ESCRT-III acts in scissioning new peroxisomes from the ER

Authors: Fred D. Mast¹², Thurston Herricks¹², Kathleen M. Strehler¹², Leslie R. Miller¹², Ramsey A. Saleem¹²†, Richard R. Rachubinski³, and John D. Aitchison¹²³,*

1. Center for Infectious Disease Research, 307 Westlake Avenue North, Suite 500, Seattle, Washington, 98109-5219, United States of America
2. Institute for Systems Biology, 401 Terry Avenue North, Seattle, Washington, 98109-5219, United States of America
3. Department of Cell Biology, University of Alberta, 5-14 Medical Sciences Building, Edmonton, Alberta, T6G 2H7, Canada

† Current address: Amgen, 360 Binney Street, Cambridge, Massachusetts, 02142-1011

Corresponding author:
John D. Aitchison, PhD
Center for Infectious Disease Research
307 Westlake Avenue North, Suite 500
Seattle, Washington, 98109-5219
Tel: (206) 256-7470
Fax: (206) 256-7229
john.aitchison@cidresearch.org

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Abstract

Dynamic control of proliferation is integral to the peroxisome’s many functions. A breakdown in the ability of cells to form peroxisomes is linked to many human health issues, including defense against infectious agents, cancer, aging, heart disease, obesity and diabetes, and forms the basis of a spectrum of genetic disorders that cause severe neuropathologies. The endoplasmic reticulum (ER) serves as a source for preperoxisomal vesicles (PPVs) that mature into peroxisomes during de novo peroxisome biogenesis and to support growth and division of existing peroxisomes. However, the mechanism of PPV formation and release from the ER remains poorly understood. Here we show that the evolutionarily ancient endosomal sorting complexes required for transport (ESCRT)-III are peroxisome biogenesis factors that function to cleave PPVs budding from the ER into the cytosol. Using comprehensive morphological and genetic assays of peroxisome formation and function we find that absence of ESCRT-III proteins impedes de novo peroxisome formation and results in an aberrant peroxisome population in vivo. Using a cell-free PPV budding assay we show that ESCRT-III proteins Vps20 and Snf7 are required to release PPVs from the ER. ESCRT-III is therefore a positive effector of membrane scission for vesicles budding both away from and towards the cytosol, a finding that has clear implications for the evolutionary timing of emergence of peroxisomes and the rest of the internal membrane architecture of the eukaryotic cell.
Introduction

Peroxisome proliferation occurs via two partially redundant mechanisms: the division of existing peroxisomes through fission and de novo formation from the ER (Mast et al., 2015; Smith and Aitchison, 2013). Fission of peroxisomes is comparatively well characterized, and requires the Pex11 family of proteins to elongate and constrict the organelle, permitting GTP-dependent scission by dynamin related proteins (DRPs) (Schrader et al., 2016). The mechanism of de novo formation remains poorly understood and the identities of many factors involved in this process are still unknown (Agrawal and Subramani, 2016).

In yeast, most peroxisomal membrane proteins (PMPs) transit through the ER on their way to peroxisomes (Hoepfner et al., 2005; Schuldiner et al., 2008; Thoms et al., 2012; van der Zand et al., 2010). A global analysis of localized protein synthesis also found that many of these PMPs are likely cotranslated at the ER (Jan et al., 2014).

A vesicular transport pathway exists to transfer proteins and membranes from the ER to peroxisomes (Agrawal et al., 2016; Agrawal et al., 2011; Lam et al., 2010), which is essential even when peroxisomes multiply by growth and division (Mast et al., 2016). Pex3 accumulates initially at an ER subdomain before being released into a PPV that buds from the ER (Halbach et al., 2006; Hoepfner et al., 2005; Tam et al., 2005). Sorting of PMPs through the ER to sites of PPV formation and egress requires both Pex3-dependent and –independent processes (Fakieh et al., 2013). The ER-shaping reticulon proteins, through physical interactions with Pex29 and Pex30, assist in regulating the sorting of Pex3 through the ER and in the release of PPVs (David et al., 2013; Mast et al., 2016). Pex30 and its paralog, Pex31, have membrane shaping
capabilities like the reticulon proteins, which may help in defining and segregating the PPV exit site in the ER from its other functions (Joshi et al., 2016).

