ERG 30, a VAP-33–related Protein, Functions in Protein Transport Mediated by COPI Vesicles

Lior Soussan,* Darya Burakov,* Mathew P. Daniels,‡ Mira Toister-Achituv,§ Amir Porat,§ Yossef Yarden,* and Zvulun Elazar§

*Department of Biological Regulation, ¶Department of Biological Chemistry, The Weizmann Institute of Science, Rehovot, 76100 Israel; and §Laboratory of Biochemical Genetics, National Heart, Lung and Blood Institute, National Institutes of Health, Bethesda, Maryland 20892-4036

Abstract. Intracellular transport of newly synthesized and mature proteins via vesicles is controlled by a large group of proteins. Here we describe a ubiquitous rat protein—endoplasmic reticulum (ER) and Golgi 30-kD protein (ERG30)—which shares structural characteristics with VAP-33, a 33-kD protein from Aplysia californica which was shown to interact with the synaptic protein VAMP. The transmembrane topology of the 30-kD ERG30 corresponds to a type II integral membrane protein, whose cytoplasmic NH₂ terminus contains a predicted coiled-coil motif. We localized ERG30 to the ER and to pre-Golgi intermediates by biochemical and immunocytochemical methods. Consistent with a role in vesicular transport, anti-ERG 30 antibodies specifically inhibit intra-Golgi transport in vitro, leading to significant accumulation of COPI-coated vesicles. It appears that ERG 30 functions early in the secretory pathway, probably within the Golgi and between the Golgi and the ER.

Key words: endoplasmic reticulum • Golgi • coated vesicles • secretion • transport intermediates

Transport of proteins between different organelles of eukaryotic cells is mediated by coated vesicles that bud from one membrane compartment and are targeted to and fuse with an appropriate acceptor organelle (Palade, 1975; Rothman, 1994).

Budding of vesicles is regulated by small GTPases and mediated by cytosolic coat proteins (COPI) that assemble on the donor membrane (Rothman and Wieland, 1996; Schekman and Orci, 1996). COPI vesicles mediate transport of proteins from the ER to the Golgi apparatus (Barmowe et al., 1994; Campbell and Schekman, 1997), whereas COPI vesicles are implicated in transport through the Golgi (Malthotra et al., 1989; Ostermann et al., 1993; Orci et al., 1997) as well as in retrograde transport of proteins from the Golgi back to the ER (Cosson and Letourneur, 1994; Letourneur et al., 1994; Orci et al., 1997).

Docking of vesicles to the appropriate target membrane involves interaction between integral membrane proteins located on the vesicle, called v-SNAREs, and the target membrane proteins, t-SNAREs (Sollner et al., 1993b; Pfeffer, 1996). Before this pairing event, initial docking of a vesicle with its specific target organelle is mediated by a peripheral membrane protein, p115 (Nakamura et al., 1997), originally identified as a protein needed for intra-Golgi transport (Waters et al., 1992). P115 interacts with two integral membrane proteins, giantin, located on COPI vesicles, and GM130, a Golgi matrix protein, thus providing a bridge between vesicles and their target membrane (Sonnichsen et al., 1998). In yeast, Uso1p (the homologue of mammalian p115) acts together with the small GTPase Ypt1p before the formation of SNARE pairs (Lupashin et al., 1996; Sapperstein et al., 1996; Lupashin and Waters, 1997), and initiates docking of ER-derived COPI vesicles to the Golgi (Cao et al., 1998).

Following pairing, the v/t-SNARE complex binds two soluble factors: NEM-sensitive fusion protein (NSF) and soluble NSF attachment protein (SNAP). These, in turn, catalyze the disassembly of the SNARE complex (Sollner et al., 1993a) after a round of fusion, thereby allowing a new round of transport (Mayer et al., 1996; Otto et al., 1997; Ungermann et al., 1998). However, the events that lead to membrane fusion following the docking of vesicles are still being investigated. It has been argued that the
The Journal of Cell Biology, Volume 146, 1999

SNARE complex allows the cell to overcome the energy barrier required for membrane fusion (Fasshauer et al., 1997; Hanson et al., 1997). Furthermore, Weber et al. (1998) used liposomes reconstituted with t- or v-SNAREs to show that the v-t-SNARE complex per se fulfills the minimal requirement for lipid mixing (hemi-fusion) and possibly fusion between two membranes. Yet, Ungermaier et al. (1998), using an in vitro system that reconstitutes homotypic fusion of yeast vacuoles, hypothesized that the formation of the SNARE complex is only an intermediate step in the overall fusion reaction. According to this view, SNARE molecules are involved in docking and possibly in hemi-fusion between donor and acceptor membranes, but another set of proteins is involved in subsequent stages of the fusion process. This notion is supported by Peters and Mayer (1998), who suggested that calmodulin and other yet-unidentified factors are involved in mediating late stages of vacuolar fusion.

