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The schizophrenia susceptibility factor dysbindin and its associated complex sort cargoes from cell bodies to the synapse

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ABSTRACT Dysbindin assembles into the biogenesis of lysosome-related organelles complex 1 (BLOC-1), which interacts with the adaptor protein complex 3 (AP-3), mediating a common endosome-trafficking route. Deficiencies in AP-3 and BLOC-1 affect synaptic vesicle composition. However, whether AP-3-BLOC-1–dependent sorting events that control synapse membrane protein content take place in cell bodies upstream of nerve terminals remains unknown. We tested this hypothesis by analyzing the targeting of phosphatidylinositol-4-kinase type II α (PI4KIIα), a membrane protein present in presynaptic and postsynaptic compartments. PI4KIIα copurified with BLOC-1 and AP-3 in neuronal cells. These interactions translated into a decreased PI4KIIα content in the dentate gyrus of dysbindin-null BLOC-1 deficiency and AP-3–null mice. Reduction of PI4KIIα in the dentate reflects a failure to traffic from the cell body. PI4KIIα was targeted to processes in wild-type primary cultured cortical neurons and PC12 cells but failed to reach neurites in cells lacking either AP-3 or BLOC-1. Similarly, disruption of an AP-3–sorting motif in PI4KIIα impaired its sorting into processes of PC12 and primary cultured cortical neuronal cells. Our findings indicate a novel vesicle transport mechanism requiring BLOC-1 and AP-3 complexes for cargo sorting from neuronal cell bodies to neurites and nerve terminals.

INTRODUCTION

Cell polarity is established and maintained, in part, by selective targeting of membrane components to distinct organelles or plasma membrane domains. This is particularly evident in neurons, where membrane components transported in vesicular carriers generated in the cell body are selectively targeted to distal compartments of axons or dendrites. Alternatively, vesicle carriers are generated locally at synaptic domains. Vesicular carriers are generated by cytosolic coats, which specify their protein and lipid composition (Bonifacino and Glick, 2004). Diverse coats and accessory proteins generate a multitude of vesicles in eukaryotic cells (Robinson, 2004). Although the diversity of vesicle carriers and their pathways have been intensely studied in yeast and mammalian fibroblastoid cell lines, knowledge about the diversity and specializations of vesicle transport pathways in polarized cells is limited. Clathrin and clathrin-binding adaptors orchestrate vesicle biogenesis, and in polarized cells they contribute to specialized transport mechanisms (Folsch et al., 1999, 2003; Deborde et al., 2008). For example, heterotetrameric clathrin adaptors AP-1–4 participate in the biogenesis of synaptic vesicles at the nerve terminal (Voglmaier et al., 2006; Glyvuk et al., 2010; Haucke et al.,...
Detected in vesicle-trafficking mechanisms may also promote pathogenesis of major psychoses, including schizophrenia (Ryder and Faundez, 2009; Karayiorgou et al., 2010). Genome-wide analyses reveal strong associations between genes encoding adaptor-binding proteins and schizophrenia (Ryder and Faundez, 2009). Of particular interest is dysbindin, the product encoded by the DTNBP1 locus. DTNBP1 ranks high among all genes studied thus far in terms of their strength of association with schizophrenia risk. Of importance, dysbindin protein levels are reduced in the prefrontal cortex, superior temporal gyrus, and hippocampal formation (hippocampus plus dentate gyrus) of schizophrenia patients, further underscoring the association between dysbindin function and schizophrenia pathogenesis (Talbot et al., 2004, 2011; Tang et al., 2009a). However, DTNBP1 genetic association with disease is not universal among all human populations (Ross et al., 2006; Allen et al., 2008; Sun et al., 2008; Talbot et al., 2009; Ghiani and Dell’Angelica, 2011; Mullin et al., 2011).

Dysbindin is a subunit of the octameric biogenesis of lysosome-related organelles complex 1 (BLOC-1 complex; Li et al., 2003; Starcevic and Dell’Angelica, 2004; Di Pietro and Dell’Angelica, 2005). The BLOC-1 complex is assembled by dysbindin, pallidin, mutated, snapin, cappuccino, and BLOS1-3 subunits (Li et al., 2004; Di Pietro and Dell’Angelica, 2005; Wei, 2006; Raposo and Marks, 2007; Dell’Angelica, 2009). The BLOC-1 complex binds to the clathrin adaptor protein complex AP-3 (Di Pietro et al., 2006; Newell-Litwa et al., 2010), a heterotetramer constituted of δ, β3, μ3, and ε3 subunits. The genes encoding the component proteins in AP-3 and BLOC-1 belong to a group of 15 genetic loci in mice. Mutations in some of these loci trigger Hermansky–Pudlak syndrome in humans, which is characterized by, but not limited to, pigment dilution, bleeding diathesis, and pulmonary fibrosis—phenotypes that are recapitulated in mouse models of this syndrome. These mutated genes encode products that belong to five distinct cytosolic complexes: AP-3, BLOC-1, BLOC-2, BLOC-3, and the HOPS complex (Li et al., 2004; Di Pietro and Dell’Angelica, 2005; Wei, 2006; Raposo and Marks, 2007; Dell’Angelica, 2009). At the cellular level, AP-3 and BLOC-1 subunits localize to nerve terminals and/or axons, and deficiencies in these complexes alter the composition of synaptic vesicles and the surface expression of neurotransmitter receptors (Talbot et al., 2006; Iizuka et al., 2007; Ji et al., 2009; Newell-Litwa et al., 2009, 2010; Tang et al., 2009b; Marley and von Zastrow, 2010). These cellular defects trigger neurobehavioral phenotypes from Drosophila to mouse, some of which resemble those found in schizophrenia patients (Hattori et al., 2008; Bhardwaj et al., 2009; Cox et al., 2009; Dickman and Davis, 2009; Talbot, 2009; Cheli et al., 2010; Papaleo et al., 2010). These observations highlight fundamental vesicle transport pathways controlled by BLOC-1 and AP-3 in neurons. However, a central question not yet addressed is whether BLOC-1 and AP-3 perform sorting functions uniquely restricted to the synapse (Voglmaier et al., 2006) and/or whether these complexes assemble vesicle carriers in cell bodies destined to deliver membrane proteins that are later incorporated into synapses.