The formation of these preperoxisomal vesicles (PPVs) requires Pex3 and Pex19 and their loss leads to an inability of cells to form peroxisomes and consequently, the eventual loss of the organelle (Hettema et al., 2000; Hoepfner et al., 2005). Pex19, a cytosolic protein that interacts with Pex3 and other PMPs, functions as a chaperone and is essential for budding PPVs from the ER. At least two classes of PPVs (V1 and V2) have been characterized (Agrawal et al., 2016; Titorenko et al., 2000; Titorenko and Rachubinski, 2000; van der Zand et al., 2012); both contain Pex3, but differ in the presence or absence of docking-factor or RING finger group proteins of the peroxisomal matrix protein import complex (peroxisomal importomer) (Agrawal et al., 2016). The separation of these two subcomplexes of the importomer could prevent premature assembly in the ER and the import of peroxisomal proteins directly into the ER (Agrawal et al., 2016; van der Zand et al., 2012). While Pex3 and Pex19 are necessary for PPV budding, they are not sufficient, and evidence suggests additional cytosolic component(s) are required, at least one of which likely consumes ATP (Agrawal et al., 2011; Lam et al., 2010). Dynamin-related proteins, which function in peroxisome division, or COPI and COPII vesicle transport pathways, all of which consume GTP, have consistently been shown to not be essential for PPV formation (Lam et al., 2010; Motley et al., 2015; Motley and Hettema, 2007; Perry et al., 2009; South et al., 2000).

Here, we identify a novel role for endosomal sorting complexes required for transport (ESCRT)-III in the de novo biogenesis of peroxisomes. In particular, through use of a series of comprehensive morphological and genetic assays of peroxisome formation and function and in
vitro biochemical assays that produce preperoxisomal vesicles from the ER, we implicate ESCRT-III proteins Vps20 and Snf7 as being essential for the scission of PPVs from the ER.

Results and discussion

Screens of an isogenic, arrayed collection of yeast gene deletion strains identified 211 genes whose disruption led to defects in the cells’ ability to form peroxisomes (Saleem et al., 2008; Saleem et al., 2010; Smith et al., 2006). We reasoned that these datasets held clues to candidates involved in the de novo biogenesis of peroxisomes, and in the formation of PPVs at the ER. A priori, candidates would be cytosolic and/or localized to the ER, and would use ATP in their activity. Candidates with these characteristics were components of ESCRT, with a statistically significant hypergeometric p-value of 0.003 (Saleem et al., 2010).

ESCRT is composed of five subcomplexes, including ESCRT-0, -I, -II, -III (and -III-associated) and the AAA-ATPase Vps4 complex (Babst et al., 2002a; Babst et al., 2002b; Babst et al., 1997; Katzmann et al., 2001; Katzmann et al., 2003) (reviewed in (Henne et al., 2011; Schoneberg et al., 2016)). These five complexes function sequentially to mediate the formation of intraluminal vesicles, and also assist in piecemeal fashion with numerous other cellular activities like cytokinesis (Carlton and Martin-Serrano, 2007), plasma membrane repair (Jimenez et al., 2014; Scheffer et al., 2014), autophagosome closure (Lee et al., 2007; Rusten et al., 2007), viral replication and budding (Garrus et al., 2001), nuclear envelope reformation (Olmos et al., 2015; Vietri et al., 2015), nuclear pore complex quality surveillance (Webster et al., 2014), neuronal pruning (Loncle et al., 2015), and microtubule severing (Guizetti et al., 2011) (Henne et al., 2011; Schoneberg et al., 2016). ESCRT-III, composed of Vps20, Snf7, Vps24 and Did4 in yeast, is evolutionarily ancient, and is the primary effector complex for all these
activities (Henne et al., 2011; Tang et al., 2015). Given this wealth of function, particularly for ESCRT-III, a key consideration was whether ESCRTs have a direct role in peroxisome biogenesis or exert indirect effects due to their diversity of activity.

