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ALG-2 Attenuates COPII Budding In Vitro and Stabilizes the Sec23/Sec31A Complex

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Abstract

Coated vesicles mediate the traffic of secretory and membrane cargo proteins from the endoplasmic reticulum (ER) to the Golgi apparatus. The coat protein complex (COPII) involved in vesicle budding is constituted by a GTPase, Sar1, the inner coat components of Sec23/Sec24 and the components of the outer coat Sec13/Sec31A. The Ca2+-binding protein ALG-2 was recently identified as a Sec31A binding partner and a possible link to Ca2+ regulation of COPII vesicle budding. Here we show that ALG-2/Ca2+ is capable of attenuating vesicle budding in vitro through interaction with an ALG-2 binding domain in the proline rich region of Sec31A. Binding of ALG-2 to Sec31A and inhibition of COPII vesicle budding is furthermore dependent on an intact Ca2+-binding site at EF-hand 1 of ALG-2. ALG-2 increased recruitment of COPII proteins Sec23/24 and Sec13/31A to artificial liposomes and was capable of mediating binding of Sec13/31A to Sec23. These results introduce a regulatory role for ALG-2/Ca2+ in COPII tethering and vesicle budding.

Introduction

Ca2+ is a ubiquitous messenger molecule regulating a wide array of cell biological processes. Recent evidence suggests that Ca2+ transients may also be involved in regulatory mechanisms related to protein trafficking. The Ca2+ binding protein ALG-2 (product of the apoptosis linked gene-2) was found to interact with Sec31A, a component of the coat protein complex II (COPII) in a Ca2+-dependent manner. It has thus been speculated that ALG-2 mediates a Ca2+-link to COPII dependent protein traffic [1,2,3]. During physiological Ca2+ transients a major part of the cytosolic ALG-2 redistributes to cytoplasmic puncta [1] where it colocalizes with Sec31A [1,2,3] and the ER exit site marker p125 [3]. Ca2+ signaling has been shown to be mandatory for some aspects of vesicle trafficking such as synaptotagmin-mediated membrane fusion [4]. Furthermore, recent work by Bentley et al. suggests that Ca2+ together with ALG-2 plays a regulatory role in the fusion of COPII vesicles after budding [5]. ALG-2 was originally assigned a functional role in apoptosis linking Ca2+ signaling to programmed cell death [6], however, no molecular mechanism underlying this function has been described. In addition, the suggested apoptotic function of ALG-2 was not confirmed by gene knock out studies in mice [7].

Protein export from the ER is facilitated by vesicles encaged by the Sar1, Sec23–Sec24 and Sec13–Sec31 proteins constituting a COPII vesicle (reviewed in [8]). Defects in COPII component expression were found to lead to skeletal abnormalities [9] and improper extracellular matrix formation [10]. Structural data suggests a COPII cage diameter size of 60–80 nm [11], contrasting with findings of COPII-dependent export of collagen [12], which would require larger vesicles (reviewed in [13]). This has led to speculation that a specialized mechanism to accommodate bulky cargo is needed, and evidence supporting this has come with the recent discovery of a role for ubiquitin conjugation of Sec31 in the formation of enlarged COPII vesicles facilitating collagen export [14]. How the COPII structures are retained at the ER exit sites in order to expand to a size large enough to accommodate bulk cargo remains unexplained. Here we show that Ca2+-ALG-2 attenuates the exit of protein from the ER through an interaction with the proline rich region of Sec31A. Furthermore, we find that ALG-2 in vitro is capable of bridging the outer and inner components, Sec31A and Sec23 of COPII.

