Influenza M2 Proton Channel Activity Selectively Inhibits Trans-Golgi Network Release of Apical Membrane and Secreted Proteins in Polarized Madin-Darby Canine Kidney Cells

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Abstract. The function of acidification in protein sorting along the biosynthetic pathway has been difficult to elucidate, in part because reagents used to alter organelle pH affect all acidified compartments and are poorly reversible. We have used a novel approach to examine the role of acidification in protein sorting in polarized Madin-Darby canine kidney (MDCK) cells. We expressed the influenza virus M2 protein, an acid-activated ion channel that equilibrates luminal and cytosolic pH, in polarized MDCK cells and examined the consequences on the targeting and delivery of apical and basolateral proteins. M2 activity affects the pH of only a subset of acidified organelles, and its activity can be rapidly reversed using ion channel blockers (Henkel, J.R., G. Apodaca, Y. Altschuler, S. Hardy, and O.A. Weisz. 1998. Mol. Biol. Cell. 8:2477–2490; Henkel, J.R., J.L. Popovich, G.A. Gibson, S.C. Watkins, and O.A. Weisz. 1999. J. Biol. Chem. 274:9854–9860). M2 expression significantly decreased the kinetics of cell surface delivery of the apical membrane protein influenza hemagglutinin, but not of the basolaterally delivered polymeric immunoglobulin receptor. Similarly, the kinetics of apical secretion of a soluble form of γ-glutamyltranspeptidase were reduced with no effect on the basolaterally secreted fraction. Interestingly, M2 activity had no effect on the rate of secretion of a nonglycosylated protein (human growth hormone [hGH]) that was secreted equally from both surfaces. However, M2 slowed apical secretion of a glycosylated mutant of hGH that was secreted predominantly apically. Our results suggest a role for acidic trans-Golgi network pH in signal-mediated loading of apical cargo into forming vesicles.

Key words: acidification • polarity • Madin-Darby canine kidney • influenza M2 • apical

Introduction

Although the pH of organelles along the secretory pathway is known to be important for proper processing and sorting of proteins and lipids, the function of acidification in protein trafficking remains poorly understood. Most studies examining the role of pH have demonstrated decreased rates of protein trafficking, both along the biosynthetic and endocytic pathways; however, the compartments affected are in dispute. In part, this is due to difficulties with current methods used to perturb organelle pH. These reagents include treatment with weak bases such as chloroquine, primaquine, and ammonium chloride (for review see Dean et al., 1984; Ilundain, 1992; Seagrave et al., 1992), which may contribute to some of the phenotypes observed in weak base-treated cells (Davoust et al., 1987; Parton et al., 1991). Indeed, some effects of chloroquine on membrane traffic have been demonstrated to be independent of its effects on organelle pH (R omanek et al., 1993). More recent studies have used inhibitors of vacuolar type H+ ATPases (V-ATPases), such as concanamycins A and B and the

1 Abbreviations used in this paper: AMT, amantadine; AV, adenovirus; AV-TA, adenovirus encoding tTA; BafA1, bafilomycin A1; endo H, endoglycosidase H; γGT, γ-glutamyltranspeptidase; ghGH, glycosylated hGH; HA, hemagglutinin; hGH, human growth hormone; pIgR, polymeric Ig receptor; PM, plasma membrane; V-ATPase, vacuolar H+-ATPase.
more specific bafilomycin A₁ (BafA₁) to perturb the pH of intracellular compartments. These inhibitors are relatively specific, effective at low concentrations, and alter the pH of all compartments that are acidified by V-ATPases. However, BafA₁ at least is only poorly reversible, and causes swelling of even nonacidic compartments (Palokangas et al., 1994). Moreover, some cells can become resistant to these treatments and are able to reacidify their organelles after even short incubations in drug (Temesvari et al., 1996). Finally, other proton transporters may also play a role in acidification of some compartments (Okhuma et al., 1982). These factors may account for the vastly different effects of these inhibitors on biosynthetic and endocytic protein traffic reported by different investigators.