We used our one-cell doubling evaluation of living arrays of yeast (ODELAY!) platform (Herricks et al., 2017) to address the role of ESCRT in peroxisome biogenesis by comparing growth on solid-phase medium containing either glucose or oleic acid, which requires functional peroxisomes for its metabolism, as the sole carbon source (Fig. 1 and Fig. S1). Unlike traditional spot-based assays and assays utilizing optical density measurements at a population level, ODELAY! provides time-resolved measurements of yeast populations from individual strains. ODELAY! therefore permits standardized analyses of the growth rates and population heterogeneity both within and between strains for up to 96 strains measured in parallel across different growth conditions. Strains with general growth defects have comparable normalized growth rates under both conditions, whereas condition-specific strains grow more slowly in one condition versus the other.

Following ODELAY! measurements, population doubling times were normalized, and the mean z-score for each deletion strain was compared between the two growth conditions (Fig. 1). The pex19Δ and pot1Δ strains, which lack the ability to form peroxisomes (Hettema et al., 2000) or perform the last step of β-oxidation (Igual et al., 1991), respectively, reveal condition-specific growth defects, as they exhibited slightly faster growth in the presence of glucose but grew 4-5 standard deviations slower than wild-type in the presence of oleic acid (Fig. 1).

ESCRT-III deletion strains have pronounced condition-specific growth defects in the presence of oleic acid, with vps20Δ cells incapable of cell division in oleic acid, while did4Δ and
snf7Δ cells registered the slowest doubling rates of all ESCRT deletions (Fig. 1). ESCRT-I deletion strains displayed general growth defects whereas ESCRT-II deletion strains tightly clustered, in line with their known structural and functional assembly as a single protein complex, and showed a condition-specific growth defect, although not as severe as ESCRT-III (Fig. 1). Other ESCRT deletion strains also had slower, but less severe than ESCRT-III, doubling times in oleic acid, except for the strain lacking the Vps4 regulator Vta1 which, like the peroxisome inheritance mutants inp1Δ and inp2Δ, had a faster doubling time than wild-type under both conditions (Fig. 1).

To determine if the growth defects observed for ESCRT-III result from defects in peroxisomes we used electron microscopy to investigate the cellular ultrastructure of cells lacking individual components of the core ESCRT-III complex under conditions that promote peroxisome biogenesis conditions (Fig. 2 and Fig. S2). Peroxisomes were readily observed in wild-type cells as orbicular structures delimited by a single lipid bilayer and containing an electron-dense, paracrystalline matrix (Fig. 2 A). In contrast, peroxisomes were not observed in vps20Δ cells, which instead contained infrequent small vesicular structures attached to ER membranes (Fig. 2 B). In snf7Δ cells, peroxisome-like structures lacking a dense matrix were infrequently seen in close apposition to, and possibly contiguous with, the ER (Fig. 2 C). Quantification revealed fewer peroxisomes and peroxisome-like structures for all deletion strains of the ESCRT-III complex (Fig. 2 D and Table 1), although peroxisomes similar in size to wild-type peroxisomes were observed in did4Δ and vps24Δ cells, but at numbers 25% and 45% less, respectively, than peroxisomes in wild-type cells (Fig. 2 E – I).
The observed growth and peroxisome morphology defects detected for deletion strains of ESCRT-III and in particular for vps20Δ and snf7Δ, suggested a role for ESCRT-III in peroxisome biogenesis. To test this, we used an in vivo peroxisome biogenesis assay in which tetracycline-control of PEX19 expression synchronizes cells for de novo peroxisome biogenesis without overexpressing peroxins (Fig. 3 A) (Mast et al., 2016). With PEX19 expressed, 97% of wild-type cells contained an average of 10 peroxisomes per cell, as assessed by the punctate localization of peroxisomal Gpd1-GFP. Repression of PEX19 expression by treatment with doxycycline removed peroxisomes from the yeast population, with only ~1.5% of cells containing an average one peroxisome per cell. Removal of doxycycline led to de novo biogenesis of peroxisomes with ~70% of cells containing ~4 peroxisomes per cell after 12 hrs. In contrast, vps20Δ and snf7Δ had fewer peroxisomes per cell in control conditions and retained more of them, 6% and 11% respectively, following doxycycline treatment. Upon stimulating de novo peroxisome biogenesis, vps20Δ and snf7Δ failed to produce peroxisomes at rates comparable to wild-type, revealing a defect in the ability of vps20Δ and snf7Δ cells to form new peroxisomes de novo (Fig. 3 A).