The vesicle-associated membrane protein (VAMP)-associated protein of 33 kD (VA P-33) was identified in Aplysia californica (Skehel et al., 1995b). This protein is conserved in evolution with homologues found in Saccharomyces cerevisiae (SCS2) (Nikawa et al., 1995), Caenorhabditis elegans (Klass et al., 1984), Arabidopsis thaliana (Galaud et al., 1997), and humans (Weir et al., 1998). Antibodies directed against VA P-33 blocked neurotransmission when injected into cultured neurons, suggesting that in A. californica this protein is involved in neurotransmitter release. The yeast SCS2 gene has been cloned as a suppressor of inositol auxotrophy of CSE1 and hac1/ire mutants (Nikawa et al., 1995) and was recently characterized as an integral membrane protein of the ER (Kagiwada et al., 1998). The C. elegans major sperm protein, a 127-amino acid long protein, also exhibits significant homology with the NH2 terminus of VA P-33. Major sperm protein is thought to be involved in sperm pseudodopodial movement, by forming a cytosolic filamentous network that translocates vesicles to the plasma membrane (Itatani et al., 1996).

In the present study we describe a VA P-33-related protein which we denote ERG30, and demonstrate its type II transmembrane topology. We found that ERG30 is localized in the ER and in pre-Golgi intermediates. Functional in vitro assays attribute to ERG30 a role in COPI vesicle transport. We put forward the hypothesis that ERG30 is involved in intra-Golgi transport and in retrograde transport of proteins between the Golgi and the ER.

Construction of a Rat Brain cDNA Library in the pACT Vector

A cDNA library was constructed from 5 μg of oligo(dT)-selected mRNA, using a Stratagene kit. RNA was prepared from rat brain by the guanidinium thiocyanate-phenol-chloroform extraction method. The mRNA was purified and used as a template for cDNA synthesis. The resulting ds cDNA was methylated by XhoI methylase and ligated to an EcoRI linker, thus generating an EcoRI site at the 5' end of the cDNA and an XhoI site at the 3'. The average size was ~25 kb. The purified ds cDNA was ligated to Xa CT. The library titer was ~1.4 x 109 pfu. The titer of the library after amplification was 3 x 109 pfu/ml. In vivo excision was performed from the phagemid Xa CT to pA CT.

Two-Hybrid Screen

The HF7c yeast strain carrying the bait plasmid pGB T9-NDFb4a290-662 was transformed with the rat brain cDNA library generated in pA CT AD vector (Clontech). Transformation efficiency was assessed by plating small aliquots onto SCD plates lacking tryptophan, leucine, and histidine and supplemented with 10 mM 3-AT. The yeast colonies were transferred to nitrocellulose filters (BA85; Schleicher and Schuell), immersed in liquid nitrogen for 5 s, and incubated at 30°C on a 3-mm Whatman paper soaked with 60 mM Na2HPO4, 40 mM NaH2PO4, pH 7.0, 10 mM KCl, 1 mM MgSO4, 50 mM β-mercaptoethanol, and 1 mg/ml X-GAL. Colonies containing the interacting pair of proteins became blue within 2-6 h. From an initial screen of 200,000 colonies, we isolated 5 individual clones containing different cDNA's corresponding to the same mRNA. To isolate library plasmids from positive clones, cells were grown in SC liquid media lacking leucine (to allow loss of bait, but not of the library plasmid), and plasmid DNA was prepared and transformed at low dilution into HB101 competent Escherichia coli cells. The transformants were selected on a M9 minimal medium containing 50 μg/ml Amp. Plasmids isolated were then used to retransform SFY 526 yeast cells either alone or with pGB T9-NDFb4a290-662. Transformants were assayed for β-galactosidase activity. cDNA isolated from the positive clones was subcloned to pbLuEscRIPT II, and then sequenced using an Applied Biosystems 373A automated DNA sequencer and an Applied Biosystems Taq Dye Deoxy™ Terminator cycle sequencing kit. Of the five colonies isolated by this screen, clone pACT17 contained the complete coding sequence of ERG 30. RT-PCR performed on rat brain mRNA, using a specific oligonucleotide derived from pACT17, confirmed that the sequence obtained from the cDNA library was the full-length cDNA.

Construction and Expression of MBP-ERG30 Fusion Proteins

ERG30 and its truncated forms were tagged at their NH2 terminus with a maltose binding protein (MBP) domain. For that purpose, full-length ERG30, ERG30 (Δcoiled-coil) (amino acids 1-140), or ERG30 (ΔNH2 terminus) (amino acids 141-243) was ligated into the EcoRI BamHI site of pMA L- p2 vector (Novagen). The different fusion proteins were overexpressed in the JM109 strain of bacteria by growing log phase bacteria in the presence of 1 mM IPTG for 4 h. Cell extracts were prepared by sonicing the bacteria in a buffer containing 50 mM Tris (pH 8.0), 50 mM KCl, 0.1 mM EDTA, and 1% Triton X-100. Bacterial extracts were centrifuged in a TI 60 rotor (Beckman) at 45,000 rpm for 60 min, and the supernatant was passed over a 1-mL amylose column at 4°C. The column was washed with 10 column volumes of 20 mM Tris/HCl (pH 7.4), 0.4 M NaCl, and 10 mM β-mercaptoethanol. The protein of interest was eluted with the above buffer plus 10 mM maltose.

