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Authors
Schuck, Sebastian
Prinz, William A
Thorn, Kurt S
et al.

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Membrane expansion alleviates endoplasmic reticulum stress independently of the unfolded protein response

Sebastian Schuck,1,2 William A. Prinz,3 Kurt S. Thorn,2 Christiane Voss,3 and Peter Walter1,2

1Howard Hughes Medical Institute and 2Department of Biochemistry and Biophysics, University of California, San Francisco, San Francisco, CA 94158
3Laboratory of Cell Biochemistry and Biology, National Institute of Diabetes and Digestive and Kidney Diseases, National Institutes of Health, Bethesda, MD 20892

Correspondence to Sebastian Schuck: sebastian.schuck@ucsf.edu

Abbreviations used in this paper: CV, coefficient of variation; ERAD, ER-associated degradation; IE, index of expansion; UPR, unfolded protein response.

Introduction

Eukaryotic cells contain a rich variety of membrane-bound organelles. Each organelle has a unique set of functions and is distinguished by a characteristic morphology. As the need for certain cellular functions changes during growth, differentiation, or disease, cells adjust the amounts, compositions, and shapes of their organelles accordingly. To make these adjustments, cells need to be able to sense an imbalance between demand and capacity for a particular function and restore homeostasis by rearranging, synthesizing, or degrading organelle components. Molecular mechanisms underlying such homeostatic regulation have been discovered, but how they coordinate the comprehensive remodeling of entire organelles is only partially understood (Haynes et al., 2007; Ron and Walter, 2007; Sardiello et al., 2009).

The ER is a large, continuous membrane system. It is responsible for the folding of all proteins that enter the secretory pathway and is the main site of lipid biosynthesis. The ER consists of the perinuclear ER, which constitutes the nuclear envelope, and the peripheral ER, which extends throughout the cytoplasm (Voeltz et al., 2002; Borgese et al., 2006; Shibata et al., 2006). The perinuclear ER is a closed membrane sheet (or cisterna), whereas the peripheral ER is a network of sheets and tubules. Sheets are typically decorated with ribosomes, whereas tubules are mostly ribosome free. ER tubules are formed by the action of reticulon and reticulon-like proteins (Voeltz et al., 2006). These morphogenic proteins contain reticulon domains, which fold into hydrophobic hairpin structures and insert into the cytoplasmic leaflet of the ER membrane. By means of their unusual mode of membrane association and their ability to oligomerize, reticulons tubulate membranes (Hu et al., 2008; Shibata et al., 2008). Reticulons thus localize to ER tubules as they generate them. Morphogenic proteins that shape ER sheets are not known, but ribosome binding to the ER membrane may stabilize sheets (Shibata et al., 2006; Puhka et al., 2007).

ER size and shape can change dramatically (Federovitch et al., 2005; Borgese et al., 2006). Perhaps the most impressive example of the great plasticity of the ER is observed during the differentiation of B lymphocytes into plasma cells, which synthesize, fold, and secrete their own weight in antibodies every day. To cope with this enormous folding load, differentiating lymphocytes drastically increase their levels of ER chaperones (van Anken et al., 2003). Concomitantly, they massively expand their ER membrane, leading to a more than threefold increase in ER chaperone levels. Converting the sheets of the expanded ER into tubules by reticulon overexpression does not affect the ability of cells to cope with ER stress, showing that ER size rather than shape is the key factor. Thus, increasing ER size through membrane synthesis is an integral yet distinct part of the cellular program to overcome ER stress.
increase in ER volume (Wiest et al., 1990). Similarly, induction of the ER-localized cytochrome P450 detoxification system in hepatocytes leads to a pronounced expansion of the ER membrane, which forms tightly packed whorls (Feldman et al., 1981). In more artificial settings, ectopic expression of ER transmembrane proteins in both yeast and mammalian cells frequently produces ordered arrays of unusually shaped expanded ER (Anderson et al., 1983; Wright et al., 1988; Snapp et al., 2003; Lingwood et al., 2009).