Few studies have focused on the function of acidification in protein sorting in polarized cells. Matlin (1986) showed that ammonium chloride slows the rate of apical delivery of newly synthesized influenza hemagglutinin (HA) to the cell surface, but does not appear to affect its polarity of delivery. By contrast, in another study, treatment with monensin or chloroquine resulted in a twofold increase in the ratio of apical to basolateral secretion of both an endogenous protein complex (gp80) that is directed apically, and an exogenous marker (lysozyme) that is secreted equally from both plasma membrane (PM) domains (Parczyk and Kondor-Koč, 1989). Finally, Caplan et al. (1987) observed that polarized M D C K cells treated with the weak base ammonium chloride misdirect about half of the newly synthesized soluble basolateral markers laminin and heparan sulphate proteoglycan to the apical medium. In this study, the polarity of secretion of apical markers was unaffected by ammonium chloride treatment, as were delivery of apical and basolateral membrane proteins; however, the rates of transport were not measured. Thus, the role of TGN pH in polarized protein sorting remains unclear.

We have developed a novel method to alter intraorganelle pH that overcomes many of these difficulties. This involves expression of the acid-activated ion channel M2, a component of influenza virus that allows protons to efflux from acidic compartments. Unlike weak bases or V-ATPase inhibitors, which globally affect the pH of all acidic organelles, M2 should alter the pH of only those compartments in which it is present. We demonstrated previously that M2 expressed in M D C K cells localizes to the PM, where it should be inactive under normal conditions, as well as to the TGN and to the apical recycling endosome (Henkel et al., 1998). M2 expression affected the rate of basolateral-to-apical transcytosis and apical recycling in polarized M D C K cells, but had no effect on the rate of basolateral recycling or on protein degradation. Thus, M2 expression is a useful tool with which to selectively perturb a subset of acidified compartments in the cell. Therefore, we examined the effect of M2 expression on the delivery of newly synthesized proteins in polarized M D C K cells. Interestingly, our data suggest that delivery of apical proteins is preferentially inhibited by M2 activity. Our results are most consistent with a function for TGN acidification in loading presorted apical cargo into forming vesicles.

### Materials and Methods

#### DNA Constructs

A secreted form of γ-glutamyltranspeptidase (gGTP) was generated by substituting the cleavable signal sequence of the herpes gD surface glycoprotein for the signal/anchor of gGTP. The cDNA corresponding to gGTP residues 1–35 and γGTP residues 28–568 were amplified from cloned cDNAs by PCR using specific primers and cloned separately into pCR2 (Invitrogen). The gD (Ec Orf-BamHI) and γGTP (BamHI-XhoI) fragments were subcloned into pEP4 (Invitrogen) to generate the final construct, which contains two additional residues (alanine and arginine) between the gD sequence and γGTP. The chimera was subsequently cloned into pcDNA 3 (Invitrogen) and a stable M D C K cell line generated (see below). The ss/uu human growth hormone (hGH)–mycHis chimera encodes a secreted version of the hGH with COOH-terminal myc and His tags. To generate this construct, the signal-anchor of rat γGTP was shortened to create a cleavable signal sequence (ss) by removal of nucleotides encoding residues 16–23. This fragment of γGTP (36 residues total) and residues 32–217 from hGH (pOGH; Nichols Institute) were amplified by PCR with specific primers and cloned into pCR2. The chimera was prepared by subcloning the ss/HuOrf-BamHI and hGH (BamHI-HindIII) fragments first into pBluescript-SK(−) (Stratagene), and a myc-His-tagged version was generated by subsequent cloning into pcDNA 3/mycHis (SA (−) (Invitrogen)). The glycosylated version of ssHGH–mycHis is (gGTP) was prepared by site-directed mutagenesis of ssHGH–mycHis based on the Morφ™ procedure (5 Prime, Inc.). Specific primers were used to convert Met 40 to Thr, and Leu 118 to Asn to generate two consensus sites for N-linked glycosylation. Selection of these sites was based on those used previously to generate glycosylated rat growth hormone (Schellffel et al., 1995).

