Intracellular Degradation of Unassembled Asialoglycoprotein Receptor Subunits: a Pre-Golgi, Nonlysosomal Endoproteolytic Cleavage

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Abstract. The human asialoglycoprotein receptor is a heterooligomer of the two homologous subunits H1 and H2. As occurs for other oligomeric receptors, not all of the newly made subunits are assembled in the RER into oligomers and some of each chain is degraded. We studied the degradation of the unassembled H2 subunit in fibroblasts that only express H2 (45,000 mol wt) and degrade all of it. After a 30 min lag, H2 is degraded with a half-life of 30 min. We identified a 35-kD intermediate in H2 degradation; it is the COOH-terminal, exoplasmic domain of H2. After a 90-min chase, all remaining intact H2 and the 35-kD fragment were endoglycosidase H sensitive, suggesting that the cleavage generating the 35-kD intermediate occurs without translocation to the medial Golgi compartment. Treatment of cells with leupeptin, chloroquine, or NH4Cl did not affect H2 degradation. Monensin slowed but did not block degradation. Incubation at 18-20°C slowed the degradation dramatically and caused an increase in intracellular H2, suggesting that a membrane trafficking event occurs before H2 is degraded. Immunofluorescence microscopy of cells with or without an 18°C preincubation showed a colocalization of H2 with the ER and not with the Golgi complex. We conclude that H2 is not degraded in lysosomes and never reaches the medial Golgi compartment in an intact form, but rather degradation is initiated in a pre-Golgi compartment, possibly part of the ER. The 35-kD fragment of H2 may define an initial proteolytic cleavage in the ER.

Many cell surface receptors and secreted proteins are composed of multiple subunits. The assembly of the individually synthesized subunits into complexes is not a perfectly efficient process; in many instances, a fraction of the subunits made is never assembled or routed to the cell surface (e.g., Dulis et al., 1982; Merlie et al., 1982; Plant and Grieninger, 1986; Corless et al., 1987; Minami et al., 1987). The human hepatic asialoglycoprotein (ASGP) receptor is an attractive system in which to study this process. This receptor is composed of two strongly homologous subunits, H1 and H2. Studies using chemical cross-linking and antibody-induced degradation showed that, in the human hepatoma cell line HepG2, the receptor is a heterooligomer (Bischoff et al., 1988). The functional complex is at least a trimer, containing at least one H2 and two (or three) H1 polypeptides. H1 is synthesized as a 40-kD core-glycosylated precursor, oriented in the ER membrane with its NH2 terminus in the cytoplasm and its COOH terminus in the ER lumen. During transit through the Golgi complex, the modification of its two N-linked oligosaccharide chains causes a size increase to ~46 kD. Similarly, H2 is synthesized as a 43-kD transmembrane protein with three high-mannose oligosaccharide chains and is then modified in the Golgi complex to the mature form of ~50 kD. In HepG2 cells, about one third of newly made H1 and H2 never acquires complex oligosaccharides and is degraded (Bischoff and Lodish, 1987).