Production of Anti-ERG30 Antibodies

An antiserum was raised in rabbits against a recombinant MBP-ERG30 protein purified from E. coli. The antiserum was first run through CNBr activated Sepharose column with covalently bound MBP, to remove anti-MBP antibodies. A nti-ERG30 antibodies were purified from the flow-through material of the first column by affinity chromatography on a CNBr-activated Sepharose column with covalently bound MBP-ERG30 fusion protein.

Subcellular Fractionation

Rat liver homogenates were fractionated over sucrose gradients as described previously (Taylor et al., 1997; Walter et al., 1998), with slight
modifications. Fresh rat livers (25 g) were mixed with 150 ml of ice-cold homogenization buffer (0.5 M sucrose, 0.1 M KPi, pH 6.8, 5 mM MgCl₂, 1 mM DTT, 1 mM PMSF, 2 µM aprotinin, 2 µM pepstatin A, and 0.5 µg/ml leupeptin) and the tissue was minced and homogenized by forcing it through a fine stainless steel mesh (aperture 150 µm). The homogenate was centrifuged in a SLA-1500 rotor (Sorvall) for 10 min at 3,000 rpm. The postnuclear supernatant was layered over a 0.86/1.25 M sucrose step gradient. The gradients were centrifuged at 4°C in a SW-28 rotor (Beckman) at 25,000 rpm for 90 min. The 0.86/1.25 M interface was adjusted to 1.6 M sucrose and layered into SW-28 tubes. This layer was overlaid with 1.25 M, 1 M, 0.86 M, and 0.5 M sucrose solutions. The gradient was centrifuged at 4°C in a SW-28 rotor (Beckman) at 25,000 rpm for 2.5 h. The samples were continuously collected from the top, tested for their sucrose concentration, and subjected to Western blot analysis with different antibodies.

**Drug Treatment and Immunofluorescence Microscopy**

N.RK or CHO cells were seeded onto microscope slides 24 h before staining. For drug treatment before immunofluorescence microscopy, cells were incubated for 1 h in RPMI (N.RK cells) or α-MEM (CHO cells) medium containing 10 µg/ml brefeldin A (BFA). To fix cells for microscopy, the growth medium was removed and cells were incubated for 10 min in methanol at −20°C. Cell staining involved a 1-min incubation in acetone at −20°C for permeabilization followed by incubation in a blocking solution containing 5% FCS in PBS. Cells were incubated for 2 h with the primary antibodies in 2% FCS in PBS, then washed three times with PBS and incubated in an incubation solution containing affinity-purified fluorescein- or rhodamine-labeled antibodies against mouse or rabbit IgG. Slides were finally washed three times with PBS, and mounted beneath coverslips. The stained cells were analyzed with an MRC 1024 confocal microscope (Bio-Rad).

**EM/Immunocytochemistry of CHO Cells**

CHO cells were grown on glass coverslips that had been coated with carboxyl and gelatin (Olek et al., 1996). Preembedding immunogold-silver labeling was performed by a modification of the method described by Tanner et al. (1996). Cultures were rinsed with serum-free culture medium and fixed for 45 min in 4% paraformaldehyde, 4% sucrose, and 0.1 M sodium phosphate buffer, pH 7.4. The first 15 min of fixation were at room temperature, followed by 30 min at 4°C. Fixed cultures were washed with ice-cold Dulbecco's phosphate-buffered saline (DPBS), then permeabilized for 1 h at room temperature in 0.05% saponin, 10% normal goat serum, and 1% BSA in DPBS. Cultures were then incubated for 1 h at room temperature with affinity-purified antibodies to ERG30 diluted to 10 µg/ml with 0.05% saponin, 1% BSA in DPBS. For controls, cultures were incubated without antibodies to ERG30 or with ERG30 antibodies that had been preadsorbed for 30 min at 36°C with a 50-fold molar excess of MBP-ERG30, and centrifuged to remove any precipitate. A first several washes with the diluent, cultures were incubated for 1 h at room temperature with 1.4 nm gold-conjugated Fab' fragments of goat anti-rabbit IgG (Nanoprobes) diluted 1:100, followed by washes with diluent and DPBS, and further fixation for 40 min in 2% glutaraldehyde, 0.1% sodium phosphate buffer, pH 7.4. The glutaraldehyde-fixed cultures were washed several times with DPBS, then with double-distilled water, before silver enhancement under a dark-red safelight for 4–8 min performed according to instructions provided by Nanoprobes with their HQ silver enhancement kit. For drug treatment before immunofluorescence microscopy, cells were incubated for 10 min in methanol at −20°C. Cell staining involved a 1-min incubation in acetone at −20°C for permeabilization followed by incubation in a blocking solution containing 5% FCS in PBS. Cells were incubated for 2 h with the primary antibodies in 2% FCS in PBS, then washed three times with PBS and incubated in an incubation solution containing affinity-purified fluorescein- or rhodamine-labeled antibodies against mouse or rabbit IgG. Slides were finally washed three times with PBS, and mounted beneath coverslips. The stained cells were analyzed with an MRC 1024 confocal microscope (Bio-Rad).