#### Cell Lines

Low passage M D C K cells (type II) were maintained in minimal essential medium (Celgro; Fisher Scientific) supplemented with 10% FBS (A bianta Biologicals), streptomycin (100 μg/ml), and penicillin (100 U/ml). G generation and characterization of the M D C K T23 cell line, which stably expresses the tetracycline-repressible transactivator ITA (Gossen and Bujard, 1992), is described in Barth et al. (1997). Stable lines of M D C K expressing gD–γGTP were generated using Lipofectamine-mediated transfection, and individual clones were selected in 0.5 mg/ml G 418 (Life Technologies, Inc.). Stable transfectants of M D C K expressing HGH or ghGH were generated using the methods described in Weisz et al. (1992), and mixed drug-resistant populations were maintained in 0.5 mg/ml G 418. Cell lines expressing γGTP, hGH, and gGTP were induced with 2–10 μM monensin immediately after adeno viral infection. Because these cell lines do not stably express ITA, recombinant adeno virus (A V) encoding ITA (A V-TA) was included in all infections with these cells (see below). Uninjected and otherwise, cells were seeded at high density (2 × 10⁶ cells/well) on 12-mm Transwells (0.4-μm pore; Costar) for 2–3 d before infection with recombinant A V. Experiments were performed the following day.

#### Recombinant A Vs and Adenoviral Infection

Construction and purification of E1 substituted recombinant A Vs encoding M2 in the correct and reverse orientations (A V-M2 and M2-rev, respectively), A V-TA, and gGTP (A V-HA) are described in Henkel et al. (1998). The cDNA encoding rabbit polymeric Ig receptor (pIgR) (provided by Dr. Gerard A Podaca, University of Pittsburgh, Pittsburgh, PA) was subcloned into the pA diox vector, and a recombinant A V (A V-pIgR) generated as described in hardy et al. (1997). In some experiments, we measured the effect of M2 activity on trafficking of pIgR stably expressed in M D C K T23 cells. Results from these experiments were similar to those in which plgR expression was expressed in M D C K cells using A V. Filter-grown M D C K or M D C K T23 cells were washed with 0.5 ml calcium-free PBS containing recombinant A V and then exposed to efflux from acidic compartments. A centrifugal solution of A V was omitted during the infection.

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ing the incubation period. Dishes were then rinsed with 2 ml PBS-M, and cells were incubated overnight in growth medium (1 ml apical, 1.5 ml basal, 20 ng/ml Doxycycline; Sigma Chemical Co.) was added as a 1,000-fold concentrated stock prepared in 95% ethanol at this step to inhibit M2 expression.

Cell Surface Delivery of HA

Cell surface delivery of HA was measured essentially as described in Henkel and Weisz (1998). Infected, filter-grown cells were rinsed once with PBS, starved for 30 min in medium A, and pulse labeled for 15 min with 0.5–1 mCi/ml [35S]methionine (in vitro labeling mix; NEN). Unless indicated, cells were then incubated for 2 h at 19°C in medium B to accumulate newly synthesized HA in the TGN. Where indicated, the M2 ion channel inhibitors amantadine (5 μM; AMT; Sigma Chemical Co.) or BL-1743 (5 μM) (gift of Dr. Mark Kyrstal, Bristol-Myers Squibb Pharmaceutical Research Institute, Wallingford, CT) were included in the starved medium and during subsequent steps. In the experiment shown in Fig. 3 A, some samples were removed at this time, immunoprecipitated, and treated with endoglycosidase H (endo H) as described in Weisz et al. (1992). The medium was replaced with prewarmed medium B and the cells were transferred to 37°C. At the indicated times, cells were rapidly chilled to 0°C by rinsing with ice-cold PBS, and the apical surface trypsinized for 30 min on ice with medium B containing 100 μg/ml 3,5-di-O-tosylamido-2-phenylethyl chloromethyl ketone trypsin (Sigma Chemical Co.). In some experiments, a lower concentration of trypsin (10 μg/ml) was added directly to the chase medium at 37°C instead. Results using either of these protocols were very similar. The trypsin was quenched by two 10-min incubations in medium B containing 200 μg/ml soybean trypsin inhibitor (Sigma Chemical Co.). The filters were rinsed with PBS, solubilized in detergent solution (50 mM Tris-HCl, 2% NP-40, 0.4% deoxycholate, 62.5 mM EDTA, pH 8.0) supplemented with 1 μg/ml aprotinin and 200 μg/ml soybean trypsin inhibitor, and HA was immunoprecipitated using mAb BcF125. This antibody quantitatively immunoprecipitates HA and its cleavage products (HA1 and HA2, which remain associated with the cell surface). A monodispersing antibody-antigen complexes using fixed Staphylococcus aureus (Pansorbin; Calbiochem-Novabiochem Corp.), samples were washed three times with RIPA buffer (10 mM Tris-HCl, 0.15 M NaCl, 1% Triton X-100, 1% deoxycholate, 0.4% NP-40, 0.1% SDS, pH 7.4). Samples were electrophoresed on 10% SDS-polyacrylamide gels and the percentage of cleaved HA was determined using a phosphorImager with Quantity One software (Personal Molecular Imager Canvas (Deneba Software)) using a Hamamatsu C5985 chilled CCD camera (8 bit, 756 × 483 pixels).