The necessity for both subunits for normal receptor function was demonstrated by the expression of cDNA clones in hepatoma or fibroblast cells. For both the rat (McPhaul and Berg, 1986) and human (Shia and Lodish, 1989) ASGP receptors, expression of both subunits is needed for high-affinity binding of proteins with triantennary sugars. Moreover, the two subunits of the human receptor have different intracellular fates when expressed separately. When H1 is expressed alone in 3T3 fibroblasts (which normally do not make the receptor), most of the H1 forms oligomers containing at least three subunits, is processed, and is targeted to the cell surface. However, it cannot bind a normal ligand, asialoorosomucoid (Shia and Lodish, 1989). Cells expressing the homologous rat protein, RHL-1, can bind and endocytose a protein containing many chemically attached galactose residues but not asialoorosomucoid (Braiterman et al., 1989). In contrast, H2 expressed alone in 3T3 cells, although it is inserted normally into the RER and receives high-mannose oligosaccharides, fails to be processed to its mature form, and disappears from the cells (Shia and Lodish, 1989). The cell
minate the pulse, we removed the radioactive medium and rinsed the
Metabolic Labeling
DME devoid of cysteine but supplemented with 10% dialyzed calf serum
least 2 d before use. These were trypsinized and split 1:10 to 1:60 into 60-mm tissue culture dishes at
yard et al., 1982), kindly provided by Dr. Daniel Louvard of the Pasteur
Cell Culture
endo D was from Boehringer Mannheim Biochemicals (Indianapolis, IN);
falce Labs (Rockford, IL); calf serum and DME were from Gibeo Laboratories (Grand
Materials
Materials were obtained from the following sources: l-[35S]cysteine (specific radioactive of >800 Ci/mmol) was from New England Nuclear (Boston, MA), Amersham Corp. (Arlington Heights, IL), or ICN Radiochemicals (Irvine, CA); 3H-methylated protein standards were from Amersham Corp.; protein A-agarose was from Bethesda Research Laboratories (Gaithersburg, MD); leupeptin was from Chemicon (El Segundo, CA); chloroquine and monensin were from Sigma Chemical Co. (St. Louis, MO); endoglycosidase (endo) H was from Genzyme Corp. (Boston, MA); endo D was from Boehringer Mannheim Biochemicals (Indianapolis, IN); bicinchoninic acid protein assay reagent was from Pierce Chemical Co. (Rockford, IL); calf serum and DME were from Gibco Laboratories (Grand Island, NY); tissue culture dishes were from Costar (Cambridge, MA) and Falcon Labs (Oxnard, CA).
Antibodies
We used several antibodies specific for the ASGP receptor subunits: an
endo H Digestion
After immunoadsorption, antigen–antibody complexes were eluted from
Immunofluorescence Microscopy
Cells grown on coverslips were fixed and permeabilized by sequential incubation with methanol and acetone for 5 min each at −20°C. They were then rinsed with PBS containing 2% BSA (PBS-BSA) three times and subjected to the following sequential incubations: (e) 30 min with normal goat IgG; (f) 60 min with rabbit anti-H2 COOH terminus IgG affinity purified on a column of protein A-sepharose; (g) three rinses with PBS-BSA; (d) 30 min with 5 μg/ml TRITC-conjugated goat anti-rabbit IgG; (e) two rinses with PBS-BSA; (j) 60 min with 100 μg/ml unlabeled goat anti-rabbit IgG; (g) three rinses with PBS-BSA; (h) 60 min with rabbit anti–RER or rabbit anti-Golgi serum; (i) three rinses with PBS-BSA; (b) 30 min with 5 μg/ml FITC-goat anti-rabbit IgG; and (k) three rinses with PBS.
Cells were viewed on a fluorescence microscope (Carl Zeiss, Inc., Thornwood, NY) with FITC and TRITC filters and photographed at identical exposure times between samples to be able to compare signal intensities. Controls, in which any of the primary antibodies were omitted or replaced with preimmune IgG, showed no detectable signal with the corresponding filter.
Materials and Methods
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Figure 1. H2 is degraded and not secreted. 2-18 cells were incubated with [35S]cysteine for 30 min then washed and incubated with nonradioactive medium for 0, 1, or 2 h. The experiment was done in duplicate. Detergent extracts of the cells (C; lanes 1-3, 5, 7, and 9) and medium (M; lanes 4, 6, 8, and 10) were immunoprecipitated with a mixture of antisera directed against the NH2 and COOH termini of H2. The immunoadsorbed material was electrophoresed using SDS-PAGE, fluorographed, and subjected to autoradiography. The open and closed arrowheads at the left indicate the intact H2 polypeptide and a 35-kD putative degradation product, respectively. The protein standards at the right are in kilodaltons.

Results

H2 Is Degraded after a Small Decrease in Size

mRNAs encoding two variants of H2, H2a and H2b, are transcribed in HepG2 cells (Spiess and Lodish, 1985). Compared with H2b, H2a contains a five-amino acid insert after amino acid number 81, which is located in the exoplasmic domain just beyond the membrane-spanning region. One difference between the variants is that, when expressed alone in 3T3 fibroblasts, a portion of H2b reaches the cell surface (Lederkremer, G., and H. E Lodish, unpublished results), while none of H2a does (Shia and Lodish, 1989). In 2-18 cells, a line of retrovirus-infected 3T3 fibroblasts expressing only H2a, the H2 polypeptide is synthesized as the usual 43-kD core-glycosylated precursor but then disappears rapidly and completely from the cells (Shia and Lodish, 1989). We used 2-18 cells to study H2 degradation in the complete absence of surface expression.