Notably, Snf7 localized to sites of de novo peroxisome biogenesis in a tetracycline-regulated PEX19 background strain. Pex3-GFP and Snf7-mCherry puncta rarely overlap under control conditions, but following doxycycline-treatment to induce de novo peroxisome formation, 13.5% of Pex3p-GFP puncta correspondingly colocalized with Snf7-mCherry signal (Fig. 3 Bb). We were unable to detect a meaningful fluorescent signal for Vps20-mCherry under these conditions.
Current models of ESCRT-III function propose that Vps20 is recruited to a membrane first, initiating activation and polymerization of additional members, especially Snf7, to form spirals and coils that deform membranes into tubes or cones to achieve membrane scission (Henne et al., 2011; Schoneberg et al., 2016). Vps24 caps the polymers and stops polymerization, whereas Did4 is integrated into the polymer to promote its disassembly by recruiting the AAA-ATPase, Vps4 (Henne et al., 2011; Schoneberg et al., 2016).

To test if ESCRT-III is required for PPV scission at the ER we used an *in vitro* budding assay that reconstitutes the packaging and release of PMPs from the ER via PPVs (Mast et al., 2016) (Fig. 4). ER membranes were prepared from a *pex19Δ* strain in which Pex3 and other PMPs are trapped in the ER (Agrawal et al., 2016; Agrawal et al., 2011). The release of Pex3 was stimulated by addition of wild-type cytosol and an ATP regeneration system (Lam et al., 2010) but not by cytosol from *pex19Δ, vps20Δ, or snf7Δ* cells (Fig. 4 A). We also tested cytosols from other ESCRT and ESCRT-III deletion strains, *e.g.*, *did4Δ*, and found that their cytosols still promoted the formation of Pex3-containing PPVs but sometimes at levels less than that produced by wild-type cytosol (Fig. 4 A and Fig. S3). Mixing the S100 fraction of cytosols from *snf7Δ* with *vps20Δ* or *pex19Δ* partially complemented the defect in Pex3-GFP release (Fig 4 A). It is known that ESCRT-III does not depend on ATP-hydrolysis to mediate membrane scission but rather relies on the AAA-ATPase Vps4 to remove and recycle ESCRT-III components. Accordingly, treatment of the reaction with apyrase to deplete ATP led to a reduction, but not abrogation, of PPV budding that could be restored to typical levels by addition of exogenous ATP. Consistent with this observation, PPV release occurs rapidly upon reaction mixing,
followed by further incremental release over time, suggesting that ATP acts primarily in
recycling scission components (Fig. 4B).

As classically defined, ESCRT-III, and particularly Vps20 and Snf7, are "peroxins" as they
are required for peroxisomal membrane biogenesis and peroxisome proliferation (Distel et al.,
1996). Our observations are consistent with a model wherein Vps20 is recruited to sites of PPV
formation and, in turn, recruits and activates the polymerization of Snf7 to drive membrane
scission and release of the PPV into the cytosol. The other ESCRT-III proteins, Vps24 and Did4,
are likely also involved but not essential for PPV scission and probably influence the dynamics
of PPV formation and recruit the machinery for disassembly of ESCRT-III at the ER. Consistent
with this hypothesis, did4Δ displayed severe growth defects when grown in the presence of
oleic acid and showed reduced budding of Pex3-positive PPVs from the ER (Fig. 1 and Fig. S3).
This is consistent with its role in recruiting the AAA-ATPase Vps4 complex to disassemble
ESCR-TIII polymers and previous observations that the amount of cytosolic Snf7 is reduced in
did4Δ cells because it is trapped in a polymerized state on membranes.