Results

ALG-2 Inhibits in vitro Budding in a Ca2+-dependent Manner

ALG-2 was previously described to interact with Sec31A in a Ca2+-dependent manner [1,2,3]. However, the significance of this interaction for ER to Golgi protein transport is not seen in the trafficking of VSV-G in cells depleted of ALG-2 [3]. In order to test the effect of ALG-2 on COPII budding under controlled Ca2+-conditions, we investigated the consequences of adding recombinant ALG-2 to a cell-free vesicle budding reaction in the presence or absence of free Ca2+. Using two transit cargo marker proteins, the SNARE protein Sec22b and the ER-Golgi cargo protein p58/ERGIC, we were able to measure the efficiency of COPII-dependent vesicle budding. Increasing Ca2+ concentrations (Figure 1, data points 4–9) correlated with decreased budding.
efficiency, which was further decreased in the presence of recombinant ALG-2 (Figure 1, data points 10–13). Ca\(^{2+}\) inhibited budding starting at concentrations greater than 1.2 mM, whereas addition of recombinant ALG-2 inhibited budding at a lower concentration of 300 uM Ca\(^{2+}\). Non-physiological concentrations of Ca\(^{2+}\) were used to override the Ca\(^{2+}\) chelator EGTA from the rat liver cytosol preparations. Mutant versions of ALG-2 that are partially deficient in Ca\(^{2+}\)-binding led to a partial recovery of the budding efficiency at elevated Ca\(^{2+}\) concentration most prominently when EF hand 1 was inactivated by mutation (Figure 1, data points 14 and 15). The inhibitory effect of wild-type ALG-2 was abolished when further EGTA was added (Figure 1, data points 17 and 19), demonstrating that ALG-2 requires Ca\(^{2+}\) for its effect on budding. In all conditions, budding was sharply reduced in incubations containing a dominant negative form of the COPII protein Sar1p (Sar1H79G, Figure 1, data points 3, 16 and 20), showing the requirement for functional COPII in the budding reaction.

ALG-2 Acts Directly on COPII to Inhibit Vesicle Budding in a Reversible Manner

To avoid the presence of chelator and auxiliary factors present in the liver cytosol that could interfere with the ALG-2/Ca\(^{2+}\) effect on budding (Figure 1), we reconstituted the budding assay with pure recombinant Sar1A, Sec23A/24D, and Sec13/31A in place of cytosol [15]. We found that ALG-2/Ca\(^{2+}\) acted directly through COPII and using various concentrations of both ALG-2 and Ca\(^{2+}\) found that budding was inhibited when the molar ratio of ALG-2 to Sec31A exceeded 2:1 (Figure 2A). In this reconstitution, budding was inhibited by ALG-2 even when no Ca\(^{2+}\) was added, indicating that in the absence of chelator, background Ca\(^{2+}\) levels from the donor membrane preparations are sufficient to inhibit budding in concert with ALG-2 (Figure 2A). It was previously shown that ALG-2 redistribution from the cytosol to ER exit site structures is observed following induction of Ca\(^{2+}\) transients with histamine or other stimuli [1]. Ca\(^{2+}\) binds to the high affinity EF hands 1 and 3 of ALG-2 with a KD of 1.3 uM [16], which is within the range of the Ca\(^{2+}\)-levels reached during cellular Ca\(^{2+}\) transients evoked by histamine [17]. To ensure that free Ca\(^{2+}\) was...
available for activation of ALG-2, we added 10 μM Ca2+ to the in vitro reconstituted budding assay unless otherwise stated. To investigate the partial inhibitory effect of the ALG-2 EF hand mutants in budding, we performed binding studies by incubating recombinant ALG-2 versions with His-tagged Sec31A immobilized on Nickel-beads. In the presence of Ca2+, only the splice variant of ALG-2, ALG-2.1 [16], and ALG-2 with the E114A substitution in EF-hand 3 were able to bind to Sec31A (Figure 2B), indicating that EF1-hand 1 is mandatory for this interaction. Furthermore, using the ALG-2 mutants in the budding assay, we showed that the binding capacity of the ALG-2 versions correlated with their ability to inhibit budding in a Ca2+-dependent manner (Figure 2C). This indicates that an EF-hand1-dependent binding of ALG-2 to Sec31A is associated with the Ca2+-mediated inhibition of vesicle budding. To support the proposed correlation between the binding of ALG-2 and Sec31A with budding inhibition and the Ca2+-dependent oscillatory pattern of ALG-2 distribution in the microscopy experiments, we performed the budding reaction in the presence of exogenous Ca2+. EGTA was added after 15 and 30 min to remove Ca2+ in order to allow disruption of the ALG-2/Sec31A complex. Following addition of EGTA, the budding efficiency was restored in the reactions where ALG-2 was present (Figure 2D), suggesting that Ca2+ chelation abolishes the ALG-2 attenuation of COPII vesicle budding. To identify possible changes in vesicular budding products as a consequence of adding ALG-2, we resolved membranes in the budding reaction on a Nycodenz buoyant density gradient and the levels of Sar1 appeared constant (Figure 4B) indicating that ALG-2 is capable of accumulating Sec23/24 and Sec13/31 to membranes irrespective of Sar1. To test whether ALG-2 could mediate binding of the outer COPII coat to the inner coat, we used flag-tagged Sec23A in complex with Sec24D as bait for the recruitment of Sec13/31A. Sec13/31A was recruited only in the presence of ALG-2/Ca2+ whereas the version of Sec13A with ABD deleted was not recruited. This was the case also for the Sec3B isoform in complex with Sec24D (Fig. 4C) as well as for Sec23A in complex with the Sec24A and Sec24C isoforms (not shown). Furthermore, we found that Sec31A itself was sufficient to recruit Sec13/31A in the presence of ALG-2/Ca2+. ALG-2 was only recruited in the presence of Sec13A suggesting that ALG-2 binding alters Sec31A to enable it to bind Sec23A rather than binding both Sec23 and Sec31A (Fig. 4C).