The main signaling pathway controlling ER homeostasis is the unfolded protein response (UPR), whose basic features are conserved from yeast to humans (Bernales et al., 2006a; Ron and Walter, 2007). All eukaryotes possess IRE1, which acts as a sensor for protein-folding problems in the ER; metazoans have two additional sensors, PKR-like ER kinase and ATF6. When misfolded proteins accumulate in the ER, which signals that the folding capacity of the ER is exceeded and constitutes a condition called ER stress, IRE1 is activated. In turn, IRE1 activates a transcription factor called Hac1 in yeast and XBP1 in metazoans that induces a large number of genes encoding parts of the ER-resident folding machinery. Import of these gene products into the ER augments the organelle’s folding capacity. In addition, the UPR activates related functionalities such as ER-associated degradation (ERAD) and lipid biosynthesis (Cox et al., 1997; Travers et al., 2000). ERAD is responsible for the retrotranslocation of terminally misfolded proteins from the ER into the cytoplasm for proteasome-mediated degradation (Venmar and Brodsky, 2008). Without the UPR, cells cannot adjust their levels of ER chaperones according to need and are unable to maintain ER homeostasis. Knockout of IRE1 or XBP1 is lethal in mice, XBP1-deficient B lymphocytes fail to develop into plasma cells, and yeast lacking Ire1 or Hac1 are hypersensitive to ER stress (Cox et al., 1993; Mori et al., 1993, 1996; Cox and Walter, 1996; Reimold et al., 2000, 2001; Urano et al., 2000).

The role of the UPR in regulating the amount of ER membrane is less clear. Expression of active XBP1 stimulates lipid biosynthesis and enlarges the ER in fibroblasts and B lymphocytes (Shaffer et al., 2004; Sriburi et al., 2004). Conversely, XBP1 deficiency impairs the characteristic ER membrane expansion during the development of specialized secretory cells (Reimold et al., 2001; Lee et al., 2005). However, it is unknown whether removal of XBP1 abolishes the ability of these cells to expand their ER or prevents them from reaching the stage of development at which ER expansion would normally take place. In addition, experiments using UPR-deficient yeast have yielded conflicting results as to whether the UPR is needed for ER expansion upon overexpression of ER transmembrane proteins (Cox et al., 1997; Menzel et al., 1997; Takewaka et al., 1999; Larson et al., 2002). Moreover, the physiological role of ER membrane expansion has not been explored. The ER of specialized secretory cells has to process an unusually large amount of cargo, and ER stress in any cell type increases cargo load as proteins stay longer in the ER before they are correctly folded or degraded. It seems reasonable that a larger ER is needed under these circumstances to accommodate increased amounts of ER client proteins. In addition, membrane expansion during ER stress may occur concomitantly with UPR target gene activation to house newly synthesized ER-resident folding machinery. However, these notions have not been tested experimentally.

In this study, we investigate ER biogenesis in response to acute ER stress in the budding yeast *Saccharomyces cerevisiae* to address the role of UPR signaling in mediating ER membrane expansion, define the pathways involved in synthesizing new ER membrane, and gain insight into the physiological significance of the resulting increase in ER size.

**Results**

To visualize the yeast ER, we fluorescently labeled Sec63, an abundant ER transmembrane protein that localizes to both sheets and tubules and has been used extensively as an ER marker (Prinz et al., 2000; Voeltz et al., 2006). We generated cells in which a functional Sec63-GFP fusion protein replaced the endogenous Sec63. Optical sections through the middle of these cells showed the evenly labeled nuclear envelope and the peripheral ER, which in yeast lies just underneath the plasma membrane (Fig. 1 A, left). Peripheral and perinuclear ER are connected by a small number of tubules, which were only occasionally captured in single optical sections. In midsections, the peripheral ER appeared as a dotted line because its tubular network is seen in cross sections (Fig. 1 A, top). Its netlike morphology was more evident in cortical sections (Fig. 1A, bottom). We estimate that ~40% of the cytoplasmic face of the plasma membrane is covered with ER (see Materials and methods).

**ER stress induces ER expansion through the generation of membrane sheets**

Exposure of cells to ER stress by treatment with DTT, which prevents disulfide bond formation, or tunicamycin, which inhibits protein glycosylation, caused massive ER expansion (Fig. 1 A, right). In midsections, the Sec63-GFP signal along the cell periphery had a more continuous appearance. Cortical sections showed that this reflected the generation of large membrane sheets so that the expanded peripheral ER covered ~85% of the plasma membrane. In addition, extensions of the peripheral ER into the cytoplasm were frequently seen, whereas the nuclear envelope retained its size and shape.