Here we explore polarized neuronal membrane-trafficking routes requiring BLOC-1 and AP-3, using the membrane-anchored lipid kinase phosphatidylinositol-4-kinase type IIx (PI4KIIx) as a reporter. Our focus on PI4KIIx is based on its capacity to bind the AP-3 complex and to regulate AP-3 recruitment to membranes (Craigie et al., 2008; Salazar et al., 2009). We demonstrate that PI4KIIx copurifies with BLOC-1 complexes assembled with either tagged dysbindin or mutated subunits, as well as with AP-3. These biochemical interactions were confirmed genetically, since a PI4KIIx synaptic depletion phenotype in the dentate gyrus of dysbindin-null sandy mice was phenocopied in that area of the brains of AP-3-null mocha mice and in mice lacking the mutated or palladin components of BLOC-1. PI4KIIx synaptic depletion suggested that BLOC-1 and AP-3 regulate delivery of membrane proteins from cell bodies to nerve terminals. Consistent with this hypothesis, analysis of the subcellular localization of wild-type PI4KIIx or a mutant form unable to bind AP-3 and BLOC-1 indicated that the interaction of PI4KIIx with AP-3-BLOC-1 was required for PI4KIIx export from cell bodies to neurites. Similarly, wild-type PI4KIIx failed to reach neurites in neurons of AP-3- or BLOC-1–mutant mice. Our findings reveal a novel vesicle transport mechanism in which BLOC-1, in association with the AP-3 complex, delivers specific cargos from neuronal cell bodies to neurites and nerve terminals. We propose that defects in the dysbindin/BLOC-1 vesicle-trafficking pathway and the resulting mislocalization of specific cargo molecules contribute to the pathogenesis of complex psychiatric disorders.

RESULTS

Phosphatidylinositol-4-kinase type IIx biochemically and genetically interacts with BLOC-1 and AP-3

We previously showed that PI4KIIx binding to AP-3 is sensitive to the dose of the dysbindin-containing BLOC-1 complex (Salazar et al., 2009). Precipitation of AP-3 complexes with AP-3 δ antibodies specifically coprecipitated PI4KIIx from wild-type fibroblasts (Figure 1A, compare lanes 3 and 5). In contrast, the association of PI4KIIx to AP-3 complexes was decreased in BLOC-1–null cells carrying the Pldδμε3α allele (Figure 1A, compare lanes 5 and 6). Thus, we tested the hypothesis that dysbindin associates with the adaptor complex AP-3 and PI4KIIx, in addition to its interactions within the BLOC-1 complex. We expressed N-terminal FLAG-tagged dysbindin in SH-SY5Y neuroblastoma cells. Protein complexes coprecipitating with FLAG-dysbindin were isolated from cells treated in the absence or presence of dithiobis(succinimidyl propionate) (DSP; Figure 1). DSP is a cell-permeable and reducible cross-linker used here to stabilize protein–protein interactions labile to stringent purification (Lornant and Fairbanks, 1976; Salazar et al., 2009; Zlatic et al., 2010). Isolation of FLAG-dysbindin protein complexes with FLAG antibodies coprecipitated the BLOC-1 subunits mutated and palldlin (Figure 1B, lane 7), as well as the AP-3 subunits δ, β3, and ε3 (Figure 1B, lane 8). Dysbindin’s associations with AP-3 subunits required stabilization with DSP (Figure 1B, lane 8). These associations with FLAG-dysbindin beads were specific, as determined by their absence from beads alone (Figure 1B, lanes 3 and 4), beads coated with control SV2 antibody (Figure 1B, lanes 5 and 6), and competition with an excess FLAG antigenic peptide during bead incubation.

Volume 22 December 15, 2011 Dysbindin-dependent protein targeting | 4855
with cell extracts (Figure 1B, lanes 9 and 10). We next tested whether endogenous PI4KIIα copurified with BLOC-1 subunits by PI4KIIα immunopurification. PI4KIIα was isolated with an antibody directed against amino acids 51–70 from human PI4KIIα, and PI4KIIα protein complexes were selectively eluted with the PI4KIIα peptide 51–70 used to generate the PI4KIIα antibody (Supplemental FIGURE 1). Dysbindin coprecipitates BLOC-1 subunits, AP-3 complexes, and PI4KIIα. (A) Wild-type (Pldn+/+, odd lanes) or pallidin-deficient (Pldn−/−, even lanes) mouse skin primary culture fibroblasts were treated with DSP, detergent solubilized, and extracts precipitated with magnetic beads with antibodies against AP-3 delta (lanes 3–6) in either the absence (lanes 5 and 6) or presence (lanes 3 and 4) of delta antigenic peptide as an immunoprecipitation control. (B) SH-SY5Y stably expressing triple FLAG dysbindin treated in the absence or presence of DSP were solubilized in detergent and extracts precipitated with magnetic beads alone as controls (lanes 3–6), with antibodies against FLAG tag (lanes 7–10). Precipitations were performed in the absence or presence of an excess of FLAG peptide (lanes 9 and 10). An irrelevant antibody (SV2, lanes 5 and 6) was used to confirm specificity. (C) SH-SY5Y FLAG dysbindin or (D) SH-SY5Y FLAG muted cell extracts were precipitated with PI4KIIα antibodies (lanes 3, 4, and 3′–5′) in either the absence or presence of PI4KIIα peptide 51–70 to outcompete binding of PI4KIIα complexes to beads (first Competition [Comp.], lanes 4 and 4′). Protein complexes bound to beads were eluted with SDS–PAGE sample buffer (lanes 2–4). The band detected in PI4KIIα blots in lanes 1 and 4 corresponds to the rabbit anti-PI4KIIα immunoglobulin G also used for immunoprecipitation. Alternatively, PI4KIIα protein complexes were eluted from beads with buffer in either the absence (lane 3′) or presence of 200 μM PI4KIIα peptide 51–70 (second elution, lane 5′). (E) Untransfected SH-SY5Y (lanes 1, 2, 5, and 6) or SH-SY5Y FLAG muted cell extracts treated in the absence or presence of DSP were solubilized in detergent and extracts were precipitated with FLAG antibodies (lanes 3, 4, and 5–8), and FLAG muted protein complexes were eluted from beads with 200 μM FLAG peptide (lanes 5–8). Note that PI4KIIα coprecipitates with FLAG-tagged muted even in the absence of DSP (lane 7). Specificity was determined by using cell extracts from nontransfected cells (lanes 5 and 6). Immune complexes resolved by SDS–PAGE were analyzed by immunoblot with antibodies against FLAG, the BLOC-1 subunits pallidin and muted, AP-3 subunits (δ, β3, σ3), and PI4KIIα. Inputs are 10%, and in B–D inputs are lanes 1 and 1′.
Dysbindin-dependent protein targeting

Volume 22 December 15, 2011

Dysbindin, a membrane protein targeted to synaptic vesicles by mechanisms independent of AP-3 or BLOC-1 (Salazar et al., 2004b, 2006; Newell-Litwa et al., 2009, 2010). The biochemical interactions among the BLOC-1 complex, AP-3, and PI4KIIα as well as the common hippocampal PI4KIIα phenotypes in BLOC-1 and AP-3 deficiencies, demonstrate that these components belong to common trafficking pathway in neuronal tissue.

