Intracellular Retention of Newly Synthesized Insulin in Yeast Is Caused by Endoproteolytic Processing in the Golgi Complex

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Abstract. An insulin-containing fusion protein (ICFP, encoding the yeast prepro-α factor leader peptide fused via a lysine-arginine cleavage site to a single chain insulin) has been expressed in Saccharomyces cerevisiae where it is inefficiently secreted. Single gene disruptions have been identified that cause enhanced immunoreactive insulin secretion (eis). Five out of six eis mutants prove to be vacuolar protein sorting (vps)8, vps35, vps13, vps4, and vps36, which affect Golgi-endosome trafficking. Indeed, in wild-type yeast insulin is ultimately delivered to the vacuole, whereas vps mutants secrete primarily unprocessed ICFP. Disruption of KEX2, which blocks intracellular processing to insulin, quantitatively reroutes ICFP to the cell surface, whereas loss of the Vps10p sorting receptor is without effect. Secretion of unprocessed ICFP is not based on a dominant secretion signal in the α-leader peptide. Although insulin sorting mediated by Kex2p is saturable, Kex2p functions not as a sorting receptor but as a protease: replacement of Kex2p by truncated secretory Kex2p (which travels from Golgi to cell surface) still causes endoproteolytic processing and intracellular insulin retention. Endoproteolysis promotes a change in insulin’s biophysical properties. B5His residues normally participate in multimeric insulin packing; a point mutation at this position permits ICFP processing but causes the majority of processed insulin to be secreted. The data argue that multimeric assembly consequent to endoproteolytic maturation regulates insulin sorting in the secretory pathway.

Key words: multimerization • assembly • secretory protein • trafficking • sorting by retention

Introduction

We are interested in better understanding the principles governing insulin trafficking in the eukaryotic secretory pathway. In this study, we have employed heterologous protein expression in the yeast, Saccharomyces cerevisiae. One might imagine that a confounding factor in this system would be the absence of specialized processing enzymes, PC1 and PC2, that higher eukaryotes normally employ for endoproteolytic processing to insulin from its protein precursor (Steiner, 1998). However, this problem is circumvented by the synthesis of a chimeric protein in which the signal peptide and leader sequence of yeast prepro-α factor is fused (via a single dibasic site that is recognized and processed by the Kex2p endoprotease, which acts in the yeast Golgi complex [Fuller et al., 1989]) to a single chain insulin (comprised of insulin B and A chains that are contiguous, linked by a short noncleaved peptide). Upon endoproteolytic cleavage to liberate the α-leader peptide, a crystallizable insulin is produced with a structure essentially isomorphous with that of authentic two-chain insulin (Thim et al., 1986; Hua et al., 1998; Kjeldsen et al., 1998).

Despite this, various insulin and/or insulin-like growth factor–containing constructs have been found to be secreted inefficiently from yeast (Steube et al., 1991; Kjeldsen et al., 1997); these constructs are apparently subject to quality control in the secretory pathway. Indeed, the poor secretion of a variety of heterologous secretory proteins from S. cerevisiae is generally attributed to the recognition and retention of these proteins in the endoplasmic reticulum (ER)1 (Kowsalski et al., 1998), typically via binding of ER molecular chaperones (Elengaard et al., 1999). Accumulated proteins that do not satisfy quality control requirements for export are gen-

1Abbreviations used in this paper: CPY, carboxypeptidase Y; eis, enhanced immunoreactive insulin secretion; ER, endoplasmic reticulum; ERAD, ER-associated degradation; ICFP, insulin-containing fusion protein; vps, vacuolar protein sorting.
Plasmids and Molecular Biology