We wanted first to establish whether the disappearance of radioactively labeled H2 after a pulse labeling of 2-18 cells was due to complete intracellular proteolysis or to partial cleavage of the polypeptide followed by fragment release into the medium; the latter occurs to some viral integral membrane glycoproteins such as the vesicular stomatitis virus G protein (Chen and Huang, 1986). To test this possibility, we pulse labeled 2-18 cells, chased for 1 or 2 h, and immunoadsorbed detergent extracts of the cells and the medium with a mixture of antipeptide antisera directed against epitopes of the cytoplasmic (NH2-terminal) and exoplasmic (COOH-terminal) domains of H2 (Bischoff and Lodish, 1987; Bischoff et al., 1988) (Fig. 1). Because we detected no immunoreactive material in the medium, we conclude that H2 is indeed intracellularly degraded and not simply cleaved once and secreted.

The major H2 polypeptide (Fig. 1, open arrowhead) migrated slightly faster after 1 h of chase than did the pulse-labeled species. This ~1.3-kD decrease in size is due to modification of the oligosaccharide, not of the peptide backbone, because after endo H digestion to remove the oligosaccharides the pulse-labeled and chased samples had the same mobility (data not shown). A faint band of ~35 kD (solid arrowhead) was seen in the chase samples; as noted below, we suspect this is an intermediate in H2 degradation. This polypeptide was never detected in 3T3 cells infected with vector alone (not shown).

Time Course of H2 Degradation

The time course of degradation of newly synthesized H2 is shown in Fig. 2. In this and similar experiments, we observed that H2 was relatively stable for 30–60 min and then degraded rapidly with a half-life of 30 min, as previously reported by Shia and Lodish (1989). The 35-kD polypeptide was detected initially at 15 min of chase and was present during the time in which H2 was disappearing most rapidly; it was undetectable by 3 h of chase. The time course of the appearance and disappearance of the 35-kD species is consistent with a role as an intermediate in the degradation of H2.

The 35-kD Polypeptide Contains the COOH Terminus of H2 and Is Formed in the ER

To characterize further this putative degradation intermediate, we tested the reactivity of the 35-kD polypeptide with
of three oligosaccharide chains. In addition, neither the intact H2 nor the 35-kD fragment was sensitive to endo D (data not shown); this enzyme hydrolyses high-mannose type oligosaccharides that have an unsubstituted α-mannose residue that is in an α1,3 linkage to the trisaccharide core. This structure is typically the product of Golgi α-mannosidase I, the first enzyme to act on glycoproteins that enter the cis-Golgi compartment. The endo H sensitivity of the two H2 species is important for two reasons: it indicates that H2 probably does not enter the Golgi complex before being degraded and that the proteolytic event generating the 35-kD polypeptide also takes place in a pre-Golgi compartment.

Because the antisera that recognized the 35-kD species was raised against the 12 amino acids at the COOH terminus (exoplasmic domain) of H2, we can use the estimated sizes of the proteins in Fig. 3 to determine the site of cleavage that would generate the 35-kD product from H2. Using the estimated sizes of either the glycosylated or deglycosylated proteins, the predicted cleavage would be at amino acids 72–84. H2 spans the membrane between amino acids 59 and 78 (Spiess and Lodish, 1985), so the cleavage is near the junction between the membrane-spanning and exoplasmic domains. Preliminary fractionation data suggest that the 35-kD polypeptide is not tightly associated with membranes (our unpublished observation), consistent with this localization of cleavage. We tried to find the remaining portion of H2, predicted to be ~8–10 kD, using a gel system that can resolve proteins as small as 1 kD but we were unable to detect any smaller band immunoreactive with the anti-NH2 terminus antiserum (data not shown). Either the NH2-terminal fragment is degraded more rapidly than the 35-kD intermediate or, after the initial cleavage, it loses the epitope recognized by the anti-NH2 terminus antiserum.