PI4KIIα is depleted in nerve terminals of mice deficient in the AP-3 complex

The subcellular compartment affected by reduced levels of PI4KIIα in the mutant mice carrying deficiencies in either BLOC-1 or AP-3 was identified by subcellular fractionation and quantitative immunoelectron microscopy of brain tissue. We focused on AP-3–null brains to facilitate these experiments because AP-3–null brain phenotypes are widespread, in contrast to BLOC-1 deficiency phenotypes, which are predominantly observed in the dentate gyrus of the hippocampus (Kantheti et al., 1998; Newell-Litwa et al., 2010). High-speed pellets (P2) from whole-brain homogenates were sedimented in Percoll density gradients to resolve fractions enriched in pinched-off nerve terminals or heavy synaptosomes (Figure 3, HS). Levels of SV2 and synaptophysin—two synaptic vesicle markers—remained unaffected in AP-3 mocha (Ap3d1mnh/mnh)–heavy synaptosomes. In contrast, the content of PI4KIIα and the synaptic vesicle AP-3 cargoes VAMP7 and ZnT3 were reduced in Ap3d1mnh/mnh–heavy synaptosomes. ZnT3 reduction in synaptosomes was due to decreased ZnT3 levels in Ap3d1mnh/mnh homogenates. In contrast, PI4KIIα was significantly diminished in synaptosomes of Ap3d1mnh/mnh brains without changes in total homogenate levels (Figure 3). This pattern is similar to that of VAMP7 (Figure 3), a membrane protein present in synaptic vesicles that we and others demonstrated to be decreased in nerve terminals of AP-3–null brains (Scheuber et al., 2006; Newell-Litwa et al., 2010).

We further explored the subcellular localization of PI4KIIα in the hippocampal formation of wild-type and Ap3d1mnh/mnh mice by immunocytochemistry with a PI4KIIα–specific antibody (Figure 4 and Supplemental Figures S1 and S2). At the light-microscopic level, PI4KIIα displayed a distinctive distribution in different regions of the dentate gyrus (Figure 2, A–D). This phenotype was similar in BLOC-1–null mice, either by deficiency of muted or pallid (Newell-Litwa et al., 2010). PI4KIIα content was decreased in the neuropil of dysbindin-null sandy dentate gyrus (Figure 2, A and E). This phenotype was similar in BLOC-1–null mice, either by deficiency of muted or pallid (Figure 2, B, C, and E), and the AP-3–deficient mocha allele (Figure 2, D and F). The selectivity of this PI4KIIα phenotype is highlighted by the absence of an effect on synaptophysin, a membrane protein targeted to synaptic vesicles.
hippocampal formation. Immunoreactivity was most prominent in cell bodies and dendrites of hippocampal pyramidal cells and in three presynaptic fields: 1) the inner molecular layer of the dentate gyrus, which is the terminal field of axons from large neurons in the dentate hilus, 2) the dentate hilus, and 3) the stratum lucidum of CA3, which (along with the dentate hilus) is the terminal field of dentate granule cells (Supplemental Figure S2). PI4KIIα subsynaptic distribution was determined by immunoelectron microscopy of the dentate gyrus. Immunoreactivity was present in dendrites (data not shown) and presynaptic elements of asymmetric axodendritic and axospinous synapses (Figure 4, A, A1, and C). PI4KIIα immunoreactivity in presynaptic elements is consistent with previous reports of PI4KIIα localization on synaptic vesicles (Guo et al., 2003; Salazar et al., 2005; Takamori et al., 2006). We quantified the number of PI4KIIα-positive synaptic elements in the dentate gyrus hilus of wild-type and mutant mice (Figure 4C). Most PI4KIIα-labeled elements were asymmetric axosynaptic terminals in the mouse dentate gyrus hilus (Figure 4C). Three-fourths of those nerve terminals were PI4KIIα immunoreactive in wild-type mice (Ap3d1+/+). In contrast, only 35% of such terminals were PI4KIIα positive in AP-3–null Ap3d1/hh/hh (Figure 4D). Because AP-3 deficiency did not affect the density of asymmetric axosynaptic terminals in the dentate (Figure 4E), the reduction in the density of such terminals positive for PI4KIIα reflects depletion of the enzyme in them.

Disruption of AP-3, BLOC-1, and PI4KIIα interactions impairs PI4KIIα targeting from cell body to processes
PI4KIIα depletion in nerve terminals might reflect failed export of this cargo from the parent cell bodies. We addressed this by expressing enhanced green fluorescent protein (EGFP)-tagged PI4KIIα or a dileucine-sorting mutant version of PI4KIIα that is unable to bind AP-3 or coprecipitate with the BLOC-1 complex, PI4KIIαL60-61A (Craigie et al., 2008; Salazar et al., 2009). PI4KIIα is targeted to brain synaptic vesicles and PC12 cell synaptic-like microvesicles by AP-3 and BLOC-1 mechanisms (Salazar et al., 2005; Newell-Litwa et al., 2009). Moreover, synaptic-like microvesicles are coated with AP-3 and BLOC-1 complexes (Salazar et al., 2005, 2006). Thus we determined the targeting of tagged PI4KIIα to PC12 synaptic-like microvesicles isolated by sucrose velocity sedimentation (Lichtenstein et al., 1998). Endosomes and synaptic-like microvesicles sediment in fractions 5–7 and 15 in these gradients, respectively (Citr-O’Grady et al., 1998; Lichtenstein et al., 1998). Wild-type EGFP-PI4KIIα was present in endosome and synaptic-like microvesicle fractions isolated from PC12 cells (Supplemental Figure S3). In contrast, EGFP-PI4KIIαL60-61A targeting to synaptic-like microvesicle fractions was reduced (Supplemental Figure S3, A and B) concomitantly with an increased EGFP-PI4KIIαL60-61A content in endosomes (Supplemental Figure S3B; compare open and closed circles). We then used nerve growth factor (NGF)–differentiated PC12 cells and assessed EGFP-PI4KIIα distribution by imaging live and fixed specimens (Figure 5). Wild-type PI4KIIα was enriched at neurite tips of differentiated PC12 cells (Figure 5, A and A1). In contrast, the EGFP-PI4KIIαL60-61A mutant signal was faint in neurites and their tips (Figure 5, C and C1). We depicted these dramatic differences in subcellular localization as x, y coordinates, where each dot depicts an individual cell defined by its PI4KIIα fluorescence intensity in cell bodies (x-axis) and processes (y-axis; Figure 5, E and F). Decomposition of these x, y-coordinate plots into cell body and process PI4KIIα fluorescence intensities (Figure 5, G and H) revealed that cells expressed similar cell body levels per voxel of wild-type or mutant EGFP-PI4KIIα (Figure 5G). However, they differed significantly in the amount of PI4KIIα present in cell processes and their tips (Figure 5H). Similar results were obtained with fixed differentiated PC12 cells, where the EGFP-PI4KIIαL60-61A mutant levels in processes were selectively reduced compared with VAMP2, a synaptic vesicle marker whose targeting is not affected by AP-3 or BLOC-1 deficiencies (Figure 5I; Salazar et al., 2004a; Newell-Litwa et al., 2009).