pAK696 is a 2-μ plasmid marked with URA3 in which the GAL1 promoter controls expression of ICFP inserted between the EcoRI and XbaI sites of pYES2 (Invitrogen). pM106 and pM162 are TRP1-marked centromeric plasmids (pRS314; Sikorski and Hieter, 1989) bearing ICFP driven by the GAL1 or GDP1 promoter, respectively. pM106 was created by excising an ~1-kb XbaI-SpeI fragment (containing GAL1-ICFP) from pAK696 and subcloning it into the SpeI site of pRS314. pM316 was created by excising an ~1-kb SalI-NotI fragment (containing GAL1-ICFP) from pM306 and subcloning it into the respective sites of pRS304 marked with URA3 (Sikorski and Hieter, 1989). pMIGLC was created by excising an ~0.6-kb BamHI-XbaI fragment from pAK666 and subcloning it into the respective sites of pUC19 and then excising an ~0.6-kb BamHI-Sall fragment from the resulting plasmid and subcloning it into the respective sites of pRSGLC, a TRP1-marked centromeric plasmid that employs the GDP1 promoter (from Dr. J. Warner, Albert Einstein College of Medicine) (Warner, 1991). pASZ-SL-GM was created by excising an ~1-kb XbaI fragment (containing GAL1-ICFP) from the commercial pSL1108 shuttle vector (Amersham Pharmacia Biotech) and subcloning it into pASZ11, an Ade2-marked centromeric plasmid (Stotz and Linder, 1990). pHSPI50 plasmid was constructed as follows. Single chain insulin was amplified from pAK696 by PCR using two primers: TATCCATGGTCGACAGCCCAGAGATCTGGTAAACACCAAC (which introduces a PstI site, underlined) and GTCCACTCTAGAGCTCGG (which introduces an XbaI site, underlined). After digestion with PstI and XbaI, the ~200-bp PCR product was subcloned into pSL1108 (Amersham Pharmacia Biotech) and then excised at PstI and Clal and subcloned again into the respective sites of pKH4536 (from Dr. M. Makarow, University of Helsinki, Helsinki, Finland) (Simonen et al., 1994). The resulting plasmid contains the HSP150 promoter and encodes the HSP150 signal and a portion of the leader peptide up to amino acid 63, linked via KR to single chain insulin; the 5’ Clal site immediately precedes the alcohol dehydrogenase terminator. An ~3-kb fragment containing all of these regions was excised by BamHI and finally cloned into the BamHI site of pRS315, a LEU2-marked centromeric plasmid (Sikorski and Hieter, 1989). pXX:HS3-Sty1, a plasmid for complete gene replacement of KEX2 with HIS3 (kex2α2::HIS3-5), and pAB23, a URA3-marked 2-μ plasmid in which the TDH3 promoter drives the overexpression of secretory Kex2p, were from Dr. R. Fuller (University of Michigan, Ann Arbor, MI). pLS1-10, a plasmid for replace- ment of the HindIII-XbaI region of fly was made by a 369-bp EcoRI-HindIII PCR-amplified fragment containing the relevant CAC(His)→ACC (Thr) mutation, which was used to replace the matching EcoRI-HindIII fragment of ICFP in pYES2.

Filter Blot Assays

To detect secretion of insulin or its precursor (defined as “immunoreactive insulin secretion”), colonies or patches were replica plated onto nitrocellulose filters placed on top of plates containing 2% galactose as the sole carbon source. After 24–40 h, cells were washed off the filter with PBS plus 0.1% Tween-20. The filter was then incubated with a 1:500 dilution of guinea pig antiinsulin serum (Linco Research) followed by peroxidase-conjugated goat anti-guinea pig secondary (1:2,500; Jackson ImmunoResearch Laboratories) and finally detected by ECL. To detect CPY secretion after overnight growth of the cells, the filter was incubated sequentially with a 1:4,000 dilution of mouse monoclonal anti-CPY (Molecular Probes) and a peroxidase-conjugated goat anti-mouse secondary antibody (1:3,000; Bio-Rad Laboratories).

Materials and Methods

Strains

The strains employed in this study are described in Table I. Strain LS145 (MATa, ks1, ura3-52, leu2-3,112, his3, trpl63, ade2, GAL+*) and LS141 that is MATa but otherwise isogenic to LS145 (from the lab of G. Fink, Whitehead Institute, Boston, MA). Unless stated otherwise, all strains used in this study are isogenic to LS145. To construct the pep4Δ strain called PA13 (Table I), a deletion construct marked with hisG-URA3-hisG (pAS173 cut with EcoRI and XhoI) was used for transformation (Chang and Fink, 1995). Pop out of the URA3 marker was obtained by selection on 5-FOA (Boeke et al., 1987). pep4Δ was confirmed phenotypically by loss of carboxypeptidase Y (CPY) processing to the mature form. A strain (LS145pM316) expressing ICFP from a single chromosomal locus was generated by transformation of LS145 with a yeast integration plasmid (pRS304) bearing GAL1-ICFP; the plasmid was linearized with Stul for integration at ura3. A kex2Δ strain was generated by transformation with a BamHI fragment from pKX:HS3-S3 (Redding et al., 1991). A vps3Δ LEU2 strain was obtained by transformation with pCRK3A (Rothman et al., 1990). A vps10 strain was obtained by transformation with XhoI and BamHI fragment of pEM10-103 (Marcusson et al., 1994).