**Discussion**

Though much is known about the molecules involved in transporting cargo from the ER to the Golgi (reviewed in [20]), little is known about the role of possible cationic regulation of this process. We have identified ALG-2 and Ca2+ as novel regulators of the COPII budding process. ALG-2 inhibited the capture of membrane cargo proteins Sec22 and p30/ERGIC into vesicles in a cell-free COPII reaction, which reproduces the sorting of transport cargo that bud from the ER. This vesicle budding inhibition is mediated through an ALG-2/Ca2+ dependent binding of Sec31A. ALG-2/Ca2+ also mediates binding of Sec31A to Sec23 in the inner layer of the coat. This connection may interfere with cargo sorting by the Sec23/24 heterodimer.

The group of JC Hay previously described that ALG-2/Ca2+ inhibited heterotrimmerization of a COPII membrane cargo protein, VSV-G protein, an assay they developed to quantify vesicle fusion [21]. They concluded that ALG-2/Ca2+ might block vesicle fusion to a target membrane by causing COPII to be retained on transport vesicles [5]. In our experiments ALG-2/Ca2+ inhibits budding though it may also block COPII vesicle targeting and fusion. Exceeding a 2:1 molar ratio of ALG-2:Sec31A caused a Sec31A-independent block of budding, in that the Sec31AdelABD mutant did not restore budding inhibited by ALG-2 (Figure 3E). The Hay group found that the Ca2+-binding sites of ALG-2 were important for inhibition of fusogenicity, however, the molecular target of this ALG-2/Ca2+-dependent inhibition was not experimentally addressed [5]. In our experiments we have minimized the effect of both auxiliary factors in COPII budding as well as endogenous ALG-2 found in liver cytosol by reconstituting the COPII budding process with purified proteins. The membrane cargo protein p56/ERGIC was detected
Previous work documented a Ca^{2+}-dependent co-localization of ALG-2 with Sec31A possibly at the ER exit sites [1,2,3]. Depletion of ALG-2 in HeLa cells reduced the localization of Sec31A in membranes and correspondingly the depletion of Sec31A decreased ALG-2 in a membrane fraction [3]. The precise site of interaction of Sec31A with ALG-2 has not yet been identified. Based on crystal structure studies of ALG-2 it was suggested that a conformational change induced by Ca^{2+} binding would expose a hydrophobic crevice on the surface of ALG-2 by rotation of the masking an arginine (R125) allowing interaction with a peptide representing Alix/AIP1 [22]. Unlike Alix/AIP1, Sec31A binds to the alternative splice variant ALG-2.1 (Figure 2A) [23,24]. This variant does not exert a switch mechanism for the corresponding R125 (reviewed in [25]), it is thus likely that the mode of ALG-2 binding to Sec31A differs from that of Alix as previously suggested [24]. Binding of Ca^{2+} to EF-hand 3 was described to cause an increase in hydrophobic residue exposure, whereas binding of Ca^{2+} to EF-hand 1 did not significantly change surface hydrophobicity [26]. Our findings show that binding of Ca^{2+} to EF hand 1 directs binding of ALG-2 to Sec31A (Figure 2A) and ALG-2/Ca^{2+}-dependent vesicle budding inhibition. Yamasaki et al. showed that knockdown of Sec31A leads to removal of ALG-2 at the ER-exit site [3]. The retention kinetics of a fluorescently tagged version of Sec31A changed upon removing the ALG-2-binding site of Sec31A [18] indicating that ALG-2 affects the turnover of Sec31A at the ER-exit sites. We were able to restore ALG-2/Ca^{2+}-inhibited budding reactions on addition of a Ca^{2+} chelator, indicating