Next we performed fluorescence recovery after photobleaching (FRAP) of PC12 cell neurite tips expressing recombinant PI4KIIα to determine 1) whether EGFP-PI4KIIα is delivered in an anterograde manner and 2) whether the EGFP-PI4KIIα delivery mechanism could be distinguished from EGFP-PI4KIIαL60-61A, as predicted by the reduced targeting of this mutant to synaptic-like microvesicles (Supplemental Figure S3). EGFP-PI4KIIα FRAP of the neurite tip reached a plateau by 45 min (Figure 6, A and B). In contrast, the EGFP-PI4KIIαL60-61A mutant recovery was accelerated, attaining steady state by 10 min (Figure 6, A and B). Rapid fluorescence recovery of PI4KIIαL60-61A could be due to diffusion of a plasma membrane EGFP-PI4KIIαL60-61A pool. This hypothesis stems from the observation that AP-3 cargos are misrouted to the cell surface when the cargo–adaptor association is perturbed (Dell’Angelica et al., 1999; Peden et al., 2004). To address this, we compared EGFP-PI4KIIαL60-61A FRAP to an EGFP targeted to the plasma membrane by the palmitoylation signal of GAP43.

FIGURE 3: PI4KIIα content in synaptosomes of AP-3–deficient mocha mice is reduced. (A) Synaptosome fractions from control brains (lanes 1–8) and AP-3–deficient mocha (Ap3d1/hm/hm) brains (lanes 1′–8′) were resolved on SDS–PAGE, and the contents were analyzed by immunoblot with antibodies against synaptic vesicle markers (SV2, synaptophysin), AP-3–dependent synaptic vesicle cargoes (PI4KIIα, VAMP7, ZnT3), and AP-3 ε3 subunit. (B) Quantification of antigen content expressed as a ratio of the heavy synaptosome fraction. Numbers in parentheses represent the number of independent immunoblots performed from three independent fractionations. *p < 0.0001; **p = 0.0157. HS, heavy synaptosomes; LS, light synaptosomes; Mit, mitochondrial-enriched fractions obtained from Percoll gradients; P1 and P2, low- and high-speed pellets, respectively. Fractions were generated as per Nagy and Delgado-Escueta (1984).
These experiments indicated that impairment of an AP-3, BLOC-1, and PI4KIIα interaction prevents cargo inclusion into synaptic-like microvesicles and thereby prevents PI4KIIα delivery to neurite tips in PC12 cells either assessed in vivo or in fixed specimens. To complement the results obtained with PC12 cells, we analyzed primary cultured neurons to determine whether PI4KIIα targeting to neurites was sensitive to the ablation of AP-3, the dileucine-sorting motif in PI4KIIα, and/or BLOC-1. We analyzed the distribution of PI4KIIα and the synaptic vesicle protein VAMP2 in 7-d in vitro cultures of cortical neurons (7 DIV). Fluorescence intensity in cell bodies and processes was scored for PI4KIIα and VAMP2, and values were represented as x, y coordinates (Figures 7 and 8). In wild-type neurons, endogenous PI4KIIα and VAMP2 were present in cell bodies and neuronal processes, but in Ap3d1m mh neurons and VAMP2 were present in cell bodies and neuronal processes, but in Ap3d1m mh neuron content of PI4KIIα in cell bodies and processes was selectively reduced (Figure 7A, B, and E1). VAMP2 distribution was not affected in this AP-3 deficiency (Figure 7, A, B, and E2). We also expressed EGFP-PI4KIIα in wild-type and AP-3−null mocha cells (Figure 7, C, D, and F). Targeting of EGFP-PI4KIIα to processes was impaired in Ap3d1m mh neurons despite cell body expression levels of EGFP-PI4KIIα spanning one order of magnitude (compare Figure 7, E1 and F1). Processes of wild-type neurons were efficiently populated by EGFP-PI4KIIα in that range of cell body expression levels (Figure 7F1). As in neurons lacking AP-3, those expressing mutant PI4KIIα unable to bind AP-3 and coprecipitate with BLOC-1 (EGFP-PI4KIIαL60-61A; Craige et al., 2008; Salazar et al., 2009) failed to populate cell processes (Figure 7, G1−H1). This EGFP-PI4KIIαL60-61A phenotype was observed irrespective of the culture age and recombinant protein expression level in cell bodies (Figure 7, G1−H1). The selectivity of these phenotypes was demonstrated by unaltered VAMP2 distribution (Figure 7, G2−H2). Our data demonstrate that integrity of interaction between the AP-3 adaptor and its cargo, PI4KIIα, is required for cargo export from cell bodies to neurites.

PI4KIIα association to AP-3 requires BLOC-1, and deficiencies in BLOC-1 complex subunits phenocopied a PI4KIIα phenotype in the AP-3−null dentate gyrus (Figure 2). Thus we tested whether endogenous PI4KIIα, EGFP-PI4KIIα, and EGFP-PI4KIIαL60-61A export from cell bodies to neurites was impaired in dysbindin-BLOC-1−deficient sandy Dtnbp1dy/dy neurons (Figure 8). We focused on dysbindin-null neurons because of strong association of dysbindin gene polymorphisms with schizophrenia (Ross et al., 2006; Allen et al., 2008; Sun et al., 2008; Talbot et al., 2009). Control (Dtnbp1+/−) and dysbindin-BLOC-1−null neurons (Dtnbp1dy/dy) expressed either...(continued)

(EGFP-GAP43-ps), since PI4KIIα is anchored to membranes by palmitate (Figure 6, A and C; Matsuda and Cepko, 2007; Barylko et al., 2009). EGFP-PI4KIIαL60-61A and EGFP-GAP43-ps FRAP were similar, suggesting that EGFP-PI4KIIαL60-61A rapid recovery is due to plasma membrane diffusion. These results indicate that wild-type PI4KIIα uses a vesicular delivery mechanism to neurite tips that is high capacity and low speed. However, a PI4KIIα mutant unable to bind AP-3 reaches PC12 neurite tips by a low-capacity mechanism compatible with diffusion in the plane of the membrane.