ESCRT-III is typically thought to be involved in vesicle budding away from the cytosol
(reverse-topology membrane scission) with or without other ESCRT complexes (subsets of
ESCRT-0, -I and -II) (Henne et al., 2011; Schoneberg et al., 2016). Our data extend ESCRT-III
function to include vesicle budding into the cytosol (normal topology membrane scission).
Consistent with our hypothesis, previous examination of ESCRT-III activity on giant unilamellar
vesicles (GUV) in vitro (Wollert et al., 2009) showed that while most vesicles formed
intraluminally, vesicles could also bud away from the GUV. Also, cryo-EM images of purified
ESCRT-III components demonstrated that ESCRT-III can deform and stabilize membranes for
normal-topology scission (McCullough et al., 2015). ESCRT-III has also been implicated in unconventional protein secretion from the ER with its mode of action unclear (Curwin et al., 2016). It is interesting to note that unconventional protein secretion has previously been linked to peroxisomes (Manjithaya et al., 2010), and may more broadly share a common mechanism of egress with PPVs from the ER. The expanding role of ESCRT-III in diverse cellular activities, including the formation of peroxisomes, suggests that this evolutionarily ancient protein complex has had a much greater influence on the sculpting of the eukaryotic bauplan than previously realized.

Materials and Methods

Yeast strains

The yeast strains used in this study are listed in Table S1 and were derived from the parental strain BY4742 or the corresponding gene deletion strain library (Invitrogen) (Giaever et al., 2002), and as described previously (Mast et al., 2016).

Yeast media and growth conditions

Yeast strains were grown in YPD (1% yeast extract, 2% peptone, 2% glucose) or YPBO (0.5% KPi, pH 6.0, 0.3% yeast extract, 0.5% peptone, 0.5% Tween 40, 0.15% oleic acid), as indicated. All cultures were grown at 30°C. When marker selection was required for each strain, defined synthetic medium (SM) supplemented with 2% glucose and the necessary amino acid(s) or drug was used. Yeast media and growth conditions for specific experiments are listed below.

YPB-Oleate medium for use in ODELAY! was prepared as follows. A solution of 300 mg of methyl-β-cyclodextrin (Sigma)/mL and 10µL oleic acid/mL was prepared in absolute ethanol for a total volume of 3 mL. The solution was then placed in a Rotovap for 3 hrs to remove the
ethanol. The resulting powder was then reconstituted using ultra-pure H$_2$O to a total volume 3 mL. Meanwhile 15 mL of 1.33% agarose, 2 mL of 10× YPB medium, and 1 mL of ultra-pure H$_2$O were melted in boiling water for 18 min. Then 2 mL of the oleate-cyclodextrin solution were added to the melted medium and vortexed to mix. The YPB-Oleate medium was then cast into molds and allowed to cool as described (Herricks et al., 2017). YPB-glucose medium was prepared similarly except 2 mL of 20% glucose were added instead of the oleate-carbon source.

To study peroxisome biogenesis, strains were grown overnight to saturation in YPD and diluted the next morning by dilution in fresh YPD to an OD$_{600}$ = 0.2. Cells were then grown to logarithmic phase (OD$_{600}$ = 0.7-1) before being diluted again in YPD, this time supplemented with 2 µM doxycycline, and incubated for 18 hrs. The logarithmic phase cells were harvested by centrifugation, washed five times in YPD to remove doxycycline, resuspended in fresh YPD medium without doxycycline, inoculated into YPD medium at an OD$_{600}$ = 0.2, and cultured for an additional 12 hrs.

One cell doubling evaluation of living arrays of yeast (ODELAY!)