Interfering with Lysosomal Activity Does Not Affect H2 Degradation

The lag in H2 degradation suggested that H2 travels from the RER to its degradation site and that this transfer requires time. One candidate for the site of degradation is the lysosome. To find out if H2 is degraded in lysosomes in these cells, we tested the effects on H2 degradation of several compounds known to interfere with lysosomal function. Incubation of cells with high concentrations of thiol protease inhibitors inhibits degradation of proteins that are degraded in lysosomes (Ascoli, 1979; Harford et al., 1983; Schwartz et al., 1986; Lippincott-Schwartz et al., 1988); this effect is presumed to be due to fluid-phase endocytosis of the inhibitors followed by delivery to the lysosomes. We incubated cells with the protease inhibitor leupeptin (400 μg/ml) for 30 min before pulsing them with [35S]cysteine and included leupeptin in the pulse, wash, and chase media (Fig. 4).
Figure 5. Effect of monensin, chloroquine, or \(\text{NH}_4\text{Cl}\) on H2 degradation. 2-18 cells were pulse labeled with \(^{35}\text{S}\) cysteine for 20 min then washed and chased for 0, 2, 4, and 6 h in medium with no addition or containing monensin (100 \(\mu\text{M}\)), chloroquine (800 \(\mu\text{M}\)), or \(\text{NH}_4\text{Cl}\) (20 mM) as indicated. Solubilized proteins were immunoadsorbed with anti-COOH terminus serum and processed as usual. The arrowheads at right indicate the migration of protein standards, given in kilodaltons. Intact H2 and the 35-kD fragment are indicated on the left by open and closed arrowheads, respectively.

faster migrating polypeptides seen in the pulse-labeled samples correspond to different numbers of N-linked oligosaccharides on H2 and on the proteolytic fragment because endo H digestion reduced each pair to a single band (data not shown).

If the lysosomes were the site of H2 degradation, we would expect that degradation would be slowed by treatment with leupeptin; however, it was unaffected, as H2 decayed with approximately the same kinetics with and without leupeptin. This experiment must be considered in the light of results by Schwartz et al. (1986): although a 1-h preincubation with 500 \(\mu\text{g}\) leupeptin/ml inhibited the degradation of internalized \(^{125}\text{I}\)-asialoorosomucoid \(\approx 80\%\), the protease inhibitor had no effect on the antibody-induced degradation of the ASGP receptor. This assay measures the degradation pathway taken by cell surface receptors after they have been induced to internalize after exposure to anti-receptor antibodies. From this and other results, including evidence that the weak base primaquine could inhibit degradation of the receptor, Schwartz et al. concluded that these internalized receptors are not degraded in the lysosomes but rather in an endosomal compartment.

To determine if H2 were targeted directly to such a degradative endosomal compartment in 2-18 cells, we tested the effects of compounds that interfere with endosome and lysosome function, at concentrations greater than the concentrations that are maximally effective at neutralizing endosomes in 3T3 fibroblasts (Maxfield, 1982). Neither chloroquine nor \(\text{NH}_4\text{Cl}\), weak bases that are thought to inhibit lysosomal and endosomal enzyme activity by raising the intraluminal pH, inhibited the breakdown of H2 nor did they affect the appearance or disappearance of the 35-kD fragment (Fig. 5). Monensin, a proton ionophore with multiple effects on cells including the neutralization of acidic compartments (Tartakoff, 1982), had very little effect on H2 degradation even at a concentration of 100 \(\mu\text{M}\), an order of magnitude higher than that used by Lippincott-Schwartz et al. (7 \(\mu\text{M}\)), which had no effect on degradation of T cell receptor subunits.