Using electron microscopy, we have shown previously that the membrane area of the peripheral ER (including cytoplasmic extensions) increases more than threefold during DTT treatment, whereas ER volume increases approximately fivefold (Bernales et al., 2006b). To quantify expansion of the peripheral ER from light microscopy images, we exploited the fact that Sec63-GFP, as seen in midsections, became more evenly distributed along the cell cortex as the expanding ER covered an increasing portion of the plasma membrane. We determined an index of expansion (IE) by measuring the variation of the cortical Sec63-GFP signal and normalizing it to the variation of the perinuclear Sec63-GFP signal, which represents maximally expanded ER (see Materials and methods). The resulting index does not provide an absolute measure for overall ER membrane area or volume but proved to be a sensitive and reproducible metric for the characteristic spreading of the cortical Sec63-GFP signal during ER expansion. Expansion occurred within 1 h of DTT treatment and reached
ER membrane expansion requires UPR signaling

To determine the contribution of UPR signaling to ER membrane expansion, we analyzed hac1 and ire1 mutants expressing Sec63-GFP. These cells have a normal ER morphology in the absence of ER stressors (unpublished data). In contrast, DTT-induced ER membrane expansion was strongly impaired (Fig. 2 A). Quantification showed that expansion of the peripheral ER was normal up to 1 h of treatment but then stalled (Fig. 2 B). In addition, large ER patches formed in the proximity of the nucleus and at the cell periphery. Colocalization with Rtn1-Cherry and electron microscopy revealed that these patches are tangles of irregularly shaped, ribosome-free ER (Fig. 2, C and D). Given that the membrane elements in these tangles cannot be resolved by light microscopy, we could not include them in the quantification of ER membrane expansion. Therefore, it is not possible to determine quantitatively to what extent peripheral and total ER membrane amounts are reduced in DTT-treated hac1 and ire1 mutants. Nevertheless, the ER patches clearly show that cells cannot generate morphologically normal expanded ER without UPR signaling.

Proper ER membrane expansion requires the Ino2/4 complex

Next, we investigated the role of lipid biosynthesis in ER membrane expansion. In yeast, many phospholipid synthesis enzymes are controlled at the transcriptional level by two transcription factors, Ino2 and Ino4, which form a heterodimer and require each other to function (Ambroziak and Henry, 1994; Schwank et al., 1995). We first analyzed the expression of the Ino2/4 target gene OPI3, which is involved in phosphatidycholine synthesis.
Figure 2. Proper ER membrane expansion requires UPR signaling. (A) Wild-type, hac1\(\Delta\), and ire1\(\Delta\) cells expressing Sec63-GFP (SSY139, SSY161, and SSY467) treated with DTT for 2 h. Expansion of the peripheral ER is impaired in UPR mutants, and aberrant cytoplasmic ER patches form at the cell periphery and adjacent to the nucleus (arrows). (B) Quantification of ER expansion from images obtained as in A. Statistical significance compared with the wild type at the same time point of \(P < 10^{-6}\) (\(* * *\)) is shown. Error bars indicate SEM. (C) Sec63-GFP Rm1-Cherry hac1\(\Delta\) cells (SSY429) untreated or treated with DTT for 2 h. The cytoplasmic ER patches in DTT-treated cells contain both Sec63 and Rm1. (D) Cytoplasmic ER patches induced by ER stress in hac1\(\Delta\) cells are tangles of smooth ER. Electron micrographs of hac1\(\Delta\) cells (SSY161) treated with DTT for 2 h. (top) Low magnification images of hac1\(\Delta\) cells with cytoplasmic ER patches (arrows), which are found either at the cell periphery or close to the nucleus. (bottom) Sequential 50-nm sections are shown at a higher magnification corresponding to the boxed area (top). The 0-nm image is the same as shown in the top panel. The ER tangle shown consists of numerous randomly arranged ribosome-free elements. N, nucleus; V, vacuole. Bars: (A and C) 2 \(\mu\)m; (D) 250 nm.