Sensitive, high-density, and multiparametric analysis of cell growth was performed as described (Herricks et al., 2017). Briefly, yeast was cultured in YPD medium in 96 well plates at 30°C overnight. Cultures were diluted to an OD$_{600}$ = 0.09 and allowed to grow for 6 hrs at 30°C. The cultures were then washed in YPB medium without a carbon source and diluted to an OD$_{600}$ = 0.02 and spotted onto YBP-Oleate agarose medium. The resulting cultures were then observed using time-lapse microscopy for 48 hrs with 30 min intervals between images. All images were collected on Leica DMI6000 microscopes equipped with 10× 0.3 NA lenses using bright field
microscopy. MATLAB scripts using the Micro-Manager interface controlled the image collection process (Edelstein et al., 2014).

Population growth rates were scored against each other using the equation:

\[ Z_{mean} = \frac{1}{n} \sum_{i} \frac{d_i - \mu_i}{\sigma_i} \]

Where \( d_i \) is the \( i \)th decile of query population doubling time, \( \bar{D}_i \) is the mean of the \( i \)th decile of the parent strains doubling time, and \( \sigma_i \) is the standard deviation of the \( i \)th decile of the parent strain's doubling time. The mean and standard deviation deciles (\( \mu_i \) and \( \sigma_i \)) were calculated from 16 separate wild-type and 8 separate deletion strain populations containing at least 200 individuals per replicate. All calculations were performed using MATLAB scripts (Herricks et al., 2017).

**Electron microscopy and quantification**

Experiments were performed as described (Tam et al., 2003). Image analysis to measure cell and peroxisome profiles was performed in Image J (National Institutes of Health).

**Fluorescence microscopy and quantification**

Experiments were performed as described previously (Mast et al., 2016). Briefly, 25 fields of view yielding at least 250 cells per strain per time point for Gpd1-GFP labelled cells and at least 75 cells per strain per time point for Pex3-GFP and Snf7-mCherry cells were acquired in a randomized fashion with brightfield or calcofluor white staining used to establish focus for each strain and time point. Images were acquired with a 100×1.4 NA objective (Olympus) on a DeltaVision Elite High Resolution Microscope (GE Healthcare Life Sciences). Images were
deconvolved with the manufacturer’s supplied deconvolution software (softWoRx) and an experimentally determined point spread function. Images were further processed using Imaris software (Bitplane), and object-based colocalisation analysis was performed using the “Spots” function as described (Mast et al., 2016). Experiments were performed in triplicate.

**In vitro vesicle budding assay**

Experiments were performed as described (Mast et al., 2016). To complement PPV budding defects, cytosols were mixed 1:1 before addition to the reaction. For experiments with apyrase, PYCs and cytosols were incubated separately with 1 U of apyrase (Sigma), resuspended in reaction buffer (25 mM HEPES-KOH, pH 7.2, 115 mM potassium acetate, 2.5 mM MgCl₂, 250 mM sorbitol) for 20 min prior to starting the reaction. For experiments in which exogenous ATP was added back, only apyrase-treated PYCs that had been washed in reaction buffer were used. Alphaview (ProteinSimple) was used to quantify the chemiluminescence signal with values normalized between the negative *pex19Δ* PYCs only control (set to 0), and the positive wild-type cytosol plus ATP control (set to 100). Experiments were performed in triplicate.

**Online supplemental material**

Fig. S1 contains supporting data that shows the population doubling time histograms of all yeast strains measured by ODELAY!. Fig. S2 contains supporting data to show additional electron micrographs of the ESCRT-III deletion mutants revealing peroxisome morphology defects. Fig. S3 contains supporting data to show the budding efficiencies of PPVs from reactions containing cytosols isolated from ESCRT deletion strains. Table S1. contains supplemental information on the genetic background of the yeast strains used in this study as well as their origin of derivation.
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The authors declare no competing financial interests.

Author Contributions: F.D.M., R.A.R, and J.D.A. designed the experiments, analyzed the results and wrote the manuscript. F.D.M. performed all the experiments. R.A.R performed the electron microscopy experiments. T.H. performed the ODELAY! experiments and analysis. K.M.S and L.R.M assisted with the experiments. R.A.S contributed to the experimental design and analysis. All authors read and commented on the manuscript.