M2 Slows Apical but Not Basolateral Biosynthetic Delivery

Our earlier studies in nonpolarized cells suggested that M2 activity slowed biosynthetic delivery of newly synthesized proteins to the PM, and that delivery from the TGN to the cell surface was directly affected by M2 activity (Henkel and Weisz, 1998; Henkel et al., 1999). Therefore, we tested whether M2 activity affected apical or basolateral biosynthetic delivery in polarized cells. Initially, we measured the effect of M2 on the rate of transport of newly synthesized HA or plgR throughout the entire secretory pathway (Fig. 1). Cells expressing HA or plgR and either M2 or M2 were radiolabeled, then chased and the kinetics of HA and plgR cell surface delivery were quantitated as described in Materials and Methods. M2 slowed the rate of HA delivery to the apical surface (Fig. 1, a and b), and the effect of M2 was abolished by inclusion of the M2 ion channel inhibitor AMT. At contrast, M2 activity expression had no effect on the rate of plgR delivery to the basolateral surface (Fig. 1, c and d). M2 had a very small effect on the rate of acquisition of endo H–resistant oligosaccharides on HA (data not shown); however, this may be due to indi-
rect effects of M2 on early secretory traffic (Henkel and Weisz, 1998).

To confirm that TGN-to-apical PM delivery is the predominant step affected by M2, we staged HA in the TGN by chasing for 2 h at 19°C. Under these conditions, HA co-expressed with either M2rev or M2 was equally resistant to treatment with endo H (>80% resistant; Fig. 2 a), suggesting that the majority of newly synthesized HA had transited the medial Golgi complex by this time. The cells were then warmed and HA delivery to the apical and basolateral surfaces was measured as described above (Fig. 2 b). As predicted, M2 slowed delivery of HA, and the effect of M2 on HA delivery is abolished by inclusion of AMT throughout the experiment. The more rapidly migrating doublet represents HA2 cleaved at the apical surface after transcytosis. All experiments were repeated at least three times with similar results.

M2 expression. The more rapidly migrating doublet represents plgR cleaved at the apical surface after transcytosis. All experiments were repeated at least three times with similar results.

membrane and soluble proteins are subject to different constraints and may traffic to the PM in different vesicles (Boll et al., 1991; de A Imeida and Stow, 1991; Saucan and Palade, 1994). Therefore, we asked whether M2 affects the rate of secretion of soluble proteins to the apical and basolateral medium. For this purpose, we used a mutant soluble form of g-glutamyltranspeptidase (gD-gGT) that is secreted predominantly apically (~70:30, apical:basolateral). The polarity of secretion of this mutant is similar to the polarity of delivery of wild-type, membrane-bound gGT. Stable cell lines expressing gD-gGT were mock-infected or infected with AV-TA and AV-M2rev or AV-M2, and the kinetics of TGN-to-apical and -basolateral secretion of gD-gGT quantitated (Fig. 3). The kinetics of apical secretion of gD-gGT were slowed in cells expressing M2, whereas basolateral secretion was unaffected. Thus, M2 selectively affects the rate of apical delivery.

M2 Expression Affects Release of Apical Proteins from the TGN

The effect of M2 on apical delivery could be due to a defect in cargo incorporation into apical vesicles, to defective vesicle release from the TGN, or to inhibition of vesicle fusion with the apical cell surface. To distinguish between the latter two possibilities, we tested whether M2 expression interfered with release of apical cargo from the TGN.