In a more detailed study of the time course of degradation, monensin slowed the decay of H2 by \(\approx 30-60\) min relative to untreated cells, and H2 became almost undetectable between 4 and 6 h of chase (see Fig. 5). Monensin also increased the accumulation of the 35-kD fragment (Fig. 5). Monensin at 100 \(\mu\text{M}\) concentration interferes not only with lysosomes; in 1-7 cells, which are 3T3 fibroblasts that synthesize HI and express it at the cell surface (Shia and Lodish, 1989), 100 \(\mu\text{M}\) monensin blocked conversion of H1 and H2 oligosaccharides to the complex form (data not shown), suggesting that Golgi function or transport from the ER to the Golgi complex was affected, consistent with effects seen in other systems (Tartakoff, 1983). Taken together, the pharmacological data suggests that H2 in 2-18 cells is not degraded in lysosomes or endosomes.

H2 Degrades Slowly at 18-20°C

Incubation of cells at \(\approx 20^\circ\text{C}\) slows some processes that depend on lipid bilayer fluidity, such as membrane fission and fusion (Dunn et al., 1980; Marsh et al., 1983; Saraste et al., 1986). Lippincott-Schwartz et al. found that incubation at 18°C blocks degradation of T cell receptor \(\alpha\) and \(\beta\) chains. To determine whether H2 degradation shows a similar behavior, we incubated 2-18 and 1-7-1 cells at 18-20°C for both a pulse and chase period. The 1-7-1 cells were included as a measure of how the low temperature was affecting the movement of H2 from the RER to the Golgi complex, as monitored by the modification of H2 oligosaccharides to the complex form. Some H2 was also degraded in the 1-7-1 cells, but the data are presented as a percentage of mature H2 compared with the total amount of H2 present at each time point; this may overestimate slightly the rate of maturation of H2.
Low Temperature Does Not Change the Subcellular Localization of H2

Incubation of cells at 18–20°C drastically reduced the rate of degradation of H2 (Fig. 6). When 2-18 cells were incubated at 18°C for 5 h, we saw no change in the immunofluorescence pattern of H2 distribution, but a stronger signal was detected in all cells (Fig. 8 A as compared with Fig. 7 A). This indicates that H2 degradation is inhibited less than H2 biosynthesis. All H2 is still in a compartment that stains with the anti–ER antiserum. It is unlikely that the reduced temperature would account for such a reduction in the degradation rate if the H2 were degraded within the RER. We believe that H2 is transported for degradation to an RER-adjacent, pre-Golgi compartment such as the transitional element of the ER and that such transport is inhibited at 18–20°C.

Discussion

Here we show that the ASGP receptor subunit H2a, expressed in fibroblasts without H1, is degraded within 2–3 h of synthesis in a compartment that may be the ER itself or near the ER. Lysosomotropic agents do not affect the rate of degradation and do not cause accumulation of intermediates detectable with our antisera. Thus, we believe that degradation occurs in a pre-Golgi, nonlysosomal compartment but cannot exclude final lysosomal degradation of intermediates that are not reactive with our two anti-peptide sera.

We have identified a 35-kD polypeptide that may result from the initial cleavage event in the degradation of H2. Evidence that the 35-kD protein is a fragment of H2 includes (a) it is not found in fibroblasts transfected with vector alone; (b) it has the same number of oligosaccharides as H2; (c) it reacts with the anti–H2 antibody specific for the COOH terminus, the part of H2 containing the sites for oligosaccharide addition; and (d) it is detected roughly during the period of time in which H2 is degraded. If we assume that the 35-kD protein results from a single endoproteolytic cleavage, then this site would be just COOH-terminal to the membrane-spanning region. Cell fractionation results (not shown) indicate that the 35-kD fragment is not tightly bound to the membrane, consistent with it being the exoplasmic, nonmembrane-spanning domain of H2. Our results indicate that the 35-kD H2 fragment is formed before H2 reaches the medial Golgi compartment, as the 35-kD H2 fragment bears endo H-sensitive, endo D–resistant oligosaccharides. We do not know whether this cleavage is an obligatory initial step in the degradation pathway or if it is one of several initial cleavages that can take place.