**Isolation of COPI Vesicles**

Golgi-derived COPI vesicles were isolated as described previously (Stamnes et al., 1995). In brief, Golgi membranes were isolated from wild-type CHO cells as described and prewashed with 250 mM KCl. The membranes (0.25 mg/ml) were then incubated with crude bovine brain cytosol (16 mg/ml) in 0.5 ml transport assay buffer (see above) for 15 min at 37°C. After incubation, KCl was added to a final concentration of 250 mM, and the Golgi membranes were pelleted as above. The supernatant was mixed with 1 ml of 70% (wt/wt) sucrose and overlayed in 5 ml SW 55 ultracentrifugation tubes with 0.5 ml 45% (wt/wt) sucrose, and 1 ml 40%, 35%, and 30% (wt/wt) sucrose in 20 mM Tris, pH 7.4. The gradient was centrifuged for 4 h at 50,000 rpm at 4°C and fractionated into 7 fractions of 0.7 ml each. The indicated fractions were diluted twofold in double distilled water and membranes were pelleted by ultracentrifugation for 40 min at 4°C in a TLA 100.1 rotor at 100,000 rpm. The membrane pellets were dissolved in SDS-PAGE sample buffer, after which the proteins were separated by electrophoresis and blotted onto nitrocellulose filters. The β subunit of COPI (p50) was detected by Western blot analysis using monoclonal anti-p78COPI antibodies (S3A5 as described (Palmieri et al., 1993).

**Formation of 20S Particles**

For the isolation of 20S SNAP particles, we used the procedure described. For the isolation of 20S SNAP particles, we used the procedure described. For the isolation of 20S SNAP particles, we used the procedure described. For the isolation of 20S SNAP particles, we used the procedure described. For the isolation of 20S SNAP particles, we used the procedure described. For the isolation of 20S SNAP particles, we used the procedure described.

**Western Blot Analysis**

To prepare rat tissue extracts, frozen organs were washed in cold PBS and lysed with a homogenizer (PCU Kinematica) in ice-cold protein extraction buffer containing 300 mM KCl, 50 mM HEPES-KOH, pH 7.0, 100 mM KCl, 1 mM EDTA, 0.5% Triton X-100, and 0.5 mM ATP-γ-S, followed by elution with buffer A containing 8 mM MgCl₂ (nonspecific elution), or with buffer A containing 8 mM MgCl₂ and 0.5 mM ATP to allow ATP hydrolysis (specific elution). The eluted fractions were precipitated with trichloroacetic acid, boiled, and analyzed by Western blotting using the appropriate antibodies.

**Immunoprecipitation**

Rat brain membranes were isolated as described previously (Söllner et al., 1993b), and solubilized with 4% Triton X-100 as described above. This membrane extract was diluted 1:4 with cold PBS and ultracentrifuged at 100,000 rpm in a TLA 100.1 rotor at 100,000 rpm. The membrane pellets were dissolved in SDS-PAGE sample buffer after which the proteins were separated by electrophoresis and blotted onto nitrocellulose filters. The β subunit of COPI (p50) was detected by Western blot analysis using monoclonal anti-p78COPI antibodies (S3A5 as described (Palmieri et al., 1993).

**Fractionation by Triton X-114**

At 0°C, Golgi fractions were washed once with Triton-salt buffer (100 mM Tris-HCl, pH 7.6) and resuspended to a protein concentration of 4 mg/ml. Triton-X-114 was added at 4°C to a final concentration of 2% (vol/vol). Solubilized membranes were incubated on ice for 4 min and then centrifuged at 18,000 rpm in a TLA 100.1 rotor at 100,000 rpm. The membrane pellets were dissolved in SDS-PAGE sample buffer after which the proteins were separated by electrophoresis and blotted onto nitrocellulose filters. The β subunit of COPI (p50) was detected by Western blot analysis using monoclonal anti-p78COPI antibodies (S3A5 as described (Palmieri et al., 1993).

**Cis- to Medial-Golgi Transport Assay**

The standard assay mixture (25 µl) contained 0.4 µCi UDP-[3H]N-acetylglucosamine (Amersham Radiochemicals), 5 µl of a 1:1 mixture of donor and acceptor CHO Golgi membranes, and crude bovine brain cytosol, as described (Balch et al., 1984).
fuged for 10 min in a Beckman TLA100.1 rotor at 37,000 g. The supernatant was layered over a cushion of 0.25 M sucrose in a Tris-salt buffer containing 0.06% Triton X-114, and incubated at 30°C for 5 min. After centrifugation at 2,500 g in a benchtop centrifuge, the Triton X-114 phase was saved. The aqueous phase was brought to 0.5% Triton X-114, and layered once more on a cushion, incubated at 30°C for 5 min, and centrifuged as described before. The detergent layers were combined and the supernatant kept separately. Before the SDS-PAGE separation the detergent was removed by Biobeads SM-2 (Bio-Rad).