DTT treatment caused a substantial induction of Opi3 protein levels (Fig. 3, A and B) in line with the previously reported induction of OPI3 mRNA levels during the UPR (Travers et al., 2000). In contrast, the increase in Opi3 protein levels was strongly reduced in hac1 or ire1 mutants. The same pattern was observed for INO1, an Ino2/4 target gene involved in phosphatidylinositol synthesis (unpublished data). Thus, ER stress activates Ino2/4-dependent expression of lipid synthesis genes through UPR signaling. We then tested whether ER membrane expansion required the Ino2/4 complex. DTT-induced expansion was diminished in both ino2 and ino4 mutants, the peripheral ER retained its dotted appearance in midsections, and cytoplasmic ER extensions did not form (Fig. 3 C). In addition, aberrant ER patches were observed occasionally. Whether these are related to the patches seen in DTT-treated hac1 and ire1 mutants remains to be determined, but their appearance emphasized that proper ER membrane expansion fails in the absence of Ino2/4. Quantification confirmed this conclusion and additionally showed that untreated ino2 and ino4 mutants had a smaller ER than wild-type cells (Fig. 3 D), underscoring the role of Ino2/4 in ER size control.

If the Ino2/4 complex is important for ER membrane expansion because it regulates lipid biosynthesis, it may be possible to bypass the need for Ino2/4 by providing lipids in the growth medium. Therefore, we tested DTT-induced ER expansion of ino2 and ino4 mutants kept in YPD, a rich medium that includes lipids. Under this experimental regimen, ER expansion no longer required Ino2 or Ino4, and the defect in basal ER size was rescued (Fig. 3, E and F). Thus, unless lipids are supplied exogenously, full ER membrane expansion requires the Ino2/4 complex, likely because it is needed for the induction of lipid synthesis genes. In addition, these results help explain the membrane expansion defects in hac1 and ire1 mutants: without UPR signaling, the induction of lipid synthesis genes through activation of Ino2/4 is reduced, likely resulting in an insufficient supply of lipids to support full ER membrane expansion.

ER membrane expansion is driven by Ino2/4 activity

The identification of the Ino2/4 complex as an important player in regulating ER size enabled us to test whether activation of Ino2/4 is not only necessary but also sufficient for ER membrane expansion. When lipids are plentiful, the Ino2/4 complex is inhibited by Opi1, which binds to Ino2 (Fig. 4 A). When more lipids are needed, Opi1 dissociates from Ino2, allowing Ino2/4 to activate its target genes (Carman and Henry, 2007). To activate Ino2/4 constitutively, we either deleted OPT1 or deletedINO2 and provided mutant ino2(L119A) on a plasmid. The ino2(L119A) mutant protein cannot be bound by Opi1 and is always active (Heyken et al., 2005). Both approaches resulted in expansion of the peripheral ER (Fig. 4, B and C). The size of the nuclear envelope remained unchanged, as observed previously (O’Harra et al., 2006). ER expansion by deletion of OPT1 requires both INO2 and INO4, confirming that oip1 mutants have an expanded ER because the inhibition of Ino2/4 is relieved (Fig. S3). In addition, constitutive ER expansion in oip1 mutants was observed in both lipid-free medium and lipid-containing YPD medium (unpublished data). Like DTT-treated wild-type cells,
ER membrane expansion alleviates ER stress

During a normal UPR in wild-type cells, ER membrane expansion goes hand in hand with an increase in the levels of ER chaperones. Accordingly, the protein levels of the most abundant ER chaperone Kar2, the Kar2-related chaperone Lhs1, and the essential protein disulfide isomerase Pdi1 increased upon...
DTT treatment (Fig. 5, A and B). Strikingly, this increase was completely lacking in OP11-deficient or ino2(L119A)-expressing cells (Fig. 5, C and D). Thus, these cells have a dilute ER with basal chaperone levels but an expanded ER membrane and volume. This finding shows that activation of Ino2/4 uncouples membrane expansion from an increase in ER chaperone levels. In addition, ER membrane expansion by deletion of OP11 or expression of ino2(L119A) still occurred in hac1 mutants (Fig. 5, E and F), showing that membrane expansion can occur independently of UPR signaling.