The membrane-spanning domain of the homologous protein H1 functions as an internal uncleaved signal–anchor sequence (Spiess and Lodish, 1986); we assume that the H2 membrane-spanning sequence plays the same role. The position of the cleavage we observe—just COOH-terminal to this internal signal–anchor sequence—suggests that signal peptidase may be the culpable enzyme. Interestingly, when derivatives of H1 cDNA that direct synthesis of a variant H1 protein that lacks the NH2-terminal (cytoplasmic) domain were translated in vitro in the presence of microsomes, a fraction of the protein made was proteolytically cleaved at the luminal side of the membrane-spanning region, suggesting that signal peptidase recognized the internal signal sequence (Spiess and Lodish, 1986). This cleavage was not detected in normal H1, suggesting that the conformation of the protein as well as the presence of the signal–anchor sequence determines...
Figure 7. Double label immunolocalization of H2 and the ER or Golgi complex. Fixed, permeabilized 2-18 cells were processed as described in Materials and Methods. A and B represent double labeling with anti-H2 and anti-ER antibodies; C and D represent double labeling with anti-H2 and anti-Golgi antibodies. H2 was detected with TRITC filter (A and C), and ER (B) or Golgi complex (D) were detected with FITC filter. Identical regions are labeled by arrows in the double label pairs, pointing out similarities in staining (A and B) or differences (C and D). Bar, 10 µm.

whether signal peptidase acts. As H2 does not fold into an H1–H2 heterooligomer when synthesized in the absence of H1, we speculate that signal peptidase could recognize a cryptic cleavage site in unfolded H2. Candidate cleavage sites predicted by the method of von Heijne (1986) are present in the area of the proteolytic clip. If cleavage by signal peptidase were an obligatory initial step in H2 degradation, however, we would expect that upon incubation at 18–20°C,
Figure 8. Effect of 18–20°C on immunolocalization of H2, the ER, and the Golgi complex. 2-18 cells were incubated at 18–20°C for 5 h before fixation, permeabilization, and immunofluorescence as in Fig. 7. (A and C) Anti-H2-TRITC; (B) anti-RER-FITC; (D) anti-Golgi-TRITC. Bar, 10 μm.

which causes H2 to accumulate in the ER, all the H2 would become cleaved; instead, we find that intact H2 is much more stable than at 37°C. Alternatively, the area of the cleavage may form a particularly protease-sensitive stalk between the membrane-spanning and more globular exoplasmic domains and be cleaved by a protease that is not found in the RER but rather in the degradative compartment.

The proteolytic cleavage we observe with H2 is similar to the processing that occurs with many viral glycoproteins. Cells infected with viruses such as murine leukemia virus,
rables, and mouse mammary tumor virus release soluble forms of viral glycoproteins into the extracellular fluid (Bolognesi et al., 1975; Dietzschold et al., 1983; Racevskis and Sarkar, 1978). The origin of the truncated glycoprotein has been well characterized for vesicular stomatitis virus, which directs the synthesis of a membrane bound glycoprotein (G protein) in the RER. A truncated, soluble form of G protein, Gs, lacks the membrane-spanning and cytoplasmic portions of the protein. G, is formed intracellularly and released by infected cells (Garreis-Wabnitz and Krupa, 1984). Use of the temperature-sensitive ts045 mutant of vesicular stomatitis virus G protein, which fails to fold into a trimmer and leave the ER (Knipe et al., 1977a,b; Bergman et al., 1981; Kreis and Lodish, 1986), was instrumental in proving that G is generated in the ER by cleavage of G protein at a site near the luminal surface of the membrane-spanning domain (Chen and Huang, 1986). Perhaps this is another example of a virus exploiting a normal cellular function, in this case quality control for multisubunit protein assembly, for its own purposes.