Metabolic Labeling and Immunoprecipitation

Cells were grown to exponential phase in minimal medium supplemented with required amino acids but without methionine and cysteine using either 2% galactose or 2% glucose as appropriate and then sedimented at 3,000 g for 5 min and resuspended at 4 OD600/ml in the same medium plus 1 mg/ml BSA. Insulin contains six cysteine residues and the α-leader peptide contains one methionine. For pulse labeling, [35S]cysteine (NEC Life Science Products) was added at 50 μCi per ml for the times indicated. For chase, the cells were sedimented and resuspended in synthetic complete (SC) medium plus 10 mM methionine and cysteine. At various chase times, 1-ml aliquots were transferred to ice, and 10 mM sodium azide and a protease inhibitor cocktail (0.25 μg/ml aprotinin, 0.1 mM leupeptin, 10
**Table I. Strains Used in This Study**

<table>
<thead>
<tr>
<th>Strain</th>
<th>Description</th>
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<tr>
<td>L5145</td>
<td>MATa kss1 ura3-52 leu2-3, 112 his3 trp1^63 ade2 GAL+</td>
</tr>
<tr>
<td>L5145*</td>
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<td>DE3*</td>
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<tr>
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<td>DVI3H</td>
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<tr>
<td>TBY102^3</td>
<td>MATa ura3-52 leu2-3, 112 his3-200 trp1-200 lys2-801 suc2-29 sec18::1 GAL+</td>
</tr>
</tbody>
</table>

*As described in Materials and Methods.

^This study.

^Brigance et al., 2000.

μM pepstatin, 5 mM EDTA, 10 μM E64, 1 mM DFP, 0.02% BSA) were added immediately. Cells were then sedimented at 3,000 g for 5 min, and the supernate-containing secreted proteins were collected for further analysis. The cells were resuspended in 100 μl breaking buffer containing 6 M urea, 1% SDS, 1 mM EDTA, 50 mM Tris, pH 7.5. In Fig. 10 B, urea and SDS were replaced by 1% NP-40 in the breaking buffer. The cells were lysed by vortexing with glass beads and then boiling for 4 min (although in Fig. 10 B the boiling step was omitted). Samples were diluted 10-fold to a final concentration of 1% Triton X-100, 150 mM NaCl, 5 mM EDTA, 50 mM Tris, pH 7.5, debris was pelleted in a microcentrifuge, and immunoprecipitations were normalized to acid precipitable counts per minute. Samples were preclearsed with 20 μl Zysorbin for 30 min (Zymed Laboratories). Media and cell lysates were then immunoprecipitated with 10 μl guinea pig antiinsulin using 20 μl Zysorbin as a secondary immunoadsorbent. Immunoprecipitates were routinely digested with PNGase F (New England Biolabs, Inc.) and analyzed by tricine-urea–SDS-PAGE (Schagger and von Jagow, 1987), fluoroxygraphy or PhosphorImaging, and quantitation using ImageQuant software (Molecular Dynamics).

**Results**

**Insulin Undergoes Retention and Degradation in the Yeast Secretory Pathway**

The ICFP cDNA was constructed as a chimera encoding the signal and leader peptides of prepro-α factor fused via a single dibasic (KR) cleavage site to a polypeptide in which the B chain (first 29 residues) and A chain of insulin are made contiguous by an alanine-alanine-lysine linker (Fig. 1 A). (For simplicity in this paper, we refer to this single chain insulin simply as insulin or mature insulin in reference to its endoproteolytic liberation from the ICFP precursor.) When ICFP driven by a GAL1 promoter (Fig. 1 A) was expressed as a single copy integrated in the genome (Ylp), secretion of immunoreactive insulin (defined as secretion of protein blatable with antiinsulin antibody; described in Materials and Methods) was at the lower limits of detection when yeast were grown on galactose as the sole carbon source (Fig. 1 B). To examine further the expression of ICFP, cells were pulse labeled with [35S]cysteine for 1 min followed by immediate lysis, insulin im-

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munoprecipitation, deglycosylation of the α-leader with PNGase F, and analysis by tricine-urea–SDS-PAGE. (Note that all cysteine residues are conserved between ICFP and mature insulin.) In this case, an intracellular ICFP band migrating at $M_r \sim 14$ kD was observed (Fig. 2 A, left lane). In a parallel sample that was labeled for 5 min (Fig. 2 A, right lane), a second smaller band was produced that comigrated with an authentic insulin standard. These data suggested that ICFP may undergo relatively rapid proteolytic processing to mature insulin (described further below).

To understand the poor secretion of immunoreactive insulin, cells expressing ICFP on a centromeric plasmid were pulse labeled for 10 min and then either lysed or chased for 30 min. Although both ICFP and single chain insulin bands were detected intracellularly immediately after pulse labeling (Fig. 2 B, left lane), secretion of radiolabeled ICFP or processed insulin at 30 min was virtually undetectable (Fig. 2 B, right lane). Moreover, after a 30-min chase essentially no immunoprecipitable forms remained intracellularly (Fig. 2 B, middle lane), suggesting relatively rapid intracellular degradation.

