The Scribble module regulates retromer-dependent endocytic trafficking during epithelial polarization

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ABSTRACT

Scribble (Scrib) module proteins are major regulators of cell polarity, but how they influence membrane traffic is not known. Endocytosis is also a key regulator of polarity through roles that remain unclear. Here we link Scrib to a specific arm of the endocytic trafficking system. *Drosophila* mutants that block AP-2-dependent endocytosis share many phenotypes with Scrib module mutants, but Scrib module mutants show intact internalization and endolysosomal transport. However, defective traffic of retromer pathway cargo is seen, and retromer components show strong genetic interactions with the Scrib module. The Scrib module is required for proper retromer localization to endosomes and promotes appropriate cargo sorting into the retromer pathway via both aPKC-dependent and -independent mechanisms. We propose that the Scrib module regulates epithelial polarity by influencing endocytic itineraries of Crumbs and other retromer-dependent cargo.

KEY WORDS: *Drosophila*, Endocytosis, Epithelia, Polarity, Retromer

INTRODUCTION

The polarized distribution of proteins is central to biological function. Foundational work has identified several multiprotein modules that act as key polarity regulators throughout vertebrates and invertebrates (St Johnston and Ahringer, 2010). Polarity control must ultimately impact vesicular trafficking to achieve a restricted protein distribution at the plasma membrane (PM), but how specific polarity-controlling modules influence the general process of membrane traffic is a long-standing mystery.

Two polarity modules, called the Par and Crumbs (Crb) modules, specify the apical membrane domain. In the *Drosophila* Par module, Bazooka (Baz; also known as Par-3) and Par-6 serve as scaffolding proteins that direct aPKC kinase activity to appropriate targets in response to a Cdc42-GTP-mediated cue (Goldstein and Macara, 2007). One potential target is the transmembrane protein Crb, which can specify apical identity via a poorly characterized aPKC-dependent pathway (Bulgakova and Knust, 2009).

A third module, called the Scribble (Scrib) module, is a major regulator of the basolateral domain, where it serves to exclude apical protein localization. In *Drosophila* this module consists of Scrib, Discs-large (Dlg) and Lethal giant larvae (Lgl) (Yamanaka and Ohno, 2008), which are ‘junctional scaffolds’ that contain multiple protein-protein interaction motifs. Lgl shows reciprocal negative regulation with aPKC, but how it and other Scrib module proteins interface with membrane trafficking machinery is not known.

Polarity control by the Scrib module is also required to prevent malignant overgrowth in several fly tissues (Bilder, 2004), leading Scrib module genes to be described as ‘neoplastic’ tumor suppressor genes (TSGs). Evidence suggests the conservation of a tumor suppressive role in mammals (Martin-Belmonte and Perez-Moreno, 2011; Pearson et al., 2011) as well as an important role in influencing the Hippo pathway (Cordenonsi et al., 2011). Currently there is thus much interest in understanding the fundamental activity of the Scrib module.

An intriguing hint comes from recent work revealing that certain canonical regulators of endocytic trafficking also act as fly neoplastic TSGs (reviewed by Shivas et al., 2010). For instance, loss of Rab5 or endosomal sorting complex required for transport (ESCRT) components results in disorganized overgrowth of imaginal epithelia, whereas mutations that disrupt subsequent stages of endocytic trafficking do not. Rab5 and ESCRT also regulate apical polarity in mammalian epithelia (Dukes et al., 2011; Zeigerer et al., 2012), while Par mutations in several systems can cause defects in cargo internalization and endolysosomal traffic (reviewed by Shivas et al., 2010). Here we investigate the hypothesis that Scrib mediates polarity through influencing endocytic itineraries. We show that the Scrib module regulates retromer-dependent sorting events that can return internalized cargo to the cell surface, thereby linking this conserved polarity-regulating module to a specific, bona fide vesicle trafficking pathway.