The characteristics of H2 degradation are essentially the same as those described by Lippincott-Schwartz and coworkers (1988) for the α and β subunits of the T cell receptor, which are also degraded in a pre-Golgi compartment in 3T3 fibroblasts. The ASGP receptor bears no striking sequence homology with the T cell receptor subunits and yet it is a substrate for a similar pre-Golgi degradation pathway. Since not all of the T cell receptor subunits have yet been coexpressed in fibroblasts, we do not know if 3T3 cells are capable of assembling the subunits and transporting them to the surface. 2B4 T cell hybridoma cells, which express all seven subunits of the T cell receptor complex, degrade the unassembled α and β subunits in the lysosomes (Lippincott-Schwartz et al., 1988). That leaves open the possibility that the fibroblasts are incapable of synthesizing the α and β subunits into a normal conformation, and the grossly abnormal conformation triggers the use of the pre-Golgi pathway. In contrast, we know that 3T3 cells are capable of making a functional ASGP receptor and yet degrade a portion of both H1 and H2 in the process (Shia and Lodish, 1989). We therefore suspect that the degradation process we describe here is the same as that occurring during cosynthesis of the two subunits in fibroblasts. It remains to be tested whether ER degradation is the mechanism operating in hepatocytes to allow only properly assembled H1–H2 complexes to mature. In addition, we would like to find out whether H2 is completely degraded in 2-18 cells because it cannot self-associate as compared with H1 which forms dimers and trimers in fibroblasts that express it alone (Shia and Lodish, 1989). A similar example would be vesicular stomatitis virus ts045 G protein, which cannot trimerize and becomes stuck in the ER (Kreis and Lodish, 1986). The generation and expression of mutant H2 proteins may help us resolve this question.

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References

Ascoli, M. 1979. Inhibition of the degradation of receptor-bound human choriogonadotropin by leupeptin. Biochim. Biophys. Acta. 586:608-614.

Bergman, J. E., J. T. Tokoyasu, and S. J. Singer. 1981. Passage of an integral membrane glycoprotein, the vesicular stomatitis virus glycoprotein, through the Golgi apparatus en route to the plasma membrane. Proc. Natl. Acad. Sci. USA. 78:1746-1750.

Bischoff, J., and H. F. Lodish. 1987. Two asialoglycoprotein receptor polypeptides in human hepatoma cells. J. Biol. Chem. 262:11825-11832.

Bischoff, J., S. Libresco, M. A. Shia, and H. F. Lodish. 1988. The H1 and H2 polypeptides associate to form the asialoglycoprotein receptor in human hepatoma cells. J. Biol. Chem. 263:10067-10074.

Bolognesi, D. P., A. J. Langlois, and W. Schaffner. 1975. Polypeptides of mamalian oncorna viruses. IV. Structural components of murine leukemia virus released as soluble antigens in cell culture. Virology. 68:550-555.

Braierman, L. T., S. C. Chance, W. R. Porter, Y. C. Lee, R. T. Townsend, A. L. Hubbard. 1989. The major subunit of the rat asialoglycoprotein receptor can function alone as a receptor. J. Biol. Chem. 264:1682-1688.

Chen, S.-S.-L., and A. S. Huang. 1986. Further characterization of the vesicular stomatitis virus temperature-sensitive 045 mutant: intracellular conversion of the glycoprotein to a soluble form. J. Virol. 59:210-215.

Chen, C., J. S. Bonifacino, L. C. Yuan, and R. D. Klausner. 1988. Selective degradation of T cell antigen receptor chains retained in a pre-Golgi compartment. J. Cell Biol. 107:2149-2161.

Coles, C. L., M. M. Matzuk, T. V. Ramabhadran, A. Krivchevsky, and J. Boime. 1987. Gonadotropin beta subunits determine the rate of assembly and the oligosaccharide processing of hormone dimer in transfected cells. J. Cell Biol. 104:1173-1181.

Dietzschold, B., T. J. Wiktor, W. H. Wiener, and A. Varrichis. 1983. Chemical and immunological analysis of the rabies soluble glycoprotein. Virology. 124:330-337.

Dolis, B. H., T. M. Kloppel, H. M. Grey, and R. T. Kubo. 1982. Regulation of assembly of IgM heavy chains in a B lymphoma cell line. J. Biol. Chem. 257:4369-4374.

Dunn, W. A., A. L. Hubbard, and N. N. Arason. 1980. Low temperature selectively inhibits fusion between pinocytic vesicles and lysosomes during heterolysis of 125I-asialofetuin by the perfused rat liver. J. Biol. Chem. 255:5971-5978.

Garreis-Wabnitz, C., and J. Krupa. 1984. Intracellular appearance of a glycoprotein in VSV-infected BHK cells lacking the membrane-anchoring oligopeptide of the viral G protein. EMBO J. (Eur. Mol. Biol. Organ.) 3:1469-1476.