**Gene Disruptions That Enhance Immunoreactive Insulin Secretion**

The foregoing results suggested some form of quality control of insulin secretion. To examine this further, a genetic approach was undertaken. Using yeast expressing ICFP from a single copy integrated in the genome (see Fig. 1 B) and a mutagenized genomic library containing random insertions of lacZ and LEU2 (Burns et al., 1994), 90,000 transformants were screened by the Western blot assay to yield nine eis mutants displaying enhanced immunoreactive insulin secretion (as described in Materials and Methods). The nine eis mutants corresponded to six distinct gene disruptions, five of which were identified as VPS35, VPS13, VPS4, VPS8, and VPS36. These genes have been shown previously to regulate trafficking in the Golgi→endosome→vacuole pathway (Stack and Emr, 1993; Bryant and Stevens, 1998). vps35 and vps8 appeared to produce the greatest enhancement of immunoreactive insulin secretion, vps4 and vps13 produced an intermediate enhancement, and vps36 produced only a slight increase (Fig. 3 A).

**Most ICFP Advances through the Golgi Complex into the Endosomal/Vacuolar System**

Even though enhanced immunoreactive insulin secretion was observed in several vps mutants acting in the distal secretory pathway, ER to Golgi transport is known to be a rate-limiting step in the trafficking of chimeras containing the prepro-α leader (Elliott et al., 1989). We therefore employed a standard assay (Finger et al., 1993; Loayza et al., 1998) to examine whether ICFP is subject to ERAD. The ICFP was expressed in a sec18 strain in which traffic to the Golgi complex is blocked at the nonpermissive temperature. After shifting to 37°C, cells were pulse labeled, lysed at varying times of chase ≤1.5 h, and analyzed by immunoprecipitation with antiinsulin, PNGase F digestion, and tricine-urea–SDS-PAGE. Strikingly, no endoproteolytic processing of ICFP was observed in the sec18 background (Fig. 4, A and B) in contrast to wild-type yeast (see Fig. 2 A). Furthermore, unlike what has been observed for ERAD substrates (Plemper and Wolf, 1999) the ICFP molecule was completely stable throughout the 90-min time course. Thus, no evidence was obtained for ERAD of the insulin-containing chimera.
We next tested directly whether immunoreactive insulin was degraded in the endosomal/vacuolar system by examining ICFP expression in a pep4Δ/H9004 strain (deficient for vacuolar protease activity) (Ammerer et al., 1986). In this case, fully processed intracellular insulin was stabilized dramatically, although no increase in insulin secretion was observed (Fig. 4 C). Indeed, insulin clearly accumulated in the vacuole (identified under Nomarski optics) as judged by indirect immunofluorescence in pep4Δ/H9004 cells (Fig. 5, top panels). Furthermore, in an eis5/vps4 pep4 double mutant (known to accumulate an enlarged prevacuolar compartment [Bryant and Stevens, 1998]) staining was concentrated in a bright spot next to the vacuole (Fig. 5, bottom panels), indicating accumulation in the prevacuolar compartment. These data prove that immunoreactive insulin is retained intracellularly by trafficking from the Golgi complex through the endosomal system to the vacuole.

Is Vps10p the Insulin Sorting Receptor?

Several groups have described previously the yeast Golgi complex as a regulatory site from which foreign, mutant, or even wild-type versions of certain yeast proteins may be recognized for delivery to the endosomal/vacuolar system (Hong et al., 1996; Luo and Chang, 1997; Roberg et al., 1997; Li et al., 1999; Liu and Culotta, 1999). In at least some of these cases, the recognition and/or targeting machinery appears to be saturable upon substrate overexpression (Hong et al., 1996). We tested whether insulin delivery to the endosomal/vacuolar system was saturable by expressing ICFP at low copy on a centromeric plasmid (CEN) or at high copy on a 2μH9262 plasmid. Indeed, higher immunoreactive insulin secretion was observed in a dosage-dependent manner (Fig. 1 C). Even greater secretion was observed when ICFP expression was driven by the strong constitutive GPD1 promoter (see below).

In addition to its receptor function in sorting of vacuolar proteases (Marcusson et al., 1994; Cooper and Stevens, 1996), Vps10p has been proposed to function as a Golgi-based sorting receptor for targeting misfolded secretory proteins to the endosomal system for vacuolar degradation (Hong et al., 1996; Durr et al., 1998; Holkeri and Makarow, 1998; Jorgensen et al., 1999). To test whether Vps10p plays a role in preventing immunoreactive insulin secretion, Western blot assays were used to compare the secretion of immunoreactive insulin and CPY in a vps10-null mutant versus the eis/vps mutants. As shown in the bottom panel of Fig. 3 B, all of the vps mutants exhibited
markedly enhanced immunoreactive CPY secretion, and vps10 arguably yielded the strongest CPY secretion phenotype. However, enhanced immunoreactive insulin secretion for vps10 was less than that seen with any other vps mutants tested (Fig. 3 B, top panel).