The ability to experimentally uncouple ER membrane expansion and chaperone induction allowed us to address the physiological role of ER size regulation. We assessed the sensitivity of cells to ER stress by growing them on plates containing sub-lethal concentrations of tunicamycin for 2–3 d. For growth on plates, tunicamycin is preferable over DTT, which is quickly rendered inactive as a result of oxidation by air. To directly compare various strains with very different tunicamycin sensitivity, we chose a relatively low tunicamycin concentration that even allowed some growth of hac1 mutants. As expected, hac1 mutants, which cannot properly expand their ER membrane or raise their chaperone levels in response to ER stress, showed hypersensitivity to tunicamycin. opi1 mutants were indistinguishable from wild-type cells. Revealingly, hac1Δ opi1Δ cells tolerated ER stress much better than hac1Δ cells (Fig. 6 A). Similarly, overexpression of Ino2 and especially Opi1-insensitive ino2(L119A) enhanced ER stress tolerance of hac1 mutants (Fig. 6 B). These results indicate that enlarging the ER alleviates ER stress independently of an increase in chaperone levels.

If ER membrane expansion were indeed important for cells to withstand ER stress, deletion of INO2 should render them hypersensitive to ER stressors. Consistent with this prediction, ino2 mutants grew more slowly in the presence of tunicamycin than wild-type cells (Fig. 6 C). However, ino2 mutants showed an obvious growth defect only at relatively high tunicamycin concentrations. An explanation for this phenotype is provided by the observation that hac1Δ ino2Δ cells already grew slowly in the absence of tunicamycin (not depicted) and were completely unable to grow at low tunicamycin concentrations (Fig. 6 D). Thus, ino2 mutants can resist considerable ER stress with the help of the UPR but cannot overcome even mild stress when additionally deprived of HAC1. Furthermore, ino2 mutants grown for an extended period of time in lipid-free medium had elevated levels of ER chaperones even in the absence of external ER stressors (Fig. 6 E). Thus, cells compensate defective ER size control after deletion of INO2 by raising ER chaperone levels. If they are unable to do so, as in the case of hac1Δ ino2Δ cells, they become exquisitely sensitive to ER stress.

**ER membrane expansion alleviates stress as a result of increased ER size rather than altered ER shape**

Finally, to extend the morphological analysis of ER expansion, we sought to understand the transition from a tubular to a cisternal peripheral ER. We focused on the reticulons, which are the morphogenic proteins responsible for tubule formation. During expansion, Rtn1 retained its localization to the peripheral ER.
physiology of ER membrane expansion by dissociating it not only from an increase in ER chaperone levels but also from changes in ER shape.

hac1Δ opi1Δ cells, which have an expanded ER but no UPR, were more resistant to tunicamycin than hac1Δ cells, and this increased tunicamycin resistance was unaffected by Rtn1 overexpression (Fig. 7E). Therefore, under these conditions, ER size rather than shape was important for cells to overcome ER stress.

Discussion

Our results show that membrane expansion in response to ER stress involves the generation of large ER sheets, is restricted to the peripheral ER, and is impaired by disruption of the UPR. ER stress also induces lipid synthesis enzymes through the UPR and the Ino2/4 transcription factor complex. In the absence of Ino2/4, stress-induced membrane expansion is diminished, likely because of reduced lipid biosynthesis. Conversely, activation of Ino2/4 causes constitutive ER membrane expansion. Importantly, membrane expansion by activation of Ino2/4 occurs without a concomitant increase in ER chaperone levels and is independent of Hac1, showing that ER expansion and the UPR can be uncoupled. ER membrane expansion on its own alleviates ER stress, indicating that enlarging the ER is an integral part of an effective UPR. Furthermore, the predominantly unchanged
Cisternal expanded ER is converted to mainly tubular by over-expression of Rtn1, suggesting that ER shape is determined by reticulon capacity. However, changing the ratio of tubules to sheets does not affect the alleviation of ER stress by membrane expansion. These findings reveal an important role of ER size control in the maintenance of ER homeostasis.

The discovery that a larger ER alone alleviates ER stress argues that the role of membrane expansion during a normal UPR, when ER size and chaperone levels increase simultaneously, goes beyond merely providing space to accommodate newly synthesized folding machinery. One possibility is that a larger ER can tolerate more misfolded proteins before essential functions break down. Moreover, a larger ER could promote protein folding itself. During folding, proteins expose hydrophobic residues that are buried in their final conformations. This makes folding intermediates vulnerable to aggregation should they encounter one another. Increasing ER volume lowers the concentration of folding intermediates, which may give proteins more time to fold by avoiding aggregate formation. This idea is consistent with in vitro experiments, showing that the unassisted folding of proteins is more efficient at low concentrations because aggregation is reduced (Apetri and Horwich, 2008). A similar mechanism might apply for membrane-associated proteins, whose dilution caused by an increase in membrane area could help avoid detrimental interactions. Finally, membrane-associated processes that support protein folding or remove misfolded proteins, such as protein glycosylation or ERAD, could operate more efficiently when a larger membrane area is available. None of these possibilities are mutually exclusive.