Harford, J., K. Bridges, G. Ashwell, and R. D. Klausner. 1983. Intracellular dissociation of receptor-bound asialoglycoproteins in cultured hepatocytes: a pH-mediated nonsosomal event. J. Biol. Chem. 258:3191-3197.

Knipe, D. M., H. F. Lodish, and D. Baltimore, 1977a. Analysis of the defects of temperature-sensitive mutants of vesicular stomatitis virus: intracellular degradation of specific virus proteins. J. Virol. 21:1140-1148.

Knipe, D. M., D. Baltimore, and H. F. Lodish. 1977b. Maturation of viral proteins in cells infected with temperature-sensitive mutants of vesicular stomatitis virus. J. Virol. 21:1149-1158.

Kreis, T. E., and H. F. Lodish. 1986. Oligomerization is essential for transport of a vesicular stomatitis viral glycoprotein to the cell surface. Cell. 46:929-937.

Lippincott-Schwartz, J. L. J., S. Bonifacino, L. C. Yuan, and R. D. Klausner. 1988. Degradation from the endoplasmic reticulum: disposing of newly synthesized proteins. Cell. 54:209-220.

Louvard, D., H. Reggio, and G. Warren. 1982. Antibodies to the Golgi complex and the rough endoplasmic reticulum. J. Cell Biol. 98:92-107.

McPhaul, M., and P. Berg. 1986. Formation of functional asialoglycoprotein receptor after transfection with cDNAs encoding the receptor proteins. Proc. Natl. Acad. Sci. USA. 83:8863-8867.

Marsh, M. E., B. Zolza, and A. Heielenius. 1983. Penetration of Semliki forest virus from acidic precysolomalic vacuoles. Cell. 32:931-940.

Maxfield, F. R. 1982. Weak bases and ionophores rapidly and reversibly raise the pH of endocytic vesicles in cultured mouse fibroblasts. J. Cell Biol. 95:676-681.

Merle, J. P., R. Sebbane, S. Tronzon, and J. Lindstrom. 1982. Inhibition of glycosylation with tunicamycin blocks assembly of newly synthesized asialo- choline receptor subunits in muscle cells. J. Biol. Chem. 257:2694-2701.

Minami, Y., A. M. Weissman, L. E. Samelson, and R. D. Klausner. 1987. Building a multichain receptor: synthesis, degradation, and assembly of the T-cell antigen receptor. Proc. Natl. Acad. Sci. USA. 84:2688-2692.

Plant, P. W., and G. Grieninger. 1986. Noncoordinate synthesis of the fibrinogen subunits in hepatocytes cultured under hormone-deficient conditions. J. Biol. Chem. 261:2331-2336.

Racevskis, J., and N. H. Sarkar. 1978. Synthesis and processing of precursor polypeptides to murine mammary tumor virus structural proteins. J. Virol. 25:374-383.

Saraste, J., G. E. Palade, and M. G. Farquhar. 1986. Temperature-sensitive steps in the transport of secretory proteins through the Golgi complex in exocrine pancreatic cells. Proc. Natl. Acad. Sci. USA. 83:6425-6429.

Schwartz, A. L., A. Ciechanover, S. Merritt, and A. Turkewitz. 1986. Antibody-induced receptor loss. J. Biol. Chem. 261:15225-15232.
Shia, M. A., and H. F. Lodish. 1989. The two subunits of the human asialoglycoprotein receptor have different fates when expressed alone in fibroblasts. Proc. Natl. Acad. Sci. USA. 86:1158–1162.

Spiess, M., and H. F. Lodish. 1985. Sequence of a second human asialoglycoprotein receptor: conservation of two receptor genes during evolution. Proc. Natl. Acad. Sci. USA. 82:6465–6469.

Spiess, M., and H. F. Lodish. 1986. An internal signal sequence: the asialoglycoprotein receptor membrane anchor. Cell. 44:177–185.

Tartakoff, A. M. 1983. Perturbation of vesicular traffic with the carboxylic ionophore monensin. Cell. 32:1026–1028.

von Heijne, G. 1986. A new method for predicting signal sequence cleavage sites. Nucleic Acids Res. 14:4683–4691.