RESULTS

AP-2-dependent endocytosis is required for epithelial organization and proliferation control

We recently reported the isolation of null mutations in *Drosophila* genes encoding regulators of endocytosis from the cell surface. These include subunits of the AP-2 adaptor complex, the Dynamin ortholog Shibire (Shi) and the Clathrin heavy chain (Che). When imaginal discs consist predominantly of cells mutant for these genes, the tissues are severely disorganized and show upregulation of Matrix metalloprotease 1 (Mmp1) (Windler and Bilder, 2010). Mutant eye disc are also larger than their wild-type (WT) counterparts, lose neuronal differentiation and epithelial monolayering, and display disrupted cell shapes (Fig. 1A-D; supplementary material Fig. S1A-D). Mutant clones in the adult follicle epithelium also lose epithelial organization (supplementary material Fig. S1I-L). These phenotypes confirm that AP-2 subunits, shi and Che act as neoplastic TSGs (Windler and Bilder, 2010).

Similar cortical polarity defects in endocytic and Scrib module mutant cells

We analyzed PM polarity in these endocytic mutants, first assessing proteins that are peripherally associated with the cell cortex. The apical markers aPKC and Par-6 and the basolateral marker Dlg are found in separate but contiguous domains in WT epithelial cells (Fig. 1E,I). In AP-2 follicle cells, aPKC is mislocalized around the
Misllocalization, exclusion and overlap between Crb and Nrg are also seen in lgl cells. Strikingly, whereas Nrg was exclusively PM localized and indistinguishable between the two genotypes, Crb showed significantly reduced PM localization in lgl as compared with AP-2 tissue, accompanied by a hazy, subcortical distribution (Fig. 1N,P,R). Subcortical Crb was also seen in dlg discs (Fig. 1H and Fig. 2D). Therefore, while Scrib module and AP-2 mutants phenocopy each other in most respects, they show a specific difference in Crb subcellular localization.

Subcortical Crb could result from defects in exocytic delivery to the PM, or from defects in endocytic traffic. To distinguish between these possibilities, we examined cells depleted simultaneously of AP-2 and lgl. In contrast to lgl-depleted cells, these dual depleted cells show levels of Crb cortical association comparable to cells depleted of AP-2 alone (Fig. 1O–R). The epistasis suggests that, whereas AP-2 is required for Crb internalization, Scrib module mutants are defective in post-endocytosis trafficking of Crb.

**Scrib module mutations do not alter AP-2-dependent internalization or lysosomal trafficking**

The evidence for endocytic trafficking defects in Scrib module mutant cells, as well as the polarity phenotypes shared with endocytic mutant cells, raised the possibility that the Scrib module controls epithelial polarity by regulating general endocytic traffic. We directly analyzed endocytosis using the cargo Notch. In WT discs, Notch is internalized by AP-2 and degraded after 5 h (supplementary material Fig. S2A) (Lu and Bilder, 2005). This process is intact in discs mutant for dlg, scrib or lgl (supplementary material Fig. S2B–D), in contrast to discs mutant for AP-2 (supplementary material Fig. S2F) or Rab5 (Lu and Bilder, 2005). We found no evidence of a decreased rate of endocytosis (supplementary material Fig. S2G-I) and the endocytic tracer Dextran was also internalized and degraded (supplementary material Fig. S2K). Because Notch internalization and degradation, like epithelial polarity and proliferation control, require AP-2 (Windler and Bilder, 2010), we conclude that the Scrib module does not regulate polarity via general control of AP-2-dependent internalization or endolysosomal traffic.

**Altered trafficking of retromer cargo in Scrib module mutants**

To reconcile the altered endocytic traffic of Crb (Fig. 1) with the normal degradative traffic of Notch (supplementary material Fig. S2) in Scrib module mutant cells, we considered whether these cells might be defective in a distinct post-endocytosis route. An alternative to endolysosomal transport is traffic through the retromer pathway from endosomes to Golgi. Crb transits this pathway, which promotes its endolysosomal traffic is traffic through the retromer pathway from endosomes to Golgi. Crb transits this pathway, which promotes its endolysosomal distribution (Fig. 2A,B,K). By contrast, E-cadherin (Ecad; Shotgun FlyBase) and transgenic CD8, as well as other transmembrane proteins, remain associated with PM discs in dlg discs as in WT (Fig. 2E-H,K; supplementary material Fig. S2), demonstrating that subcortical trapping is seen only with specific cargo, is not due to general exocytic defects, and is not an artifact of overexpression. Altered localization of Wls resembled that of Crb (Fig. 2C,D,K), which colocalized poorly with the vesicular markers examined (supplementary material Fig. S4). Moreover, treatment with lysosomal inhibitors revealed increased lysosomal accumulation of both Wls and Crb.