The observation that the shape of the expanded ER can be shifted from cisternal to tubular by simple overexpression of a reticulon suggests that ER shape depends on the balance between the amount of ER membrane and the reticulons’ capacity to generate tubules. According to this view, the sheet morphology of the expanded ER during the UPR results from membrane growth without a corresponding increase in reticulon activity so that their tubulation capacity is exceeded and sheets form either by default or through the action of sheet-stabilizing proteins. A similar model invoking limiting reticulon capacity has been proposed recently to explain the formation of an appropriately sized nuclear envelope at the end of mitosis (Webster et al., 2009). We note that raising reticulon levels may only be a crude experimental substitute for how their capacity is normally regulated. Reticulon capacity could be controlled posttranslationally, perhaps by changes in oligomerization behavior (Shibata et al., 2008). The physiological significance of the transition from a tubular to a cisternal ER during the UPR remains an open question. It is not obvious whether the tubule to sheet conversion contributes to the up to fivefold increase in ER volume, and accurate measurements of the dimensions of sheets and tubules before and after ER stress as a result of increased ER size rather than altered ER shape.

Western blot of Cherry tag from Rtn1-Cherry-expressing wild-type cells treated with DTT for up to 4 h and from untreated Rtn1-Cherry-expressing wild-type, opi1Δ, and ino2Δ (L119A) cells (SSY421, SSY478, and SSY473). Pgtk1 served as a loading control. (B) Quantification of Western blots shown in A with values normalized to Pgtk1. (C) Overexpression of Rtn1 converts sheets (arrows) into tubules (arrowheads). Untreated wild-type and opi1Δ cells expressing dsRed-HDEL and Rtn1-GFP were used to mark the entire ER lumen and ER tubules, respectively, and carrying an empty vector or an expression plasmid encoding untagged Rtn1 (SSY523, SSY531, and SSY532). (D) ER expansion is unaffected by Rtn1 overexpression. Quantification of ER expansion from images of untreated wild-type, opi1Δ, and Rtn1-overexpressing opi1Δ cells (SSY523, SSY531, and SSY532). Statistical significance compared with wild-type cells of P ≤ 10−6 (***) is shown. Error bars indicate SEM. (E) Rtn1 overexpression does not affect sensitivity to ER stress. Tunicamycin sensitivity of wild-type, hac1Δ, and hac1Δ opi1Δ cells carrying empty vectors and hac1Δ opi1Δ cells carrying an expression plasmid encoding untagged Rtn1 (SSY510, SSY533, SSY535, and SSY536) as assessed by plating dilution series of cells onto solid SC medium (without uracil) containing 0.05 μg/ml tunicamycin. Series represent fivefold dilutions from one step to the next. Bar, 2 μm.
The appearance of tangles of smooth tubular ER in UPR-deficient cells exposed to ER stress is intriguing. These tangles could reflect disruption of ER structure by misfolded proteins. Alternatively, they could arise from the lack of a sheet-stabilizing protein. A candidate for such a protein is Sec61, which forms the translocation channel for protein import into the ER. Sec61 is also needed for the binding of ribosomes to the ER membrane, and ribosome binding has been suggested to stabilize ER sheets (Shibata et al., 2006; Puhka et al., 2007). In addition, Sec61 is induced by ER stress in a UPR-dependent manner (Travers et al., 2000). However, opi1 mutants and cells expressing ino2(L119A) have expanded rough ER sheets despite normal Sec61 protein levels (Fig. S4), indicating that Sec61 is not limiting for the generation of new ER sheets.