FIGURE 4: PI4KIIα is present in synapses, and its presynaptic levels are decreased in AP-3−null brains (Ap3d1m mh). (A, A1) PI4KIIα immunoperoxidase labeling in the active zone of axon terminals forming asymmetric, axospinous synapses in the dentate gyrus of a wild-type mouse (Ap3d1+/+). (B, B1) The lack of such labeling in a AP-3−null mouse (Ap3d1m mh/mh). Note that the spine in A also displays a low level of immunoreactivity (arrows). (C) Relative prevalence of neural elements immunoreactive for PI4KIIα in random fields of view of the dentate gyrus taken at a magnification of 75,000× in three wild-type animals. One hundred thirty-four dentate gyrus fields were analyzed from three mice. (D) Percentage of PI4KIIα-positive terminals over the total number of asymmetric synapses counted in control and AP-3−null mocha (Ap3d1m mh/mh) dentate gyrus sections. Here, n1 corresponds to number of animals, and n2 is the number of terminals scored per genotype. Note the significant difference in percentage of labeled terminals between wild-type and AP-3−null mocha mice. (F) Total number of axon terminals forming axospinous, asymmetric synapses per square micron of dentate gyrus tissue in three control and three AP-3−null mocha (Ap3d1m mh/mh) mice. Numbers in the boxplot are the total area of tissue analyzed. Scale bars, 200 nm.
endogenous (Figure 8E) or EGFP-Pi4KIIα to a similar extent in cell bodies (Figure 8, A, C, and F). However, Pi4KIIα or EGFP-Pi4KIIα did not populate neurites in Dnbp1+/+/sdy neurons (Figure 8, E and F; compare closed circles [Dnbp1+/+] and open circles [Dnbp1+/sdy]). EGFP-Pi4KIIαL60-61A remained constrained to cell bodies both in control and BLOC-1–null sandy cells (Figure 8G). All Pi4KIIα phenotypes were selective, since the distribution of VAMP2 in neurons was not affected by the Dnbp1+/sdy allele or the expression of wild-type or mutant forms of Pi4KIIα (Figure 8, E1–F1; compare closed triangles [Dnbp1+/+] and open triangles [Dnbp1+/sdy]). Therefore, the dysbindin-containing BLOC-1 complex is required for the delivery of Pi4KIIα to neurites from neuronal perikarya. We showed here that the schizophrenia susceptibility gene product dysbindin, which is contained in the BLOC-1 complex, and its interacting AP-3 adaptor are required to target cargoes into vesicles assembled at cell bodies for delivery into neurites and nerve terminals. These carriers selectively deliver a subset of synaptic vesicle membrane proteins to the synapse. In contrast, synaptic vesicle proteins such as synaptophysin and VAMP2 are not affected by null alleles of these protein complexes. We explored the BLOC-1–AP-3 transport mechanism by assessing the subcellular distribution and movement of Pi4KIIα, a lipid kinase that both binds to AP-3 by a BLOC-1–dependent mechanism and regulates AP-3 recruitment to endosomes (Craigie et al., 2008; Salazar et al., 2009). Pi4KIIα is depleted in dentate gyrus neuropil of dysbindin-null sandy mice, a trait phenocopied in mice deficient in the dysbindin-interacting BLOC-1 subunits palldin and in AP-3–null mice carrying the Ap3d1<sup>+/min</sup> mocha allele. The common Pi4KIIα phenotype among these four mutant mice results from disrupted association of Pi4KIIα with BLOC-1 and AP-3. Pi4KIIα was retained in the cell body of neurons lacking AP-3 or BLOC-1 protein complexes, a phenotype emulated by mutagenesis of the dileucine-sorting motif in Pi4KIIα. This motif is necessary for Pi4KIIα association with AP-3, its copurification with BLOC-1, and its exit from early endosomes in human fibroblastoid cells (Craigie et al., 2008; Salazar et al., 2009).

We predicted the existence of a BLOC-1–AP-3 pathway that delivers vesicles from cell bodies to nerve terminals from our “seesaw” sorting hypothesis (Newell-Litwa et al., 2009). This seesaw model was postulated to explain the opposing effects that ubiquitous and neuronal AP-3–null alleles had in cargo delivery to synaptic vesicle fractions (Newell-Litwa et al., 2009). A BLOC-1–AP-3 route between cell bodies and nerve terminals was further supported by the existence of 1) BLOC-1– and AP-3–decorated vesicle carrier in PC12 cells (Salazar et al., 2005), 2) the presence of a BLOC-1–AP-3 supracomplex in isolated nerve terminals (synaptosomes; Newell-Litwa et al., 2010), and 3) BLOC-1– and AP-3–null nerve terminal phenotypes in brain tissue in toto (Newell-Litwa et al., 2010). However, points 1–3 were similarly compatible with a local role of BLOC-1 and AP-3 in nerve terminals. Moreover, such a local role is additionally supported by the observation that AP-3–dependent mechanisms acutely regulate vesicle traffic in nerve terminals (Voglmaier et al., 2006). Thus the origin of BLOC-1 and AP-3 vesicles in neurons remained an untested prediction from our previous work. Our data presented here demonstrate that the cell body is the most upstream site where BLOC-1 and AP-3 are required for membrane protein sorting toward the synapse. This
is clearly illustrated by the trapping of endogenous and exoge- nously expressed PI4KIIα in cell bodies of neurons defective in ei- ther BLOC-1 or AP-3. In addition to the assembly and loading of vesicular carriers in the cell body, it is possible that BLOC-1 and AP-3 may perform functions along axons and dendrites, because subunits of these complexes are found in these subcellular compart- ments from cell bodies. This hypothesis is supported by the presence of PI4KIIα in both cell bodies and dendritic compartments as demonstrated here, as well as AP-3 and dysbindin as demonstrated previously (Talbot et al., 2004, 2006, 2011; Seong et al., 2005; Newell-Litwa et al., 2010). Alternatively, BLOC-1 and/or AP-3 could participate in the local recycling of specific membrane proteins, such as the dopa- mine D2 receptor and the NR2A subunit of the N-methyl-D-aspartic acid receptor, to and from the synaptic plasma membrane (lizuka et al., 2007; Ji et al., 2009; Tang et al., 2009b; Marley and von Zastrow, 2010). Im- paired cargo delivery not only could affect membrane dynamics in mature neurons but also could impair the development of neuronal processes (Ghiani et al., 2009; Ito et al., 2010).