**Results**

**Cloning cDNA Encoding ERG30**

We have serendipitously cloned by the two-hybrid screen system a cDNA from a rat brain cDNA library that encodes a 30-kD protein. Because our analysis indicated that ERG30 is located in the ER and Golgi (see below), we have tentatively termed it ERG30. The nucleotide and deduced amino acid sequence of the cDNA are shown in Fig. 1 A. The hydrophobicity profile of ERG30 suggests that its COOH-terminal region is highly hydrophobic [residues 224–243 (Kyte and Doolittle, 1982)] (Fig. 1 B). In addition, we identified a predicted coiled-coil motif at positions 161–194 (Fig. 1, A and C). The amino acid sequence of ERG30 exhibits a high degree of homology to three integral membrane proteins: Scs2p, found in *S. cerevisiae*; the VAMP-associated protein, VAP-33, of *A. californica*; and the homologous hVAP-33 of humans (Nikawa et al., 1995; Skehel et al., 1995b; Weir et al., 1998) (Fig. 1 D). Compared with hVAP-33, aVAP-33, and Scs2p, ERG30 displays 62%, 52%, and 27% identity and an overall 86%, 70%, and 50% similarity, respectively.

**ERG30 Is a Type II Integral Membrane Protein**

The expression pattern of ERG30 in various rat tissues was examined by immunoblot analysis using affinity-purified anti-ERG30 antibodies. As evident from Fig. 2 A, the 30-kD ERG30 protein is expressed in all tissues studied with a smaller 28-kD isoform, or a proteolytic product in the kidney, liver, and heart.

Because the amino-acid sequence of ERG30 suggested that it might contain a COOH-terminal transmembrane domain (Fig. 1 B), we examined its putative transmembrane topology by using anti-ERG30 antibodies for immunoblot analyses of cytosolic and membrane fractions. In rat brain, ERG30 was detected almost exclusively in the membrane fraction (Fig. 2 B). The association of ERG30 with the membrane fraction was resistant to washing with 1 M KCl (data not shown) and the protein could be extracted entirely into a detergent phase upon solubilization with Triton X-114 (Fig. 2 B). Using an in vitro translation system, we demonstrated that ERG30 was translated into the microsomal membranes (Fig. 2 C). To exclude the possibility of peripheral association with the microsomal membranes, the translated products were incubated with
100 mM Na₂CO₃, pH 11. Under these conditions ERG30 remained associated with the membrane fraction (Fig. 2 C). We next addressed the topology of ERG30 with respect to the cytosol by using a protease protection assay. Treatment of the in vitro translated ERG30 (in the presence of microsomes) with proteinase K fully digested the translated protein, whereas the mature form of E. coli β-lactamase, serving as a control protein translocated into the microsomes lumen, was fully protected (Fig. 2 C).

Taken together, these results indicate that ERG30 is a type II integral membrane protein, with an NH₂-terminal domain facing the cytoplasm and a very short COOH-terminal hydrophobic domain located inside the membrane (Fig. 2 D).

**Self-oligomerization of ERG30**

ERG30 shares with SNAREs a similar domain organization, including a predicted membrane-proximal coiled-coil domain, a motif common to various self-oligomerizing proteins involved in protein-protein interactions (Weimbs et al., 1997). To test whether ERG30 is capable of self-oligomerization we employed the yeast two-hybrid system. Two ERG30 truncation mutants were prepared: ERG30 (NH₂ terminus) containing residues 141–243, and its complementary coiled-coil deletion mutant (coiled-coil) containing residues 1–140. Yeast cells were cotransfected with a construct of ERG30 fused to the Gal4 DNA binding domain, and ERG30 fused with pACT Gal4-activation domain. Only cells that contained both constructs were able to grow on a selective medium and exhibited significant β-gal activity. Furthermore, as shown in Fig. 3, only the full length ERG30 was able to self-oligomerize in vivo, whereas the truncated forms, i.e., ERG30 (Δcoiled-coil) or ERG30 (ΔNH₂ terminus), were inactive. Our results indicate that ERG30 can self-oligomerize and both the coiled-
ERG30 Is Localized to the ER and the Pre-Golgi Intermediates

Intracellular targeting of a protein to a particular organelle often provides a valuable insight into its specific biological role. To examine the subcellular localization of ERG30 in NRK cells, we performed indirect immunofluorescence analysis using affinity-purified polyclonal anti-ERG30 antibodies. As illustrated in Fig. 4 A (panels 2 and 4), ERG30 is localized in a juxta-nuclear crescent resembling the Golgi complex and possibly in parts of the ER. No labeling was observed when anti-ERG30 antibodies were incubated with excess recombinant ERG30 in the form of a MBP fusion protein (data not shown). To identify the subcellular localization of ERG30, we performed a double labeling experiment using monoclonal antibodies directed against βCOP, a commonly used marker for the Golgi, together with anti-ERG30 antibodies. Using confocal microscopy, we found that labeling with the anti-ERG30 antibodies partially coincided with that of βCOP, indicating that in NRK cells ERG30 is localized in the vicinity of the Golgi complex (Fig. 4 A, panels 3 and 4). Treating cells with the drug BFA was shown previously to specifically disrupt the Golgi complex in vivo (Lippincott-Schwartz et al., 1989). Here we showed that in the presence of BFA, the labeling observed by anti-βCOP spread throughout the cytoplasm, whereas labeling with anti-ERG30 formed a characteristic ER pattern (Fig. 4 A, panels 6 and 8). To confirm the localization of ERG30 in ER membranes, the cells were double labeled with monoclonal antibodies directed against protein disulfide isomerase (PDI), an ER resident protein, and with anti-ERG polyclonal antibodies. As shown in Fig. 4 A (panels 1 and 2), part of the labeling observed with the anti-ERG30 antibodies coincided with that of PDI, indicating that the two proteins might share the same compartment. Upon treatment with BFA, the colocalization of PDI and ERG30 increased significantly (Fig. 4 A, panels 5 and 6).