![Fig. 1. Comparison of Scrib module and endocytic polarity phenotypes.](supplementary material Fig. S1)
but not Ecad, specifically in dlg tissue (Fig. 2L-Q; supplementary material Fig. S5). The demonstration that Wls, like Crb, is defectively trafficked in dlg discs suggests that the Scrib module is required for proper sorting into and/or transit of endocytic cargo through the retromer pathway.

**Disrupting retromer trafficking enhances Scrib module phenotypes**

If endocytic sorting into the retromer pathway is functionally involved in polarization by the Scrib module, then genes regulating the two processes should genetically interact. Mild knockdown of lgl in the dorsal wing disc leads to ruffling of the adult wing (Fig. 3A,B). This phenotype is enhanced when flies are heterozygous for scrib (Fig. 3C), but not shi or AP-2 subunits (Fig. 3D), demonstrating that it represents a specifically sensitized background. Strikingly, mild knockdown of the retromer subunits Vps35 and Vps26, which have little effect on WT wings (Fig. 3E,F), dramatically enhanced the effect of mild lgl knockdown, resulting in a lethal ‘giant larvae’ phenotype with mislocalized and tumorous discs when Vps26 and mild lgl knockdown are combined (100%, n=43; Fig. 3G,H). These genetic interactions are consistent with a model in which Scrib module proteins regulate polarity by influencing endocytic sorting into retromer pathways.

**The Scrib module influences retromer-dependent sorting**

We sought further evidence for Scrib module involvement by examining vesicular trafficking compartments. Antibodies and tagged transgenes showed that, although polarized distribution is lost, the overall morphology of exocytic and endolysosomal compartments in dlg discs is similar to WT (supplementary material Fig. S6). A marker for the recycling endosome, Rab11, is also not obviously changed. By contrast, dlg tissue shows clear alterations of two markers associated with retromer sorting compartments: Rab9 and Vps29 (Burgess et al., 2012; Dong et al., 2013). The restricted and punctate localization of these markers seen in WT is replaced by widespread and diffuse staining in dlg mutant cells (Fig. 3I-N). Vps29 and Rab9 colocalize with endosomal and Golgi markers in WT cells (Burgess et al., 2012; Dong et al., 2013), but as these compartments are unaltered in dlg tissue (supplementary material Fig. S6) the data suggest that the Scrib module specifically controls the enrichment of retromer at sites of endocytic sorting.

We further investigated the relationship between the regulation of retromer sorting and the Scrib module by carrying out double-depletion experiments. Wls traffics via retromer (Eaton, 2008), and strong RNAi-mediated knockdown of Vps26 in otherwise WT cells reduces steady-state PM levels (Fig. 3O,P). When compared with dlg knockdown alone (Fig. 3Q), simultaneous depletion of Vps26 with dlg prevents Wls from reaching the PM and achieving a subcortical distribution, and Wls is found instead in endosomal puncta (Fig. 3R). These data, showing that the dlg trafficking phenotype requires retromer activity, are consistent with the genetic interactions uncovered above and suggest that the Scrib module normally regulates trafficking via retromer.
aPKC-dependent and -independent trafficking regulation by the Scrib module

The above data indicating specific and functionally relevant retromer defects raise the question of exactly which cargo is mistrafficked to alter apicobasal polarity. Crb is mistrafficked in Scrib module mutant cells (Fig. 1H,N and Fig. 2D) and is basolaterally mislocalized when endosomal entry is blocked (Lu and Bilder, 2005). Mislocalization of Crb is also sufficient to specify apical character on PMs (Wodarz et al., 1995) and to induce neoplastic growth (Lu and Bilder, 2005). We tested whether Crb was the single relevant cargo by completely removing it from Scrib module mutant cells using a null allele. However, discs and follicle cells completely lacking Crb and the Scrib module, or Crb and an endocytic regulator, remained mispolarized and neoplastic (supplementary material Fig. S1Q-X) (Leong et al., 2009). These data rule out Crb as the sole polarity-regulating cargo that requires Scrib module-dependent trafficking.