Presynaptic or postsynaptic functional deficits in neurons lacking either BLOC-1 or AP-3 complexes likely result from the type of proteins depleted from synapses and the extent of their depletion. For example, vesicle fusion may be impaired as a result of reduced PI4KIIα and SNAREs, including VAMP7. Consis- tent with this, dysbindin sandy mice and a knockout of the BLOC-1 subunit snapin re- veal a role for BLOC-1 complex subunits in modulating calcium-regulated exocytosis of chromaffin granules and synaptic vesicles (liardi et al., 1999; Tian et al., 2005; Chen et al., 2008). Similarly, Drosophila dysbindin func- tions presynaptically in adaptive homeostatic modulation of vesicle release (Dickman and Davis, 2009). Of importance, these changes in the physiology of presynaptic secretory organelles occur concom- itant with changes in organelle morphology. Chromaffin granules from dysbindin-null mice are larger, a phenotype observed in both chromaffin granules and synaptic vesicles from dentate gyrus gluta- matergic terminals of the AP-3 moca mouse (Grabner et al., 2006; Chen et al., 2008; Newell-Litwa et al., 2010). These similar morpho- logical changes in dysbindin and AP-3-null cells further support that BLOC-1 and AP-3 participate in the same pathway.

Dysbindin, its interacting partner pallidin (unpublished data), and AP-3 are widely expressed in the brain. Judging from the synaptic fields in which dysbindin is concentrated and the synaptic effects of dysbindin loss (Talbot et al., 2004, 2006, 2009; lizuka et al., 2007; Chen et al., 2008; Ji et al., 2009; Tang et al., 2009b; Papaleo et al., 2010), multiple neurotransmitter systems (especially dopamine, GABA, and glutamate) may be affected by deficiencies in the dys- bindin/BLOC-1/AP-3 pathway. Because vesicle-trafficking mecha- nisms control the subcellular delivery of multiple membrane pro- teins to nerve terminals, defects in specific membrane-protein sorting events are almost certainly involved in the diverse neuro- chemical phenotypes observed in schizophrenia, given widespread synaptic dysbindin reductions observed in the disorder (Talbot et al., 2004, 2011; Tang et al., 2009a). We propose that pathways defined by schizophrenia susceptibility genes, such as the dysbindin/ BLOC-1/AP-3 pathway, offer encompassing mechanisms to explain multiple, pleiotropic neurochemical and neurodevelopmental phe- notypes observed in schizophrenia brains.

FIGURE 6: Distinct mechanisms mediate the delivery of wild-type and dileucine mutant PI4KIIα into neurites. (A) Look-up table (LUT) of photobleached neurite tips of PC12 cells expressing EGFP-PI4Kα, EGFP-PI4KIIαL60-61A, or EGFP-GAP43-ps. In vivo images were taken before (Pre) during photobleaching (0') and every 5 min thereafter for 30 min, after which an image was acquired every 15 min for an additional 45 min. (B, C) Time course of neurite tip fluorescence intensity (%) during FRAP, normalized to their fluorescence intensity before photobleaching. (B) EGFP-PI4KIIαL60-61A (n = 14 cells) recovers faster than EGFP-PI4Kα (n = 23 cells) following photobleaching, reaching a plateau within 10 min vs. 45 min, respectively. (C) No differences are observed in the time course of recovery between EGFP-PI4KIIαL60-61A and EGFP-GAP43-ps (n = 8 cells). Scale bars, 20 μm.
MATERIALS AND METHODS

Antibodies, plasmids, recombinant proteins, and mice

The following antibodies were used in this study: mouse monoclonals against AP3-δ (SA4) and SV2 from the Developmental Studies Hybridoma Bank at the University of Iowa (Iowa City, IA), synaptophysin (SY38) from Chemicon International/Millipore (Billerica, MA), and VAMP7-TI (a generous gift of Andrew Peden, Cambridge University, Cambridge, United Kingdom), as well as rabbit polyclonals against PI4KIIα peptide 51-71 PGHDREQLPLLARGAAGAQ (UniProt/Swiss-Prot entry Q99M64 [P4K2A_RAT] UniProtKB/Swiss-Prot) generated in this study and VAMP-2 from Synaptic Systems (Göttingen, Germany). Chicken anti-GFP was obtained from Aves Labs (Tigard, OR). Rat monoclonal anti-HA was from Roche (Indianapolis, IN). Glutathione S-transferase full fusion protein of PI4KIIα was prepared as previously described (Craigie et al., 2008). pEGFP-C2 wild-type rat PI4KIIα and pEGFP-C2-PI4KIIαL60-61A mutant plasmids were previously described (Craigie et al., 2008). C-Terminally FLAG-tagged muted (EXT4795-M14) and N-terminal–taggedFLAG-tagged Dysbindin (EX-Mm12550-M12) were obtained from Genecopoeia (Rockville, MD). Both constructs were in a pReceiver vector backbone, and sequences were independently confirmed. EGFP-GAP43-ps was expressed from pCAG-mGFP Addgene (Cambridge, MA) plasmid 14757 (Matsuda and Cepko, 2007).

mocha (STOCK gr+/+ Ap3d1+/-), here referred to as Ap3d1+/m, and its control grizzled (STOCK gr-/- Ap3d1-/-), here referred to as Ap3d1-/-, and pallid (B6.Cg-Pldn+/J, here referred to as Pldn+/j) breeding mouse pairs were obtained from Jackson Labs (Bar Harbor, ME) and bred in-house following Institutional Animal Care and Use Committee (IUCAC)-approved protocols. Muted mice and their controls (B6.C3 A+/-/A-Muted+/j, Mutedc/+m, CHML1c/+m; Zhang et al., 2002) were obtained from Richard Swank (Roswell Park Cancer Institute, Buffalo, NY) and bred in-house. Sandy mice in C57B6 background were previously described (Cox et al., 2009). All mice were bred in-house following IUCAC-approved protocols.

Cell culture

Cerebrocortical neurons were cultured from postnatal day 4 (P4) mice (Ap3d1+/-, Ap3d1+/m, CHMU, muted, C57 and sandy) and maintained in neurobasal media containing B27, l-glutamine, and 100 μg/ml penicillin and streptomycin (Hyclone, Logan,
UT) at 5% CO$_2$ and 37°C. Dissociated neurons were plated on poly-l-lysine (Sigma-Aldrich, St. Louis, MO)–coated glass coverslips and cultured for 3–7 d in vitro (DIV). Dissociated neurons (2 × 10$^6$) were transfected with 3 μg of plasmid DNA using Amaxa nucleofection electroporation (Lonza, Cologne, Germany). Neurons were plated at a density of 6 × 10$^4$ cells per well in a 12-well plate.