that ALG-2 during Ca^{2+}-transients attenuates vesicle budding. ALG-2 could be functioning as a safeguard during elevated cellular Ca^{2+} to ensure that COPII vesicles do not merge directly with the Golgi apparatus as proposed by Bentley et al. [5], but fuse to form ERGIC. Interestingly ALG-2 is conserved in higher eukaryotes (reviewed in [27]) whereas yeast, which are believed to be void of ERGIC, has a common ancestral penta-EF hand (PEF) family protein. It is possible that ALG-2 has evolved in higher eukaryotes in order to regulate sorting of proteins to ERGIC. The PEF-family yeast homologue, PeFp was recently
reported to bind to the Sec13/31p in a Ca²⁺-independent manner [28]. We were not able to detect binding between Sec31A and the mammalian homologues of Pef1p, Peflin (not shown). We propose that the attenuation of the COPII budding process facilitates transport of specific cargo in a Ca²⁺-dependent manner. Perhaps ALG-2 acts to stall the budding process to synchronize cargo sorting and vesicle morphogenesis. A role in cargo-dependent regulation of export processes was recently discovered for Sedlin, a member of the TRAPP complex. Sedlin knockdown was shown to specifically decrease procollagen packaging whereas neither secretion of other tested proteins nor the trafficking of VSV-G was affected. Sedlin directly interacted with Sar1 preferentially in its GTP bound state presumably regulating Sar1 cycling at ER exit sites and thereby the stability of membrane buds [29]. It is possible that ALG-2 exerts a similar effect through Sec31A by regulating the availability of Sec13/31A for the Sec31A/Sec23 interaction. Previously it was shown that addition of cytosol enhanced the recruitment of COPII proteins to membranes indicating that cytosolic factors assist coat subunit recruitment or coat assembly [15]. We find that ALG-2 facilitates the binding of Sec13/31A and Sec23, although previous reports have shown that Sar1 in concert with Sec23 is needed for interaction with Sec31 [30,31] and more specifically bind an active fragment of Sec31A, which stimulates the GAP activity of Sec23 [31]. Both the ALG-2 binding site and the active fragment of Sec31A are situated in the proline-rich region of Sec31 and it is possible that ALG-2 modulates this domain to accommodate the Sec31A binding to Sec23. Perhaps ALG-2 replaces the bridging effect of the active fragment and by this inhibits GAP activity and vesicle release.

It is possible Ca²⁺/ALG-2 signals a cellular requirement to arrest cargo transport vesicle budding during periods of ER stress or other cellular processes where a protein export halt would be advantageous. The recent discovery that monoubiquitination of Sec31A is essential for collagen secretion in mouse embryonic stem cells [14] opens for novel experimental approaches in concert with the present discovery of an ALG-2/Ca²⁺-dependent attenuation of vesicle budding. Furthermore, Sec31A phosphorylation and membrane association was found to be regulated by casein kinase 2, which also affected ER to Golgi traffic [32]. Future work in this field will be directed at investigating whether ALG-2/Ca²⁺ contributes to regulation of the formation of large COPII vesicles through these posttranslational modification processes. Aberrant trafficking and enhanced surface expression of the T-cell receptor could explain the apparent role of ALG-2 in promoting T-cell receptor-mediated cell death [6]. Based on our previous research we do not find a direct function of ALG-2 in apoptosis, rather a