We have proposed previously that the Hac1 transcription factor coordinates the induction of chaperone genes and membrane biogenesis (Cox et al., 1997). The finding that Hac1-dependent Ino2/4 activity is needed for proper ER membrane expansion strengthens this model. In fact, the relationship between Hac1 and Ino2/4 is remarkably similar to that between the UPR and ERAD. The ERAD machinery operates at a basal level at all times but is activated during ER stress by Hac1-dependent induction of ERAD components. ERAD-deficient yeast are hypersensitive to ER stress and show constitutive activation of the UPR. Deletion of either IRE1 or an ERAD component is tolerated well, but combined deletion causes severe synthetic phenotypes (Travers et al., 2000). Likewise, Ino2/4 activity is stimulated during ER stress through Hac1, and ino2 mutants show increased sensitivity to tunicamycin, have elevated ER chaperone levels indicative of constitutive UPR signaling, and display synthetic sickness upon additional deletion of HAC1. Thus, Ino2/4 is another functional module that is recruited by Hac1 to help cells mount an effective UPR.

Nevertheless, many questions remain concerning the cascade of events that culminates in ER membrane expansion. First, it is unclear how UPR signaling activates Ino2/4-dependent transcription. A plausible mechanism is that Hac1 inhibits Op1, thereby derepressing Ino2/4 (Cox et al., 1997; Brickner and Walter, 2004). There are several ways in which Hac1 could inhibit Op1, e.g., by directly binding to Op1 to promote dissociation from Ino2 or by inducing the transcription of an Op1 inhibitor. Interestingly, Op1 translocates from the nucleus to the peripheral ER after inositol depletion (Loewen et al., 2004) but not after DTT treatment (unpublished data), indicating different mechanisms of Ino2/4 derepression. Second, we do not know which Ino2/4 target genes are critical for ER membrane expansion. Given that the requirement for Ino2/4 is bypassed when lipids are provided exogenously, lipid synthesis genes are probably a key. We tested several Ino2/4-regulated lipid synthesis genes, including INO1, PSD1, CHO2, and OPI3, but no single deletion phenocopied the ER expansion defect seen in ino2 and ino4 mutants (unpublished data). Third, it remains to be determined whether deletions of INO2 and INO4 are truly equivalent. It is generally accepted that neither transcription factor can function without the other, but some gene promoters appear to be bound by only one of the two proteins (Lee et al., 2002), and a previous study concluded that membrane proliferation after expression of the canine ribosome receptor in yeast required INO2 but not INO4 (Block-Alper et al., 2002).

Fourth, the residual expansion seen in hac1 and ire1 mutants and the residual increase in Opi3 and Ino1 protein levels in HAC1-deficient cells suggest that another signaling pathway exists in yeast that can sense ER stress and induce membrane expansion. This putative second pathway, which may correspond to the recently described super-UPR pathway (Leber et al., 2004), could also help explain why overexpression of ER transmembrane proteins can still trigger ER expansion in IRE1-deficient yeast (Menzel et al., 1997; Larson et al., 2002). Perhaps this alternative pathway is sufficient to allow long-term adaptation of ER size but is overwhelmed by the acute ER stress caused by DTT or tunicamycin. Finally, it is intriguing that the size of the nuclear envelope does not change during UPR. Unlike mammalian cells, yeast do not have nuclear lamins that could act as a scaffold to restrict nuclear size during ER membrane expansion. However, it has been found that at least part of the yeast nuclear envelope can resist expansion by an unknown mechanism (Campbell et al., 2006).

Similar to yeast, full ER expansion in mammals requires the Hac1 homologue XBP1, but some residual expansion still seems possible in its absence (Lee et al. 2005). This points to additional signaling pathways that can regulate ER size, and the ATF6 pathway has recently been suggested to play such a role (Bommiasamy et al., 2009). Also, similar to yeast, UPR signaling activates lipid biosynthesis in fibroblasts, and experimentally activating phosphatidylcholine synthesis leads to ER membrane expansion without an accompanying increase in ER chaperone levels (Sriburi et al., 2004, 2007). Although the expansion elicited by increased phosphatidylcholine production was modest compared with that achieved by expression of active XBP1, these results indicate that ER membrane expansion may be driven by lipid biosynthesis also in mammalian cells. Because there is no known mammalian master regulator of lipid biosynthesis analogous to the yeast Ino2/4 complex, it is difficult to test whether a more comprehensive activation of lipid biosynthesis would recapitulate UPR-mediated ER membrane expansion, as is the case in yeast. Nevertheless, it would be interesting to further explore the poorly understood regulation of mammalian lipid biosynthesis by the UPR (Acosta-Alvare et al., 2007).

