatant and pellet fractions were subjected to SDS-PAGE and analyzed with Coomassie Blue staining.

Antibodies and immunofluorescence analysis

A polyclonal antibody was produced against a mixture of two peptides derived from the mouse shroom2 protein: mShrm2 (MEGAEPARPRLEAE, aa 1-115) and mShrm2P2 (GSSFYSTYKEHLKAA, aa 695-709). Antibodies from two rabbits (R1 and R2) were used. The specificity of the immunopurified antibodies was assayed by immunocytofluorescence and immunoblot analysis. Substitution of the preimmune serum for the purified antibody against shroom2 and preadsorption of the antibodies with the corresponding antigens were used as negative controls.

The following monoclonal antibodies were used: anti-ZO-1 (Zymed), anti-occludin (Zymed), anti-E-cadherin (Transduction laboratories), anti-β-catenin (Transduction laboratories), anti-GST (Amersham). F-actin was visualized using TRITC-phalloidin (Sigma).

Immunofluorescence analyses were carried out on fixed cells (grown on glass coverslips or on transwell filters) and cryostat sections of tissues or whole-mount preparations of the organ of Corti of RJ Swiss mice (Janvier, France) as described previously (Kussel-Andermann et al., 2000). Cells, tissue sections and whole-mount preparations were analyzed with a laser scanning confocal microscope (LSM-510, Zeiss).

Cells, transfection and Ca2+-switch assays

HeLa, Caco-2, MDCK, LLCPK, CHO, L and LE cells were grown in DMEM supplemented with 10% FCS, containing penicillin and streptomycin. Transient transfections were performed using Effectene (QIAGEN) for HeLa and CHO cells and Lipofectamine Plus (Invitrogen) for the other cell lines, according to the manufacturer’s instructions. Stable MDCK cell lines expressing GFP-mShrm2 and GFP alone were obtained by Jet-PEI transfection (Polyplus-transfection). Cells were transfected with 0.8 µg of GFP (GAI, PAA) and 10 days to stable transfectants. Cells were then sorted by FACS using MoFlo setup of the Pasteur Institute cytometry platform. We selected small subpopulations for a weak intensity of fluorescence to avoid very high levels of transgene expression. Stable cell lines were maintained under selection in 0.2 mg/ml G418. For the Ca2+-switch experiments, 1.3×105 MDCK cells/cm2 were grown overnight (20 hours) in low-Ca++ medium; i.e. Ca++-free D-MEM supplemented with 5% dialyzed FCS (Invitrogen), according to the protocol by Gumbiner (Gumbiner et al., 1988). Cells were then incubated in D-MEM containing physiological concentrations of Ca++ for 0, 1, 2, 4, 7, and 24 hours, fixed in 4% PFA and analyzed by immunofluorescence. Fluorescence intensity profile analysis was performed using the linefunction of MetaMorph (version 7.0, Universal Imaging Corp., Downingtown, PA) as described (Sousa et al., 2005). The profile of fluorescence intensity was measured along the line in two channels.

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References

Fig. S1

A In vitro binding assay

Immobilized myosin VIIa fragments

Biotin-MyTH4/FERM
Biotin-FERM
Biotin-CAT

In vitro binding assay

1 2 3

GST-mShrm2MBR

1 2 3

GST-mShrm2MBR

kDa
62 49 38

B Antibody characterization

mShrm2P1 (aa 1-15)
mShrm2P2 (aa 695-709)

My-mShrm2

Anti-mShrm2R1
Anti-myc
Anti-mShrm2R2

kDa
196 98 62

C mShrm2 immunoprecipitation (IP)

Inputs: P3 cochlea

Blot: anti-mShrm2R1

mShrm2

kDa
250 148 98 64

D Myosin VIIa immunoprecipitation

Inputs: P3 cochlea

Blot: anti-myosin VIIa

Myosin VIIa

kDa
250 148 98 64

E Pull down assay

GST-ZO1 (aa 444-1015)

Untagged-mShrm2

Inputs

GST
GST-ZO1

Blot: anti-mShrm2R1
Fig. S2

GFP-tagged mShrm2 fusion proteins in Caco2 cells

GFP-mShrm2FL

GFP-mShrm2\(\Delta\)PDZ

GFP-mShrm2PSP

GFP-mShrm2MBR-ASD1

GFP-mShrm2ASD2
mShrm2 in mouse epithelia, brain, and vasculature

Pancreas

Submandibular gland

Intestine

Gastric gland

Liver

Myosin Vila + ZO1

+ myosin Vila

+ mShrm2

Central nervous system

Forebrain

Hindbrain

Cerebellum

Vasculature (endothelial cells)

Kidney

Choroid plexus

ZO1

ZO1

ZO1

E-cadherin
Fig. S4

Myosin VIIa, mShrm2, and ZO1 in the embryonic and adult mouse retina

A

E14

Myosin VIIa + ZO1

B

Myosin VIIa

ZO1

C

P90

ZO1

Myosin VIIa + ZO1

MyRIP + ZO1

TJ

PhR

D

RPE

E

F

E14

mShrm2 + ZO1

mShrm2

mShrm2 + ZO1
**Fig. S6**

### A  GFP-tagged mShrm2 full length (aa 1-1487) at cell-cell contacts

<table>
<thead>
<tr>
<th>Island of MDCK cells</th>
<th>Confluent MDCK cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFP-mShrm2 + ZO.1</td>
<td>GFP-mShrm2 + ZO.1</td>
</tr>
</tbody>
</table>

### B  GFP-tagged mShrm2-MBR (aa 350-721) at cell-cell contacts

<table>
<thead>
<tr>
<th>Isolated or subconfluent MDCK cells</th>
<th>Confluent MDCK cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFP-mShrm2MBR + F-actin t = 16 hours</td>
<td>GFP-mShrm2MBR + F-actin t = 48 hours</td>
</tr>
<tr>
<td>GFP-mShrm2MBR + F-actin t = 24 hours</td>
<td>GFP-mShrm2MBR + F-actin t = 48 hours</td>
</tr>
</tbody>
</table>

### C  Distribution of GFP and ZO-1 in MDCK cells producing GFP alone

<table>
<thead>
<tr>
<th>t = 0</th>
<th>t = 1 hour</th>
<th>t = 2 hours</th>
<th>t = 7 hours</th>
</tr>
</thead>
</table>

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**Graphs:**

- Fluorescence intensity (arbitrary units) vs. position (µm) for each time point (t = 0, t = 1 hour, t = 2 hours, t = 7 hours).