The intracellular localization of ERG30 was also determined by subcellular fractionation of bovine liver postnuclear supernatant on equilibrium density sucrose gradients (Fig. 4 B). Fractions were analyzed by immunoblotting with affinity-purified anti-ERG30 antibodies and with antibodies that recognize either Gos28, a marker of the Golgi apparatus, or PDI, an ER marker. Membranes that were concentrated at the 0.86/1.25 interface of the first gradient were harvested, adjusted to 1.6 M sucrose, and loaded onto the bottom of a second gradient (Fig. 4 B). Immunoblot analysis of the second gradient showed that ERG30 predominantly colocalizes with PDI and to some lesser extent with Gos28, indicating that it associates with both Golgi and ER membranes.

ERG30 subcellular localization was further analyzed by immunoelectron microscopy. Silver grains representing sites of immunoreactivity for ERG30 were located predominantly on the cytoplasmic faces of the RER and on the outer leaflet of the nuclear membrane—both sites of synthesis for membrane and secreted proteins (Fig. 4 C, panel 1). Labeled cisternae of RER were found throughout the cytoplasm. Little immunoreactivity was localized to the Golgi apparatus. However, silver grains often were observed on RER cisternae that were very close to the Golgi, and on cisternae that appeared to be transitional between RER and the cis-Golgi (Fig. 4 C, panels 2 and inset). Very few silver grains were seen on other structures such as the plasma membrane, mitochondria, or the nucleus. These represented nonspecific labeling since they were not eliminated by absorption of ERG30 antibodies with excess antigen, whereas labeling of the RER, nuclear envelope, and RER-Golgi transitional structures was virtually eliminated (data not shown). Taken together, our results indicate that ERG30 is localized on the cytosolic surface of the ER and on the pre-Golgi intermediates.

ERG30 Is Not Part of the Synaptic SNARE Complex

It has been demonstrated in Aplysia that VAP-33 directly interacts with the synaptic v-SNAREs, VAMP, suggesting its involvement in docking and fusion of synaptic vesicles (Skehel et al., 1995b). We used two approaches to examine whether ERG30 interacts with synaptic SNAREs. First, we used monoclonal antibodies against SNAP-25 and syntaxin-1 to coimmunoprecipitate ERG30 from rat brain membrane extract. As shown in Fig. 5 A, ERG30 did not precipitate with any of the known synaptic SNAREs. Next, we examined whether ERG30 interacts with synaptic SNAREs by testing its incorporation into 20S fusion particles (Söllner et al., 1993b). The 20S particles are formed when detergent extracts of membranes containing SNAP receptors are mixed with SNAPs and NSF in the presence of the nonhydrolyzable analogue of ATP, A TPγS. The 20S fusion particle assembly reaction can therefore be used as a cell-free read-out system to test whether candidate proteins are SNAREs, or specifically interact with a SNARE. The results of such a 20S particle experiment, using rat brain membrane extract as a source for SNAREs, are presented in Fig. 5 B. Specific (Mg-ATP) and nonspecific elutions (Mg-ATPγS) were analyzed by Western blots. As expected, the known synaptic membrane proteins VAMP, syntaxin, and SNAP-25 assembled into the 20S particle derived from brain membrane extract, but ERG30 did not. These results indicate that ERG30 is not part of the synaptic SNARE complex.
ERG30 Is Involved in Intra-Golgi Transport

The subcellular distribution of ERG30 indicates that it might play a role early in the secretory pathway. We used the cell-free intra-Golgi transport system (Balch et al., 1984) to examine this possibility. Affinity-purified anti-ERG30 antibodies specifically inhibited intra-Golgi transport by up to 90% of the control in a concentration-dependent manner (Fig. 6A, open squares); neither nonrelevant control antibodies (Fig. 6A, open triangles) nor preimmune IgGs had any effect on this assay (data not shown). Recombinant ERG30 specifically reversed the inhibition by these antibodies (Fig. 6C). Anti-ERG30 Fab' fragments were also found to partially inhibit transport (Fig. 6A, open rhombuses) excluding the possibility that the inhi-