References


etc. etc.
did not divide on medium containing oleic acid, so only the mean Z-score and SEM for growth on medium containing glucose are displayed.

**Figure 2.** ESCRT-III deletion strains have reduced and aberrant peroxisome populations. (A) *Wild-type*, (B) *vps20Δ*, and (C) *snf7Δ* cells were grown in medium containing oleic acid to induce peroxisomes and then prepared for electron microscopy. Cell ultrastructure and representative organelle profiles are depicted in a. Arrowheads in (B) and (C) point to aberrant peroxisomes. Bar = 1 µm. (D–I) Morphometric analysis of peroxisomes. For each strain analyzed, the areas of individual peroxisomes were determined. Bar graphs display the numerical density of peroxisomes (D) and the population distribution of the area of peroxisomes (E–I) for *wild-type* and ESCRT-III deletion strains.

**Figure 3.** Vps20 and Snf7 positively regulate de novo peroxisome biogenesis. (A) Genomically encoded *PEX19* was placed under the control of a tetracycline-repressible Tet07 promoter to allow regulatable de novo peroxisome production in *wild-type*, *vps20Δ*, and *snf7Δ* cells expressing Gpd1-GFP as a peroxisomal marker. Cells were imaged before (control) and after an 18 hr incubation with 2 µM doxycycline (+DOX), and 12 hrs after the removal of doxycycline (recovery). The percentage of cells containing peroxisomes and the average number of peroxisomes per cell in peroxisome-positive cells were measured at each time point and are depicted in bar plots with error bars representing the SEM of 3 biological replicates. Scale bar = 5 µm. (B) Snf7 localizes to sites of de novo peroxisome biogenesis. *Wild-type* cells expressing endogenously tagged Pex3-GFP and Snf7-mCherry with tetracycline-repressible *PEX19* were imaged before (control) and 1 hr following an 18 hr incubation with 2 µM doxycycline (recovery). Arrowheads point to areas of colocalization, see zoom window for enlargement.
the merged image, calcofluor white staining (cyan) was used to demarcate cell boundaries. Bar graphs report the percent overlap of Pex3-GFP puncta colocalizing with Snf7-mCherry puncta with error bars representing the SEM of 3 biological replicates. Scale bar = 5 µm.

**Figure 4.** Vps20 and Snf7 are required for budding of PPVs from the ER. (A) Permeabilized pex19Δ yeast cells (PYCs) containing microsomes and expressing Pex3-GFP were incubated with the S100 fraction of cytosol isolated from wild-type (lanes 2 – 4), vps25Δ (lane 5), vps20Δ (lanes 6 and 8), snf7Δ (lanes 7 – 9) or pex19Δ (lanes 9 and 10) for 90 min at room temperature in the presence of an ATP-regenerating system. Controls included incubating the PYCs alone (lane 1), with cytosol but no ATP (lane 2) or with cytosol and ATP, but at 4 °C (lane 3). (B) ATP is not required for PPV release but rather to recycle scission components. PYCs and the S100 fraction of cytosol isolated from wild-type were pretreated with apyrase before starting the reaction (lanes 3 and 5). A time course was also performed at the indicated time points (lanes 6 – 10).

**Table 1.** Average area and numerical density of peroxisomes in cells of **wild-type** and ESCRT-III deletion strains.

<table>
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<th>cell area assayed (µm²)</th>
<th>peroxisome count</th>
<th>numerical density of peroxisomes</th>
<th>average area of peroxisomes (µm²)</th>
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<td>138</td>
<td>0.51</td>
<td>0.044</td>
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</tbody>
</table>

* denotes peroxisome-like structures present.
A

control +DOX recovery
wild-type

Gpd1-GFP | pTet07-PEX19
vps20Δ

snf7Δ

% cells with peroxisomes
peroxisomes per cell

B

pTet07-PEX19

Pex3-GFP Snf7-mCherry merge

control recovery

% Pex3-GFP foci colocalizing with Snf7-mCherry

1.1.