In summary, ER stress induces membrane expansion through UPR-mediated activation of lipid biosynthesis, and the subsequent increase in ER size on its own is sufficient to alleviate stress. Thus, the UPR maintains ER homeostasis by two intimately connected but distinct mechanisms: by providing new ER-folding machinery and by providing more ER surface area and lumenal space.

Materials and methods

Antibodies and plasmids

The following primary antibodies were used: mouse anti-HA [Covance], mouse anti-Pgk1 [Invitrogen], rabbit anti-Kar2 [Walter laboratory, University of California, San Francisco, San Francisco, CA], sheep anti-Us1p [provided by C.J. Stirling, University of Manchester, Manchester, England, UK]; Tyson and Stirling, 2000], rabbit anti-Pdi1 [provided by J. Winther, Carlsberg Laboratory, Copenhagen, Denmark], rabbit anti-DrxRed [MBL International], and rabbit anti-Sec61 [Walter laboratory]. Secondary antibodies conjugated to alkaline phosphatase were obtained from Millipore. Centromeric expression plasmids pRS415-MET25-INO2

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and pRS415-MET25-ino2(L119A) (Heyken et al., 2005), which are derived from pRS415-MET25 (Mumberg et al., 1994), were provided by H.J. Schüller (Institut für Genetik und Funktionelle Genomforschung, Greifswald, Germany). The integrative expression plasmid YIpAC-dsRED-HDEL-NatMX (Madrid et al., 2006) was provided by K. Weiss (University of California, Berkeley, Berkeley, CA) and encodes dsRed-HDEL that is targeted to the ER lumen by a signal sequence and retained there by an HDEL sequence. To make the multicopy expression plasmid YEpAC1955::RTN1, which encodes Rtn1 controlled by its own promoter, the coding sequence of RTN1 plus 400 bps upstream of the start was amplified by PCR from chromosomal DNA and cloned into YEpAC1955::RTN1 (Gietz and Sugino, 1988) between the Spfl and KpnI sites.

Yeast strains

All strains used in this study, derived from a W303 wild-type strain (MATa; leu2-3,112; trp1-1; can1-100; ura3-1; ade2-1; his3-11,15), are listed in Table S1. Gene deletions and modifications were introduced by a PCR-based method (Longtine et al., 1998). Strains expressing dsRED-HDEL were created by transformation with EcoRv-linearized YIpAC-dsRED-HDEL-NatMX. Tagging the essential Sec63 protein with GFP did not affect cell viability, indicating that the Sec63-GFP fusion protein was functional.

Light microscopy

Strains without plasmids were grown at 30°C in YPD medium unless indicated otherwise. When cultures had reached early log phase (OD600 = 0.15 – 0.2), cells were washed with 1 vol of SC medium (containing yeast nitrogen base, amino acids, and 2% dextrose) and resuspended in the same volume of fresh SC. The only exception to this switch from lipid-containing YPD to lipid-free SC was the experiment shown in Fig. 3 E, in which cells were washed and resuspended in fresh YPD. Strains carrying plasmids were grown, washed, and resuspended in SC without leucine or uracil as appropriate. Cells were left untreated or treated with 8 mM DTT (Roche) or 1 µg/ml tunicamycin (EMD) for up to 150 min. Fig. S2 shows electron micrographs of untreated cells and DTT-treated wild-type cells. Fig. S3 shows Sec63-GFP expressing cells, treated with DTT or tunicamycin. Plates were incubated at 30°C for 2–3 d.

Online supplemental material

Fig. S1 shows Sec63-GFP expressing wild-type cells treated with DTT for up to 150 min. Fig. S2 shows electron micrographs of untreated and DTT-treated wild-type cells. Fig. S3 shows Sec63-GFP expressing opi1∆, opi1∆ ino2∆, and opi1∆ ino4∆ cells. Fig. S4 shows Sec63 protein levels of untreated and DTT-treated wild-type and hac1∆ cells and of untreated opi1∆ and ino2(L119A) cells. Table S1 lists all of the yeast strains used in this study. The MatLab script used for image analysis is also provided. Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.200907074/DC1.

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