We considered whether other apical regulators might be controlled by Scrib-influenced trafficking. Baz, Par-6 and aPKC remained at the PM in Scrib module mutant cells, and, unlike Crb (Moberg et al., 2005), they were not trapped in endocytic compartments in ESCRT mutant cells (Fig. 1F; data not shown). Antibodies and a tagged transgene (Fletcher et al., 2012; Harris and Tepass, 2008) revealed a significant cytosolic population of Cdc42 in WT cells, preventing an assessment of altered distribution in mutants. We then asked whether Par module activity was involved in Scrib-mediated trafficking. To test sufficiency, we expressed an activated form of aPKC and found that it induces subcortical trapping of Crb and Wls in imaginal discs (Fig. 2I,J). To test necessity, we analyzed mutant follicle cells in which both the Par and Scrib modules are inactivated. In these cells, the subcortical haze of Crb is eliminated (Fig. 4A-F) and cells almost completely lack an apical domain (Fig. 4G-I). However, double-mutant and depleted cells do not show the extensive degradation of Crb seen when the Par module alone is inactivated (Fig. 4A,D). Instead, Crb accumulates in internal puncta, and some residual PM localization is evident (Fig. 4C,F). This incomplete epistasis with respect to cargo localization contrasts with the strong epistasis with respect to polarity (Bilder et al., 2003; Tanentzapf and Tepass, 2003), revealing that the Scrib module regulates endosomal trafficking in part through an aPKC-independent mechanism. However, the necessity and sufficiency experiments together indicate that excess Par module activity in Scrib module mutant cells is a major contributor to defective trafficking, suggesting that the Scrib module influences trafficking of aPKC-regulating cargo in addition to Crb.

DISCUSSION

Our data identify a specific trafficking role for the Scrib module, a core player in the conserved polarization machinery. The evidence that the Scrib module has an endocytic mechanism integrates two major pathways that control cell polarity. Our results rule out AP-2-dependent endolysosomal transport and instead identify a role for the
Scrib module in sorting cargo that passes through the retromer. The data further indicate that this relationship is direct and specific, given the requirement of the Scrib module for retromer organization on endosomes and the strong genetic interaction seen with retromer subunits.

Our data point to complexity in the action of the Scrib module. It is clearly not a positive regulator of retromer activity, as the depletion of PM Crb and Wls, their shunting to the lysosome and the loss of apical polarity seen in retromer mutants (Poche et al., 2011; Zhou et al., 2011) are largely opposite to the Crb misdistribution seen in Scrib module mutants. However, the Scrib module does not simply negatively regulate retromer sorting, since reducing retromer function potently enhances Scrib module hypomorphic phenotypes, and the Scrib module null phenotype induces defects in retromer component localization and retromer-dependent trafficking.

A recent paper describes a role for mammalian Scrib in stabilizing the Ecad-p120 interaction and in preventing retromer sorting of lysosomally destined Ecad (Lohia et al., 2012); however, our data, which show that Scrib module mutant cells display PM-localized Ecad, lysosomal Wls and Crb, and no evident Golgi trapping, demonstrate that a different mechanism is at work in the fly.