**Figure 3. Binding of ALG-2 to Sec31A attenuates COPII budding.** A. Peptide array mapping of the ALG-2-binding domain (ABD) of Sec31A. Binding efficiency of fluorescein tagged recombinant ALG-2 binding to 20-mer peptides (upper panel). Various lengths of the indicated proline rich repeats were used as controls (lower panel). B. Diagram representing the ABD of Sec31A and the sequence removed from the Sec13aAdelABD. C. Recombinant ALG-2 was incubated with Ni-beads alone, with purified His-tagged Sec13/Sec31A (wt) or Sec13/Sec31A with the ABD deleted (delABD) in the presence of Ca²⁺. Proteins in the gel were visualized using SyproRed. D. Budding was performed using purified Sar1A, Sec23A/24D and either wt Sec31A (wt) or Sec31A with the ABD of Sec31A deleted (delABD) in the presence of 0.15 ug ALG-2. Background budding levels were found by omitting nucleotides (-nuc). Budding efficiency was normalized to the Sec13/31A wt and delABD respectively. SEM of three independent experiments. E. Addition of excess (5 μg) ALG-2 inhibits vesicle budding independent of Sec31A.

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necessity for ALG-2 in cell proliferation [33,34]. It could be that the correct expression at the cell surface of certain growth regulators depends on ALG-2 through its effect on ER to Golgi trafficking. Experiments investigating the plasma membrane proteome following elevated Ca$^{2+}$-levels in the presence and absence of ALG-2 will be important to further study the role of ALG-2/Ca$^{2+}$ in protein transport.

Materials and Methods

Buffers

Phosphate-buffered saline without calcium and magnesium (PBS, pH 7.4) was purchased from Mediatech (Herndon, VA). TBS contains 50 mM Tris-HCl (pH 7.4), 150 mM NaCl. TBST is TBS supplemented with 0.1% (w/v) Tween 20. Buffer A (budding): 20 mM HEPES-KOH (pH 7.4), 250 mM sorbitol, 150 mM potassium acetate; buffer B (protein purification): 20 mM HEPES-KOH (pH 8.0), 10% (w/v) glycerol, 250 mM sorbitol, 500 mM potassium acetate, 0.1 mM EGTA, 5 mM β-mercaptoethanol, 10 mM imidazole; buffer C (protein purification): 20 mM HEPES-KOH (pH 8.0), 10% (w/v) glycerol, 250 mM sorbitol, 0.1 mM EGTA, 5 mM β-mercaptoethanol, 10 mM imidazole; buffer D (protein purification); Buffer B with 50 mM imidazole; buffer E (protein purification): Buffer B with 250 mM imidazole; buffer F (Liposome flotation): 20 mM HEPES-KOH (pH 6.8), 110 mM potassium acetate, and 2 mM MgCl$_2$; buffer G (M2 immunoprecipitation): Buffer A with 0.1% NP40 and 100 μM CaCl$_2$; Buffer H consists of 150 mM Tris-HCl (pH 6.8), 15% (w/
v) SDS, 25% (w/v) glycerol, 0.02% (w/v) bromphenol blue, and 12.5% (w/v) 2-mercaptoethanol. Buffers A–H were added EDTA-free protease inhibitor mix from Roche (Roche).

**Mapping of Sec31A ALG-2-binding Site**

The ALG-2 binding sequence of human Alix/AIP1 was used in silico to find the most probable binding motif of Sec31A. Overlapping peptides (20-mer) representing amino acids 808–869 were synthesized on a nitrocellulose membrane as previously described [35] and overlayed with fluorescent labeled recombinant ALG-2 (0.2 µg/ml) in a buffer containing 50 mM Tris-HCl, pH 7.5, 0.5% BSA, 0.05% Tween 20, 0.15 M NaCl, 0.3 M arginine and either 1 mM CaCl2 or 5 mM EDTA. Spot intensities were measured using a Typhoon scanner.

**Construction of the ALG-2-binding Deficient Sec31A**

Deletion of the ALG-2 binding site corresponding to amino acids 827–852 of human Sec31A was carried out using forward and reverse primers 23 bp upstream and downstream of the deleted sequence. Two PCR reactions were carried out in parallel, one with the forward primer in combination with a primer containing a unique Eco47III site in the Sec31 sequence and the forward primer with a unique SpeI site in the plasmid sequence. The PCR products were mixed and used as primers and templates in a second PCR reaction. The PCR product was then cut with the two enzymes and cloned back into the vector. Sequencing confirmed the correct deletion.