Figure 4. Localization of ERG30 in the Golgi and ER. (A) Indirect immunofluorescence microscopy of endogenous ERG30 with and without BFA treatment of NRK cells. Localization of ERG30, PDI, or β-COP was performed in NRK cells with and without BFA treatment (10 μg/ml, 1 h). PDI (1 and 5 plus BFA) and β-COP (3 and 7 plus BFA) immunoreactivity were detected with fluorescein-conjugated secondary antibodies; ERG30 immunoreactivity (2, 4 and 6, 8 plus BFA) was detected with rhodamine-conjugated secondary antibodies. (B) Determination of ERG30 localization by subcellular fractionation. Bovine liver postnuclear supernatant in 0.5 M sucrose was layered on top of a sucrose step gradient composed of 0.86/1.25 M sucrose layers. The gradients were centrifuged and the interfaces was collected (see Materials and Methods). The 0.86/1.25 M sucrose interface was adjusted to a 1.35 M sucrose and loaded at the bottom of a second step gradient with 1.25, 1.0, 0.86, and 0.5 M sucrose. After centrifugation, the different fractions were analyzed by SDS-PAGE and immunoblotting with affinity-purified anti-ERG30 antibodies or with anti-PDI or anti-Gos28 antibodies. (C) Immunogold-silver localization of ERG30 in CHO(K1) cells. (Panel 1) Most silver grains are located on the cytoplasmic face of RER cisternae (arrows). Some clusters of grains are found on indistinct structures in the cytoplasm, probably RER cisternae sectioned tangentially (asterisks). (Panel 2) Silver grains are often found on the cytoplasmic face of the outer leaflet of the nuclear envelope (arrows), on RER cisternae (small arrows) close to the Golgi (G), and on structures that appear to be transitional between the RER and the Golgi (T-arrowheads). The inset shows an area on the right hand side of the transitional zone and Golgi at twofold higher magnification, making it easier to see two small silver grains (arrowheads). Bars, 0.5 μm.
The involvement of ERG30 in intra-Golgi transport was also demonstrated by using soluble recombinant MBP-ERG30. The effect of recombinant full-length MBP-ERG30, MBP-ERG30 (Δcoiled-coil) or MBP-ERG30 (ΔNH2 terminus) mutants on VSV-G transport in vitro was therefore examined. As shown in Fig. 6 D, addition of increasing amounts of recombinant MBP-ERG30 fusion protein inhibited transport in vitro by nearly 90%. No inhibition was detected in the presence of equivalent concentrations of MBP-ERG30-Δcoiled-coil, MBP-ERG30-ΔNH2 terminus, or MBP-control. This result is in agreement with the fact that only the wild-type ERG30 can interact with the endogenous ERG30, whereas the truncated proteins could not (Fig. 3 B). We therefore concluded that inhibition observed in the presence of the soluble MBP-ERG30 results from blocking the function of the endogenous membranal ERG30.

Anti-ERG30 Antibodies Cause an Accumulation of COPI-coated Vesicles

A anti-ERG30 antibodies were used to establish the stage in the transport pathway at which ERG30 is required. For that purpose we used conditions that promote budding of COPI vesicles from Golgi membranes. Under such budding reactions, Golgi membranes were incubated with crude cytosol in the presence or absence of either GTPyS or anti-ERG30 antibodies. The Golgi cisternae were then pelleted at 14,000 rpm and the supernatant was fractionated on a sucrose gradient to isolate the COPI-coated vesicles. As shown in Fig. 7, incubation of Golgi membranes in the presence of GTPyS resulted in a significant accumulation of COPI-coated vesicles. A significant quantity of COPI vesicles also accumulated in the presence of affinity-purified anti-ERG30 antibodies. When both GTPyS and anti-ERG30 30 were present in the budding reaction, even more COPI vesicles accumulated (data not shown). Notably, the vesicles accumulated in the presence of anti-ERG30 antibodies appeared more homogeneous in comparison to those accumulated in the presence of GTPyS. These results show that ERG30 is not involved in the budding process but rather in the consumption of these vesicles. Most of the ERG30 remained associated with the Golgi cisternae and did not migrate with the accumulated COPI vesicles (data not shown).

Discussion

We show here that ERG30, the rat homologue of AAVP33, is ubiquitously expressed and is localized primarily within the ER and the pre-Golgi intermediates. The localization of ERG30 suggests that it functions early in the secretory pathway rather than in the plasma membrane. This is further supported by the observation that ERG30 plays a role in intra-Golgi transport in vitro. We propose that ERG30 represents a novel integral membrane protein family which is involved in the process of vesicle fusion with target membranes.

Previous studies demonstrated that A. californica VAMP-33 can interact with VAMP (synaptobrevin) and that it participates in the process of synaptic release (Skehel et al., 1995a,b). The yeast homologue, however, was local-
ERG30 participates in COPI-mediated vesicular transport.

Soussan et al.

ERG30 Participates in COPI-mediated Vesicular Transport

...ized to the ER and was shown to be required for inositol metabolism (Kagiwada et al., 1998). Our data clearly demonstrate that the mammalian homologue of these proteins is localized in the ER and pre-Golgi intermediates, playing a role in protein transport in the early secretory pathway. We could not identify an interaction between ERG30 and synaptic SNAREs. Our immunolabeling experiments on neuronal cells indicate that ERG30 is localized on endomembranes, primarily the Golgi and the ER. No labeling of ERG30 was seen on or near the plasma membrane, where most of the VAMP labeling was observed (Soussan, L., and Z. Elazar, unpublished data). We clearly demonstrated here that ERG30 is not part of the synaptic SNARE complex. Our data, however, does not exclude the possibility that ERG30 interacts weakly with VAMP, in a manner that is not resistant to immunoprecipitation conditions. It is also possible that mammals carry other, yet-unidentified genes that encode VAP-33 homologues which function at later stages of the secretory pathway.