HEK-293, SH-SY5Y, wild-type and pallidin-deficient mouse skin primary culture fibroblasts, and PC12 cells (American Type Culture Collection, Manassas, VA) were cultured in DMEM supplemented with either 10% fetal bovine serum (FBS) or, in the case of PC12 cells, a mix of 5% FBS plus 10% equine serum, respectively (Hyclone). Media were supplemented with 100 μg/ml penicillin and streptomycin (Hyclone). Cells were maintained at 37°C with 10% CO$_2$. PC12 cells were transfected with 3 μg/μl DNA by nucleofection using Amaxa Cell Line Nucleofector Kit V (Lonza) and plated in PC12 culture media supplemented with 100 ng/ml NGF 2.5S (murine, natural) (Invitrogen, Carlsbad, CA) on Matrigel-coated, glass-bottom culture dishes (MaTek, Ashland, MA). PC12 cells were differentiated for 48–72 h at 37°C with 10% CO$_2$.

**Immunohistochemistry**

We analyzed PI4KIIα distribution using two immunoperoxidase-labeling protocols. First, 11 male and 11 female C57BL6/J mice 3–6 mo old were deeply anesthetized with sodium pentobarbital (1.0 mg/kg) and perfused transcardially with saline, followed by neutral buffered Formalin. Their brains were then postfixed in the same fixative overnight, embedded in paraffin, and sectioned coronally at 6 μm. The sections were mounted and air dried. They were next de-waxed in xylenes, rehydrated in descending concentrations of ethanol, and immersed for 30 min in 5% hydrogen peroxide dissolved in absolute methanol to quench endogenous peroxidase activity. Following a 10-min water rinse, the tissue was subjected to antigen retrieval by boiling in 1 mM EDTA in 0.1 M Tris buffer, pH 8.0, for 10 min (Pileri et al., 1997). After cooling and rinsing, the sections were reacted immunohistochemically with the PI4KIIα antibody (1:300) generated for this study using a standard avidin/biotin/peroxidase method with nickel sulfate amplification of the 3,3’-diaminobenzidine (DAB) reaction product (Talbot et al., 2004). Results were analyzed on a BX61 Olympus (Center Valley, PA) research microscope equipped with an Olympus DP71 cooled charge coupled device (CCD) digital camera.

**Immuno–electron microscopy**

Tissue used in brain slice preparations was obtained from either male or female mice between 6 and 8 wk of age, unless otherwise indicated. Following deep anesthesia with Nembutal, animals were transcardially perfused with fixative (4% paraformaldehyde with 0.1% glutaraldehyde). Brains were postfixed in 4% paraformaldehyde, which was replaced with phosphate-buffered saline (PBS) within 12–18 h. With use of a vibrating microtome, brains were cut into 60-μm-thick sections and stored in antifreeze (0.1 M sodium phosphate monobasic, 0.1 M sodium phosphate
dibasic heptahydrate, 30% ethylene glycol, 30% glycerol) at −20°C until immunohistochemical preparation.

The 60-μm-thick brain sections were rinsed in PBS and then incubated in sodium borohydride, followed by 100% cryoprotectant (phosphate buffer 0.05 M, pH 7.4, 25% sucrose, 10% glycerol) for 20 min at −80°C and returned to decreasing amounts of cryoprotectant. Sections were preincubated in PBS with 1% normal horse serum (NHS) and 1% BSA, followed by primary antibody incubation with 1:500 affinity-purified anti-PI4KIIα. Sections were rinsed in PBS and then incubated in a 1:1000 dilution of rabbit peroxidase antiperoxidase (Jackson ImmunoResearch Labs). Sections were rinsed in PBS with a final rinse in Tris buffer (50 mM, pH 7.6) before a 10-min incubation in 0.025% DAB, 1% mima- zole, and 0.005% hydrogen peroxide in Tris buffer at room temperature.

The 3D point sections were mounted and analyzed by light microscopy or they were further processed for electron microscopy after rinsing sections in phosphate buffer (0.1 M, pH 7.4). Sections were incubated in 1% osmium tetroxide for 10 min and then returned to phosphate buffer before being dehydrated in increasing concentrations of ethanol. At the 70% ethanol incubation, 1% uranyl acetate was added, and sections were incubated in the dark for 35 min. After dehydration, sections were treated with propylene oxide and embedded in epoxy resin overnight (Durcupan ACM; Fluka, Buschs, Switzerland). Next tissues were mounted onto slides and incubated at 60°C for 48 h. Tissue samples of the dentate gyrus were removed from the slides, mounted on resin blocks, cut into 60-nm-thick sections, collected on Pioloform-coated copper grids, and stained with lead citrate for 5 min.

Electron microscopy was performed with a Zeiss EM-10C electron microscope with a CCD camera (DualView 300W; Gatan, Pleasanton, CA). Images were acquired with Gatan Digital Micrograph Software, version 3.10.1 (Gatan). Analysis was focused on the interface between the granule cells and hilar neuropil, where PI4KIIα was concentrated across mice strains. In the electron microscope, only tissue areas from the surface of the blocks with optimal antibody penetration were examined. These sections were scanned at 10,000×, and random fields of view containing at least one asymmetric synapse were photographed at 75,000×. One hundred ninety micrographs from three blocks of tissue in three animals covering 773 μm² were examined for the control and 172 micrographs from 700 μm² were examined for the control. From this material, the total number of PI4KIIα-immunoreactive or immunonegative terminals forming asymmetric axosomatic synapses was counted to estimate the relative percentage of positively labeled terminals. In addition, in wild-type (Ap3d1+/−) mice, all positive immunoperoxidase-labeled neuronal elements in the field were counted and categorized as axons, spines, dendrites, or glia, based on ultrastructural criteria defined by Peters et al. (1991). Light microscopy of brain sections was performed with a Leica DMRB microscope with a 10×/0.3 differential interference contrast (DIC) objective (Leica Microsystems, Bannockburn, IL), and images were captured with a CCD camera and the Leica IM50 software (Leica DC500).

Immunofluorescence labeling for confocal microscopy

Confocal microscopy was performed with an Axiovert 100M microscope (Carl Zeiss, Jena, Germany) coupled to Ar and He–Ne lasers. Images were acquired using Plan Apochromat 10×/0.5 dry, 20×/0.5 dry, and 40×/1.3 and 63×/1.4 DIC oil objectives. Emission filters used for fluorescence imaging were BP 505-530 and LP 560. Images were acquired with ZEN and LSM 510 software (Carl Zeiss). Hippocampal-formation 60-μm-thick brain sections were first rinsed with PBS and then incubated in 1% sodium borohydride in PBS for 20 min at room temperature, followed by extensive washing with PBS. Samples were preincubated in a solution of PBS with 5% NHS and 1% BSA and 0.3% Triton X-100 for 60 min at room temperature. Samples were incubated overnight at 4°C in primary antibody solutions of PBS with 1% NHS and 1% BSA and anti-PI4KIIα with anti-synaptophysin (SY38) (dilutions of 1:500 and 1:10,000, respectively). After rinsing in PBS, sections were incubated for 60 min in a secondary antibody PBS solution with 1% NHS and 1% BSA and anti-PI4KIIα with anti-synaptophysin (SY38) (dilutions of 1:500 and 1:10,000, respectively). After rinsing in PBS, sections were incubated in cupric sulfate (3.854 wt/vol ammonium acetate, 1.596 wt/vol cupric sulfate in distilled water, pH 5) for 30 min. Sections were washed with PBS and mounted on slides with Vectashield (Vector Laboratories, Burlingame, CA).