A quantitative analysis of immunoreactive insulin secretion from vps mutants was then performed by following [35S]cysteine-labeled protein. First, the effect of each of the five eis/vps mutations and vps10 was examined in strains where ICFP expression was driven by a GAL1 promoter on a centromeric plasmid. To improve intracellular recovery, a pep4 mutation was introduced into each strain. As shown in Fig. 6, each vps mutant tested showed an increase in secretion of protein immunoprecipitable with antiserum from the control strain secreted only ~8% of the total, the vps36, vps4, vps13, vps8, and vps35 strains secreted ~19, ~26, ~41, ~55, and ~76%, respectively. The vps10 strain showed the lowest level of enhancement over the control, secreting labeled insulin at a level approaching that of vps36 (~19%).

To quantify the saturability of endosome/vacuole delivery, identical pulse–chase experiments were performed in which ICFP expression was driven by the GPD1 promoter (which increases ICFP expression 5–10-fold in this strain background; data shown below). This maneuver resulted in an increase in the fractional secretion of protein immunoprecipitable with antiserum (~36%). In addition, an assortment of vps mutants showed a further increase in fractional secretion (vps4, ~47; vps1, ~53; vps8, ~57; vps13, ~64; vps35, ~79%). The one exception was vps10, which showed no further increase in fractional secretion (measured at ~27%). Together, these data are inconsistent with a central role of Vps10p as a sorting receptor for ICFP targeting from the Golgi complex to the endosomal system.

**Kex2p Is a Saturable Component Conferring Intracellular Retention of Insulin**

The observations of proteolytic maturation of ICFP to a form comigrating with authentic insulin (Fig. 2 A and Fig. 4 C) and blockade of this processing in a sec18 mutant (Fig. 4, A and B) are consistent with the notion that cleavage of ICFP in the Golgi complex is catalyzed by the yeast endoprotease, Kex2p (Fuller et al., 1989). Additionally, a striking finding in most of the vps mutants tested was that increased fractional secretion of protein immunoprecipitable with antiserum was comprised primarily of unprocessed ICFP. Although these findings are an expected side effect of perturbed Kex2p cycling between Golgi and endosome in vps mutants (Bryant and Stevens, 1998), we noted that increased ICFP secretion as a consequence of simple overexpression (in the absence of VPS mutations) was also enriched in unprocessed precursor (described further below). These findings raised the possibility that Kex2p itself might be a limiting factor required for insulin sorting.

Therefore, we reexamined ICFP expression (driven from a GAL1 promoter on a centromeric plasmid) in a kex2 pep4 strain. As demonstrated before, in the presence of wild-type levels of Kex2p, virtually all ICFP was processed to single chain insulin, and only a small fraction (~10%) was secreted (Fig. 7, left). However, in the absence of Kex2p not only was there no ICFP cleavage, but the protein was near quantitatively rerouted to the medium (Fig. 7, right).
Secretion of Unprocessed ICFP Does Not Involve a Dominant Secretion Signal in the ω-Leader Peptide

All evidence to date indicates that luminal protein targeting from the Golgi complex to the endosomal/vacuolar system requires specific signal recognition, and loss of this sorting results in protein secretion (Marcusson et al., 1994). Nevertheless, we wished to formally exclude the possibility that ICFP secretion might be mediated by a dominant secretion signal in the ω-leader peptide and that loss of this signal upon endoproteolytic cleavage might cause single chain insulin to be delivered to the vacuole. Because published evidence indicates that a fragment of the leader peptide from the secretory protein Hsp150 does not contain a dominant secretion signal (Holkeri and Makarow, 1998), we replaced the ω-leader with this fragment fused to single chain insulin (as described in Materials and Methods). This new insulin-containing chimera was quantitatively secreted (Fig. 8), indicating that secretion of the unprocessed ICFP does not require specific sorting information contained within the ω-leader peptide. Thus, intracellular retention of mature insulin cannot be explained by endoproteolytic removal of a dominant secretion signal.

Is Kex2p the Insulin Sorting Receptor?