One possibility is that Scrib module mutants cause neither a wholesale gain nor loss of retromer activity, but rather inappropriate sorting that results in cargo ectopically returning to an incorrect PM domain. In addition to retromer-dependent retrograde transport and ESCRT-dependent lysosomal targeting, cargo can also exit the sorting endosome via Rab11 recycling, and Crb is known to pass through Rab11 compartments (Blankenship et al., 2007; Fletcher et al., 2012; Roeth et al., 2009); cargo could be aberrantly shunted into this route when Scrib module loss alters retromer activity. Because Rab11 is also involved in biosynthetic transport (Ang and Fölsch, 2012), rendering its inhibition toxic, and Rab11-dependent recycling cargoes are not well-validated in fly epithelia, we are currently unable to test this model. An activity of Scrib module proteins in influencing the sorting and subsequent destination of transcytotic cargo, which can involve retromer activity (Su et al., 2010; Vergès et al., 2004), would be consistent with many of the results reported here. The Scrib module could influence transcytotic sorting by regulating cargo modifications at the basolateral surface in a manner distinct from the apical surface [for instance, via Lgl-mediated inhibition of aPKC (Yamanaka and Ohno, 2008)]. Alternatively, the requirement for proper Rab9 and Vps29 localization on endosomes points to Scrib affecting more general aspects of retromer function. Overall, a model consistent with our data is that Scrib regulates polarity by influencing sensitive sorting steps within endosomes, specifically the itinerary of apically destined proteins that can transit the retromer pathways.

As data demonstrate that polarity regulators can influence endocytic trafficking of distinct cargo in different ways (Shivas et al., 2010), strict tests of these hypotheses must await identification of the specific polarity-regulating cargoes involved. Crb is one of these, and our data build on recent advances in understanding Crb trafficking (Fletcher et al., 2012; Poche et al., 2011; Roeth et al., 2009; Zhou et al., 2011). However, studies of double mutants show that Crb is not the sole cargo responsible for polarity control. The Scrib module phenotypes show a strong requirement for the Par module, consistent with previous data pointing to Cdc42/Par endosomal sorting activity (reviewed by Harris and Tepass, 2010), although the data also reveal a Par-independent role. Overall, our findings point to an additional Par-regulating cargo that undergoes AP-2-dependent, retromer-mediated recycling to specify the apical surface; the identification of this cargo will open the door to defining the precise molecular mechanisms by which Scrib controls its trafficking.

MATERIALS AND METHODS

Fly stocks and genetics

Mutant eye discs and follicle cell clones were generated as described (Lu and Bilder, 2005). Follicle cell knockdown employed traffic jam-Gal4 (Tanentzapf et al., 2007) to drive expression of RNAi stocks, except for Fig. 4D-G, which used hsFLP; act\(\Rightarrow\)STOP\(\Rightarrow\)GAL4 UASGFP with S\(\Rightarrow\) induction. WT control flies were w; isogenized FRT stocks. Owing to the similar mutant phenotypes of AP-2 complex subunits, representative experiments carried out with the AP-2\(\Delta\) allele (Windler and Bilder, 2010) are labeled AP-2. Additional alleles used included shi\(^{FL34}\), Che\(^{J}\), lgl\(^{MS106}\), fab\(^{F1}\), Vps23\(^{H}\), scrb\(^{J}\), dig\(^{G20}\), Vps45\(^{AN11}\), crb\(^{1432}\). Other transgenes included tub-Rab5-YFP, tub-Rab7-YFP, tub-Vps29-GFP, en-Gal4, Msl1096-Gal4, UAS-CD8-GFP, UAS-apKCA; Act\(\Rightarrow\)LS, UAS-wls-V5, UAS-Rab-YFP, UAS-Vps26-myc, UAS-cdc42-V5. RNAi constructs were created by the Transgenic RNAi Resource Project (TRiP) (Cdc42-IR, Vps26-IR), Vienna Drosophila Resource Center (VDRC) (AP-2a-IR 15566, dig-IR 41134), the D.B. lab (lgl-IR ‘weak’ or provided by X. Lin (Cincinnati Children’s Hospital, OH, USA) [Vps35-IR III vp2], Vps26-IR ‘mild’).

Mutant eye discs were generated as described (Menet et al., 2007).
Descriptions of Drosophila stocks can be found on FlyBase. The crb coding region was PCR amplified and sequenced from heterozygous crb^{142Z} adults; on the mutant chromosome, the nucleotide change C902T replaces amino acid Q950 within the EGF repeats to create a stop codon.

**Immunohistochemistry and microscopy**

Ovaries and L3 larvae were dissected in PBS, fixed in 4% formaldehyde in PBS for 20 min at room temperature, and stained using standard procedures (Bilder and Perrimon, 2000). The following primary antibodies were used: rat anti-Elav (7E8A10, 1:50), mouse anti-Notch^{EC}

References


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