The accumulation of COPI vesicles caused by anti-ERG30 antibodies coupled with the localization of ERG30 both in the Golgi and ER suggest that this protein is involved in transport between these organelles, possibly in the retrograde direction. The accumulation of COPI vesicles may also indicate that ERG30 is involved in regulating the uncoating of these vesicles. It is not clear why the accumulated vesicles did not uncoat in the presence of the anti-ERG30 antibodies. ERG30 might be involved in triggering ADP-ribosylation factor (ARF)-GTPase activating protein (GAP), an activity which, in turn, stimulates the uncoating process. Additional experiments are needed to determine whether uncoating of vesicles is affected by ERG30 directly, or is coupled to the vesicles’ docking; the...
latter would implicate a role for ERG30 in targeting vesicles to the appropriate organelle.

ERG30 is a type II integral membrane protein, most of which is present to the cytosol. Examining the protein sequence by the Paircoil program revealed a strong probability for a coiled-coil domain at positions 161–194 followed by several basic residues. This structure resembles that of the SNARe family (Weimbs et al., 1998). We did not yet find an interaction between ERG30 and SNARe molecules, though we demonstrated here that ERG30 can self-oligomerize. We also demonstrated that the recombinant protein, which is capable of interacting with the endogenous membrane bound pool of ERG30, blocked the cell-free intra-Golgi transport assay possibly by inhibiting the function of the membrane-associated ERG30. Although it is not clear whether this interaction is direct or requires another membrane protein, similar to the interactions between v- and t-SNAREs, the evidence presented above implicates ERG30 in the docking and fusion machinery.

We found that ERG30 functions in the early secretory pathway, predominantly within the ER and the Golgi complex. Our immunoelectron microscopy studies indicated that it is found mainly in the ER and in transitional elements found between this organelle and the cis-Golgi. These structures might represent the ER–Golgi intermediate compartment, known also as pre-Golgi intermediates (PGIs). It has been suggested by Balch and co-workers that ER–derived transport vesicles fuse to form vesicular-tubular clusters (VTCs) (Bannykh et al., 1996, 1998). These structures are the target for ER–derived COPII and Golgi-derived COPI vesicles. Considering the functional data presented in this study, specifically the involvement of ERG30 in COPII vesicle transport and its subcellular localization, we speculate that in addition to its intra-Golgi localization, we speculate that in addition to its intra-Golgi localization, ERG30 may play a role in the docking and fusion of v- and t-SNAREs, the evidence presented requires another membrane protein, similar to the interaction between v- and t-SNAREs. The evidence presented requires another membrane protein, which is capable of interacting with the endogenous membrane bound pool of ERG30, blocked the cell-free intra-Golgi transport assay possibly by inhibiting the function of the membrane-associated ERG30. Although it is not clear whether this interaction is direct or requires another membrane protein, similar to the interactions between v- and t-SNAREs, the evidence presented above implicates ERG30 in the docking and fusion machinery.

We thank Ms. Frida Shimron for her excellent technical assistance. We also thank Drs. Evelyn Ralston and Jung-Hwa Tao Cheng for their advice on immunogold labeling and Ms. Virginia Tanner for the preparation of sections. We are grateful to the members of Dr. Elazar’s lab for stimulating discussions and practical help. Z. Elazar is an incumbent of the Shlomo and Michla Tomaarin Career Development Chair of Membrane Physiology.

This work was supported in part by the German-Israeli Foundation and the Weizmann Institute Minerva Center (to Z. Elazar), and in part by a Shloimo and Michla Tomarin Career Development Chair of Membrane Physiology.

Submitted: 26 January 1999
R evised: 25 May 1999
A ccepted: 3 June 1999

References


Sapperstein, S. K., V. V. Lupashin, H. D. Schmitt, and M. G. Waters. 1996. A s-
Söllner, T., M.K. Bennett, S.W. Whiteheart, R.H. Scheller, and J.E. Rothman. 1993a. A protein assembly-disassembly pathway in vitro that corre-
respond to sequential steps of synaptic vesicle docking, activation, and fusion. Cell. 75:409–418.
Söllner, T., S.W. Whiteheart, M. Brunner, B.H. Erdjument, S. Geromanos, P. Tempst, and J. E. Rothman. 1993b. SNAP receptors implicated in vesicle tar-
Sonnichsen, B., M. Lowe, T. Levine, E. Jamsa, B. Dirac-Svejstrup, and G. War-
Tanner, V.A., T. Ploug, and J.H. Tao-Cheng. 1996. Subcellular localization of
SV2 and other secretory vesicle components in PC12 cells by an efficient
method of preembedding EM immunocytochemistry for cell cultures. J. His-
tochem. Cytochem. 44:1481–1488.
Walter, D.M., K.S. Paul, and M.G. Waters. 1998. Purification and characteriza-
tion of a novel 13 S hetero-oligomeric protein complex that stimulates in
membrane protein is required for intercisternal transport in the Golgi stack.
Weber, T., B.V. Zemelman, J.A. McNew, B. Westermann, M. Gmachl, F. Par-
lati, T.H. Sollner, and J. E. Rothman. 1998. SNARE pins: minimal machinery
1997. A conserved domain is present in different families of vesicular fusion
tural similarity between different SNARE complexes based on sequence re-
logue of the vesicle-associated membrane protein (VAMP)-associated protein
of 33 kDa (VAP-33): a broadly expressed protein that binds to VAMP.