Our screen for Eis genes did not yield any candidate sorting receptors for insulin because none encoded a protein bearing a luminal domain. However, like the Vps10p sorting receptor Kex2p follows a generally similar itinerary in which it is delivered to the endosomal system before recycling back to the Golgi complex (Brickner and Fuller, 1997). Moreover, it has been hypothesized recently in mammalian cells that proteases in the secretory pathway might have the potential to perform double duty as noncatalytic sorting receptors (Cool et al., 1997; Cool and Loh, 1998; Normant and Loh, 1998). Therefore, it was important to test a possible role for Kex2p as a sorting receptor for insulin.

Trafficking of Kex2p from the Golgi complex into the endosomal system requires specific information included in the COOH-terminal region of the protein: a COOH-terminal deletion removing the serine/threonine-rich domain, the transmembrane domain, and the cytosolic tail domain results in a truncated Kex2p, which is catalytically active but behaves as a secretory protein, traveling quantitatively from the Golgi to the cell surface (Brenner and Fuller, 1992). Consequently, this secretory Kex2p cannot function as a sorting receptor to convey ligands from the Golgi to the endosomal system. Therefore, we tested ICFP secretion in a kex2 pep4 strain expressing secretory Kex2p. Confirming previous work, secretory Kex2p was massively secreted (Fig. 9 A). Loss of Kex2p expression resulted in nearly quantitative ICFP secretion when its expression was driven from a GAl1 promoter (Fig. 9 B, middle two lanes). Importantly, however, expression of secretory Kex2p restored both endoproteolytic processing and intracellular retention of insulin (Fig. 9 B, right two lanes). When the GPD1 promoter was used to further overexpress ICFP in excess of the ability of secretory Kex2p to cleave it, the fractional secretion of protein immunoprecipitable with antiinsulin was markedly increased, and all of the increase was comprised of unprocessed precursor (Fig. 9, C compared with B). Moreover, endoproteolytic processing of ICFP (expressed from a GAl1 promoter) by secretory Kex2p also restored intracellular insulin retention in vps35 cells (Fig. 9 D). These findings confirm that (a) Kex2p is a specific saturable component responsible for intracellular insulin retention, and (b) Kex2p acts catalytically as an endoprotease rather than as a luminal sorting receptor for insulin trafficking.

Endoproteolytic Processing of ICFP Causes a Change in the Biophysical Properties of the Insulin Moiety

In mammalian β cells, endoproteolytic processing to generate insulin results in polymerization and intracellular retention (Kuliawat and Arvan, 1994; Kuliawat et al., 2000). To examine the biophysical state of insulin retained in yeast cells, we modified two assays developed originally for mammalian insulin. Multimeric insulin recovered from pancreatic β cells has been detected by rapid sedimentation upon sucrose velocity gradient centrifugation (Michael et al., 1987). Although this sedimentation in vitro is not particularly quantitative, it nevertheless represents a feature that is not shared by the insulin precursor (Kula-
A second approach detects multimeric assembly of mammalian insulin as measured by a loss of accessibility of its disulfide bonds to reduction by DTT under nondenaturing conditions (Huang and Arvan, 1995). Single chain insulin was examined from pep4Δ mutant cells expressing ICFP under control of the strong GPD1 promoter. Cells were labeled continuously with [35S]cysteine for 45 or 60 min; under these conditions, significant amounts of labeled insulin and ICFP precursor coexist. First, we found, using a simplified sucrose velocity gradient (as described in Materials and Methods), that upon processing to insulin about half of the mature molecules exhibited very rapid sedimentation, which was not observed for the ICFP itself (Fig. 10 A). Using a second assay, in the experiment shown in Fig. 10 B insulin immunoprecipitates were resuspended and divided into various aliquots. As a control, one aliquot was denatured in conventional boiling SDS-containing gel sample buffer in the presence of 20 mM DTT and then subsequently alkylated with iodoacetamide. Denaturation allowed DTT to reduce all disulfide bonds in both the unprocessed precursor and mature insulin, causing a marked upward mobility shift for both bands (Fig. 10 B, lane 1). For comparison, a second aliquot was similarly denatured but without reduction, being alkylated only (Fig. 10 B, lane 2). A third aliquot was tested for disulfide accessibility to 20 mM DTT under nondenaturing conditions and then finally alkylated before SDS-PAGE. As shown, mature insulin was extremely resistant to reduction under nondenaturing conditions (equals 5% reduced), reflecting an inaccessibility of disulfide bonds in its tertiary/quaternary structure, whereas approximately half of the insulin precursor was reduced upon DTT exposure in the identical sample (Fig. 10 B, lane 3). Thus, by two independent assays endoproteolytic processing was associated with a significant change in the biophysical properties of insulin.