**Protein Purification**

Recombinant ALG-2 was purified as previously described [16]. Mammalian COPII proteins were inserted in the Bac-to-Bac baculovirus expression system (Invitrogen) and purified in a mammalian COPII proteins were inserted in the Bac-to-Bac baculovirus expression system (Invitrogen) and purified in Miniprep kits.

**Protein Visualization**

Proteins were resolved on 10% or 4–20% gradient SDS gels and normalized to TX-PE fluorescence. Protein intensities were measured using the LI-COR infrared imaging system or stained with SYPROred (1:500, Life Sciences). Quantification of protein intensities was performed using polyclonal anti-ERGIC-53, anti-Ribophorin-I, and BD Biosciences, respectively. Detection by immunoblot analysis using polyclonal anti-ERGIC-53, anti-Ribophorin-I, and Sar1 rabbit antiserum was performed as previously described [37].

**In vitro Vesicle Budding Assay**

The vesicle budding assay was performed as described previously [37]. In brief, HeLa cells were harvested in PBS and permeabilized by 5 min incubation in Buffer F containing 40 µg/ml digitonin. Permeabilized cells were washed in Buffer A and used at 40 µg protein/reaction. The budding reaction was assembled using either rat liver cytosol at 4 mg/ml or purified Sar1A/B, HA-Sec13/His-Sec31A and Flag-Sec23/His-Sec24D. Unless otherwise stated, an ATP-regenerating system was added as stated in Figure 4. Binding was performed for 30 min at 30°C and the liposome/protein solution was mixed with 30 µl 2.5 µg sucrose in HKM buffer followed by overlaying first with 100 µl 0.75 M sucrose in HKM and then with 20 µl HKM. Following a 20 min centrifugation at 100,000 rpm using a TLX100 rotor, the top fraction was collected and loaded on a gel normalized to TX-PE fluorescence.

**Sec23 Binding**

Anti-Flag M2 (Sigma-Aldrich) affinity gel was washed twice with Buffer G and 4 µg Flag-Sec23/His-Sec24 complexes per reaction were immobilized on the matrix and incubated for 20 min at 4°C. Sec31A (5 µg) or Sec13/31Ade/ABD were added to the matrix along with 0.3 µg rALG-2. Proteins were incubated with matrix for at least 2 h at 4°C before three washes of matrix in Buffer G. Bound proteins were eluted using 0.25 mg/ml Flag peptide in Buffer G.

**Antibodies**

Polyclonal antibodies against ALG-2 were as previously described [39]. Monoclonal antibodies against the His-tag (Penta-His) and Sec31A (clone 32) were purchased from Qiagen and BD Biosciences, respectively. Detection by immunoblot analysis using polyclonal anti-ERGIC-53, anti-Ribophorin-I, anti-Sec22b, and Sar1 rabbit antiserum was performed as previously described [37].

**Protein Visualization**

Proteins were resolved on 10% or 4–20% gradient SDS gels and either transferred to PVDF membranes by wet electroblotting followed by visualization using the LI-COR infrared imaging system (Li-cor Biosciences) or stained with SYPRORed (1:5000, Invitrogen) in 7.5% acetic acid and scanned in a Typhoon (GE Life Sciences). Quantification of protein intensities was performed using either the Odyssey or ImageJ image analysis software.

**Supporting Information**

**Figure S1 Buoyant budded vesicles containing p58/ERGIC do not contain ALG-2.** The product of vesicle budding reactions performed with or without recombinant ALG-2 was resolved in a 10–40% Nycodenz gradient and fractions were analyzed for the presence of p58, Sec31A and ALG-2. The right hand side input lanes were run on separate gels. (EPS)

**Figure S2 Titration of recombinant COPII proteins for quantification of liposome binding.** 10–200 ng of recombin-
nant proteins were analyzed following SDS-PAGE and Western blot analysis using the antibodies described in materials and methods.

(EPS)

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References


Author Contributions

Conceived and designed the experiments: JMC RS. Performed the experiments: JMC AJS. Analyzed the data: JMC AJS. Contributed reagents/materials/analysis tools: JMC AJS MWB RS. Wrote the paper: JMC RS.