HEK293 cells, PC12 cells, and cortical neurons were washed in ice-cold PBS and fixed in 4% paraformaldehyde for 20 min on ice. Cells were then incubated in blocking solution (2% BSA + 1% fish skin gelatin plus 15% horse serum plus 0.02% saponin in PBS) for 30 min at room temperature. Next cells were incubated with antibody for 30 min at 37°C, rinsed, and then incubated with secondary antibody diluted in block in 60 min at 37°C. Cells were then rinsed and mounted with Gelvatol and sealed. Cortical neurons were selected from a field of neurons using the following criteria. Neurons were chosen where a single neuron could be discerned from neighboring neurons, where the morphology met the criteria for the proper development in vitro (Goslin and Banker, 1989), and only chosen based on the staining of the control vesicle marker illuminating the entire neuron. Micrographs were analyzed by creating a region of interest (ROI) outlining only the axon or only the cell body and then determining total number of fluorescent pixels in that specific ROI for the VAMP2 channel and the PI4KIIα channel.

Live imaging of PC12 cells expressing PI4KIIα-GFP, PI4KIIαL60-61A-GFP, or EGFP-GAP43-ps was performed on an A1R Laser Scanning Confocal Microscope (Nikon, Melville, NY) equipped with a hybrid scanner, Perfect Focus, and an environmental chamber for regulation of temperature to 37°C and 10% CO2. Confocal images with a Z-step of 1 μm were captured for 10 min (no delay) with an Apo total internal reflection fluorescence 60×/1.49 oil differential interference contrast (DIC) objective on NIS-Elements AR 3.1 (Nikon) software. Neurite tips of PC12 cells were photobleached for 2 s at 30% laser power. Images were captured for 15 s (no delay) before photobleaching and for 15 min every 5 min after photobleaching, followed by 2 h every 15 min. PC12 cell imaging was performed in Hank’s balanced salt solution minus phenol red and NaHCO3 (Sigma-Aldrich) and supplemented with 10% Donor Equine Serum (Hyclone), 5% fetal bovine serum (Hyclone), and 100 ng/ml NGF 2.5S. Imaris 6.3.1 (Bitplane, St. Paul, MN) and ImageJ 1.41 (National Institutes of Health, Bethesda, MD) software were used for image analysis. For FRAP experiments an ROI representing neurite tips was selected, and fluorescence intensity was measured using ImageJ and normalized to a second ROI in the cell body to compensate for photobleaching due to imaging. Voxel fluorescence intensity was measured in neurites and cell bodies of PC12 cells using Imaris software.
Synaptosome preparation

Synaptosomes were prepared according to Nagy and Delgado-Escueta (1984) from 4-wk-old mice. Briefly, mice were anesthetized by CO2 and brains quickly transferred to ice cold PBS. Tissue was homogenized by 16 strokes of a Potter-Elvehjem homogenizer at 800 rpm in 0.32 M sucrose, 5 mM 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid (HEPES), and 0.5 mM EDTA supplemented with Complete antiprotease inhibitor (Roche). Homogenates were spun at 1000 × g for 10 min, and S1 supernatants were further sedimented at 12,000 × g for 20 min. This P2 pellet was resuspended in 8.5% Percoll (Sigma-Aldrich) and then loaded on a discontinuous gradient comprised of 10 and 16% Percoll. Gradients were spun at 15,000 × g for 20 min.

Microvesicle isolation

PC12 cell microvesicles were prepared as described (Clift-O’Grady et al., 1998). Briefly, cells were lifted from culture dishes with PBS plus 5 mM EDTA on ice. Cells were spun at 800 rpm for 5 min and resuspended in bud buffer (38 mM potassium aspartate, 38 mM potassium glutamate, 38 mM potassium gluconate, 20 mM 4-morpholinoethanesulfonic acid, pH 7.2, 5 mM reduced glutathione, 5 mM sodium carbonate, 2.5 mM magnesium sulfate) and spun again for 5 min at 800 rpm. Cells were then passed through the cell homogenizer (Isobiotec, Heidelberg, Germany) for 16 passes. Cell homogenates were spun for 5 min at 1000 × g and supernatant resolved 10–45% sucrose gradient. Gradient were spun in a SW55 rotor for 1 h at 116,000 × g (Lichtenstein et al., 1998).

Immunofluorescence chromograpy

To assess low-affinity interactions between PI4KIIα, AP-3, and BLOC-1 subunits, we performed cross-linking in intact cells with DSP (Clift et al., 2006; Zizic et al., 2010). Briefly, SHSY5Y cells stably transfected either with FLAG-dysbindin or FLAG-mutated were placed on ice, rinsed twice with PBS, and incubated either with 10 mM DSP (Pierce, Rockford, IL) or as a vehicle control DMSO, diluted in PBS for 2 h on ice. Tris, pH 7.4, was added to the cells for 15 min to quench the DSP reaction. The cells were then rinsed twice with PBS and lysed in buffer A (150 mM NaCl, 10 mM HEPES, 1 mM ethylene glycol tetraacetic acid, and 0.1 mM MgCl2, pH 7.4) with 0.5% Triton X-100 by incubation for 30 min on ice. Cells were scraped from the dish, and cell homogenates were centrifuged at 16,100 × g for 10 min. The clarified supernatant was recovered, and at least 50 μg was applied to 30 μl of Dynal magnetic beads (Invitrogen) coated with antibody and incubated for 2 h at 4°C. In some cases, immunoprecipitations were done in the presence of the antigenic peptide as a control. The beads were then washed four to six times with buffer A with 0.1% Triton X-100. Proteins were eluted from the beads either with sample buffer or by 2 h of incubation with 200 μM antigenic peptide (either PI4KIIα peptide 51-71 or 3x FLAG peptide) on ice. Samples were resolved by SDS-PAGE and contents analyzed by immunoblot.

Statistical analysis

Experimental conditions were compared with the nonparametric Wilcoxon–Mann–Whitney rank sum test or one-way analysis of variance, Dunnett’s multiple comparison using Synergy KaleidaGraph, version 4.03 (Reading, PA) or StatPlus Mac Build5.6.0pre/Universal (AnalystSoft, Vancouver, Canada). Data are presented as boxplots displaying the four quartiles of the data, with the "box" comprising the two middle quartiles, separated by the median. The upper and lower quartiles are represented by the single lines extending from the box.

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