The foregoing data raised the question of whether sorting consequent to insulin precursor processing reflects any established features of insulin assembly. It is known that some key residues affecting insulin multimeric interactions lie along the proximal (that is NH2-terminal) portion of the insulin B chain. The B1–B8 sequence is notable for exhibiting great conformational flexibility, interconverting in a dynamic equilibrium between extended and more compact (α-helical) configurations (Renscheidt et al., 1984; Wollmer et al., 1989; Kadima et al., 1992); in particular, the B5 histidine residues in the insulin hexamer play not only an important local role in conformation of the proximal B chain (Bentley et al., 1976; Kim and Shields, 1992) but also make structural contact in neighboring hexamers shown in B, the enzyme digestion was performed in the complete absence of a reducing agent. The positions of reduced ICFP and insulin standards (ICFP-R and INS-R) and oxidized standards (ICFP-O and INS-O) are shown to the left of the panel.
(Baker et al., 1988). Recently, it has been suggested that mutation of BSH can cause structural perturbations in adjacent hexamers, which may affect insulin packing in vivo (Tang et al., 1999). Interestingly, examination of an H90T-ICFP mutant in which the insulin BSH residue is replaced by B5T showed that the majority of processed mutant insulin was secreted rather than being retained intracellularly (Fig. 11 A, open arrows).

The B5T mutation creates a potential NH₂-linked glycosylation site within insulin in addition to the NH₂-linked glycosylation sites that are actually used within the α-leader peptide of ICFP. Notably, however, our studies showed clearly that the BST insulin is not glycosylated as demonstrated by an identical SDS-PAGE mobility to that of nonmutagenized insulin and a lack of effect of PNGase F digestion (Fig. 11 A). Moreover, whereas the nonmutagenized insulin exhibits multimeric assembly as judged by sucrose velocity gradient centrifugation in vitro (Fig. 10 A and Fig. 11 B), the BST mutant insulin was unable to sediment from the upper to the lower half of a sucrose velocity gradient (Fig. 11 B), supporting the notion that perturbation of insulin targeting in the secretory pathway is related to structural effects of the threonine mutation itself. Together, these data suggest that intracellular retention of insulin in yeast cells is dependent on insulin structural maturation, which is remarkably similar to recent conclusions about intracellular insulin retention in the regulated secretory pathway of mammalian cells (Kuliawat and Arvan, 1994; Huang and Arvan, 1995; Kuliawat et al., 2000).

Discussion

It has been reported that improved secretion efficiency of some insulin-containing chimeras can be achieved by replacing an α-leader peptide with synthetic leader sequences that alter ER residence time, suggesting that ER quality control is an important feature of insulin secretion in yeast (Kjeldsen et al., 1997). However, we have discovered several additional features of the system not typical of ER quality control. First, using the ICFP construct described in Fig. 1 A, simple overexpression caused significantly enhanced secretion of immunoreactive insulin (Fig. 1 C), suggesting that one or more saturable components in the yeast secretory pathway limits insulin secretion. Second, newly-synthesized ICFP, containing a single dibasic cleavage site, was rapidly processed to a band comigrating with authentic insulin (Fig. 2 A) in a manner dependent on arrival in the Golgi complex (Fig. 4 A) and Kex2p activity (Fig. 7). Third, a direct assay for ERAD (in a sec18 mutant) showed ICFP to be completely stable over a 90-min time course (Fig. 4, A and B), suggesting that it is not a ready substrate for typical ubiquitin-mediated proteasome-dependent proteolysis (Plemper and Wolf, 1999). Fourth, in the absence of Pep4p (vacuolar proteinase A) insulin accumulates not in the ER but in the vacuole (Fig. 4 C) where it is delivered via the endosomal system (Fig. 5). These novel features of ICFP and insulin sorting are summarized in Fig. 12.

The targeting of insulin expressed from ICFP is decided upon in the Golgi complex (Fig. 12). Initially we thought that vacuolar targeting of insulin might be mediated by a Golgi-based quality control system like that responsible for the degradation of a mutant lambda repressor protein fused to invertase (Hong et al., 1996) and a variety of other proteins in the secretory pathway (Chang and Fink, 1995; Luo and Chang, 1997; Beck et al., 1999; Li et al., 1999). Certainly, routing of insulin to the vacuole via the endosomal system provides a rationale for why five out of six eis gene disruptions identified in our genetic screen are vps mutants (Fig. 3 A) that impair post-Golgi trafficking of CPY (Fig. 3 B) and other vacuole-bound proteins. Nevertheless, there appear to be significant differences in the molecular mechanisms accounting for inefficient secretion of ICFP versus that of other proteins subject to Golgi quality control. First, the vacuolar delivery of the lambda repressor-containing fusion protein occurs primarily when the sequence is mutated to induce misfolding. By contrast, single chain insulin folds similarly to authentic insulin (Thim et al., 1986; Hua et al., 1998; Kjeldsen et al., 1998), and no mutations inducing misfolding have been introduced. Furthermore, all three insulin disulfide bonds appear intact (data not shown), and the band comigrates by nonreducing SDS-PAGE with authentic insulin. Indeed, our current evidence suggest that the unsecreted single chain insulin takes on quaternary structural features (Fig. 10) observed for authentic insulin, which are dependent on a native tertiary structure (Kuliawat and Arvan, 1994; Huang and Arvan, 1995). Second, although Vps10p has been proposed to operate as a quality control receptor in the Golgi complex for certain substrates (Hong et al., 1996; Durr et al., 1998; Holkeri and Makarow, 1998; Jorgensen et al., 1999), vps10 cells did not show significantly increased secretion of ICFP (Fig. 3 B and Fig. 6). Thus, a Vps10p-mediated mechanism does not appear to contribute significantly to the sorting of insulin in the secretory pathway.

A novel aspect of the present studies was our discovery that deletion of KEX2 causes quantitative secretion of
intracellular retention of the newly synthesized protein (Kuliawat et al., 2000). This may occur because homomultimerization limits the ability of insulin to enter post-Golgi transport intermediates leading ultimately to the cell surface (Kuliawat and Arvan, 1992). It seems quite possible that related phenomena could account for insulin trafficking in the secretory pathway of yeast cells. Our evidence supports the idea that there is a change in biophysical properties upon endoproteolytic conversion to the mature insulin species (Fig. 10). Intriguingly, recent proposals for mechanisms that alter post-Golgi targeting of other proteins include homomultimerization facilitated by endoproteolytic cleavage at dibasic sites (Silletti et al., 2000) and ordered luminal protein aggregation (Wolins et al., 1997). Indeed, we find that upon endoproteolytic processing, a BST mutant insulin is no longer efficiently retained, the majority being secreted instead (Fig. 11 A), and this is correlated with an inability of the protein to form a stable multimeric assembly, as measured by sucrose gradient centrifugation (Fig. 11 B). In conclusion, although the issue remains unresolved of whether a Golgi/post-Golgi membrane-associated receptor plays any role in intracellular insulin targeting, it would appear that precursor endoproteolysis unmasks information required for sorting by retention for the vast majority of, if not all, insulin molecules in the eukaryotic secretory pathway.

ICFP (Fig. 7). We considered initially the possibility, albeit unprecedented, that the α-leader peptide might contain a dominant secretion signal, the loss of which would result in intracellular insulin retention. This possibility was excluded from the results of experiments in which the α-leader was replaced with a fragment of another leader peptide known to lack a dominant secretion signal (Fig. 8). These findings led us to consider a second hypothesis that Kex2p itself might serve as a sorting receptor that causes intracellular insulin retention. However, in either a kex2-null strain (Fig. 9 B) or a vps35 strain (Fig. 9 D), expression of secretory Kex2p is sufficient to cause intracellular insulin retention even though secretory Kex2p itself is delivered from the Golgi complex to the cell surface (Fig 9 A). Moreover, the degree to which secretory Kex2p (or wild-type Kex2p) conferred intracellular retention was limited to the extent that the precursor protein was processed to mature insulin (Fig. 9 C). This indicates that Kex2p enzymatic activity in the Golgi complex is a saturable limiting component in the molecular sorting of the insulin precursor (Fig. 12). Moreover, when ICFP is mutated to make substitutions at the dibasic cleavage site, secretion of immunoreactive insulin (precursor) is also increased (our unpublished data). Altogether, our data indicate that it is endoproteolysis itself that prevents rapid secretion of the insulin precursor (Fig. 12).

Although our data do not formally exclude the possibility of sorting receptors for processed insulin, no genes encoding proteins with a luminal domain (that could serve as potential sorting receptors) were identified in our genetic screen. The fact that kex2 was not isolated in the eis screen may be accounted for by the fact that in our strain background, kex2 mutant cells seem to grow more slowly, and the filter blot assay used for screening is indirectly dependent on the size of the colonies secreting ICFP. Likewise, other gene disruptions that adversely affect cell growth would also be overlooked in the screen, and this conceivably could contribute to the fact that we did not recover a potential sorting receptor.

We have proposed in mammalian-regulated secretory cells that endoproteolytic conversion to insulin facilitates intracellular trafficking. To test this hypothesis, we used an insulin analog that “mimics” the behavior of the precursor insulin, with the α-leader peptide containing two cysteine residues (Fig. 12). In this manner, we have not analyzed the fate of the α-leader peptide after cleavage from the insulin moiety.

References


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