Figure 1. M2 activity slows delivery of proteins to the apical but not the basolateral surface of MDCK cells. Filter-grown MDCK cells were infected with AVs encoding M2rev or M2 and either HA (a and b) or plgR (c and d). Cells were starved, radiolabeled for 15 min, chased at 37°C for the indicated times, and the kinetics of protein delivery to the PM quantitated using surface trypsinization assays as described in Materials and Methods. (a and b) Kinetics of HA delivery to the apical surface of polarized MDCKs. Quantitation of the gel in a is shown in b. In this experiment, HA2 migrated as a diffuse band in some samples. This was not typically observed. M2 slows cell surface delivery of HA, and the effect of M2 on HA delivery is abolished by inclusion of AMT throughout the experiment. (c and d) Kinetics of plgR delivery to the basolateral surface. Quantitation of the gel in c is shown in d. Delivery of plgR to the basolateral surface is unaffected by M2 expression.
Mechanism of M2 Effect on Apical Delivery

The effect of M2 on release of apical cargo from the TGN could occur at several steps. M2 could affect the recognition of apical sorting signals in the TGN, although this is unlikely given that the overall polarity of delivery is unaffected by M2 expression. Alternatively, M2 could affect loading of presorted cargo into apical vesicles at the TGN. Finally, M2 could disrupt the regulation or mechanics of apical vesicle formation or budding. To determine whether M2 activity affects the rate of formation or number of apically derived vesicles formed at the TGN, we asked whether M2 affects apical delivery of hGH, a non-polarized secreted protein that does not contain intrinsic apical sorting signals. If M2 activity causes a general defect
in apical vesicle formation, we would expect to observe an inhibition in apical secretion of hGH. By contrast, if M2 activity interferes with the loading of apically sorted cargo but does not affect vesicle formation, no effect on hGH secretion should be observed. Stable MDCK cell lines expressing myc-tagged hGH were generated and screened for expression and polarity of hGH secretion (Fig. 5). Intracellular hGH was localized to the ER and Golgi complex, as predicted for a secreted protein (Fig. 5 a). Infection of these cells with A V-TA and A V-M 2 resulted in M 2 expression in a large percentage of the cells (Fig. 5 b). Previous studies using MDCK cells have shown that the effect of M 2 on other transport steps (basolateral-to-apical transcytosis and apical recycling) are maximal at similar levels of M 2 expression, and that increasing M 2 expression 10-fold has no further effects (Henkel et al., 1998). Secretion of the newly synthesized hGH was essentially nonpolarized (∼55% apical on average), as reported previously (Scheiffele et al., 1995). We then tested whether M 2 activity altered the rate or polarity of hGH secretion (Fig. 6). Virally infected cells were starved, radiolabeled, then chased for 2 h at 19°C. No radiolabeled hGH was released into the medium during this incubation (data not shown). The cells were then incubated with prewarmed medium and hGH secretion quantitated. Interestingly, we observed no effect of M 2 activity on either the rate or polarity of hGH secretion. This result suggests that M 2 expression does not affect the rate of formation of apically destined vesicles at the TGN.

To confirm this possibility, we converted hGH to an apically sorted protein and asked whether its delivery was now affected. Scheiffele et al. (1995) have shown previously that N-linked glycosylation of rat growth hormone confers apical sorting information to this normally unglycosylated protein. Thus, we used site-directed mutagenesis to create two N-glycan consensus addition sites in hGH, and tested the polarity of secretion of the resultant mutant (gHGH) expressed in MDCK cells. Initial experiments suggested that chasing radiolabeled cells at 19°C significantly inhibited secretion of gHGH upon subsequent warming to 37°C; thus, the 19°C chase was omitted from these experiments (control experiments confirmed that omitting the 19°C chase had no effect on the release of nonglycosylated hGH; data not shown). As expected, gHGH was secreted predominantly apically (∼85%; Fig. 7 a), suggesting that N-glycosylation conferred apical sorting information to this protein. In addition, the rate of apical but not basolateral secretion of gHGH was significantly decreased when it was coexpressed with active M 2 (Fig. 7, b and c). The effect of M 2 on apical secretion of gHGH was blocked by inclusion of AMT, suggesting that M 2 ion channel activity was responsible for the observed inhibition. Thus, our data are consistent with an effect of M 2 activity on loading of apically sorted cargo into vesicles at the TGN.

Discussion

We have examined the effects of M 2 expression on TGN-to-cell surface delivery of newly synthesized proteins in polarized MDCK cells. M 2 expression slowed apical cell surface delivery of HA and delayed the apical release of glycosylated soluble proteins; however, transport of basolateral proteins was unaffected. The delay in transport was due to a block in apical protein export from the TGN, and was not observed when M 2 ion channel activity was inhibited. Interestingly, M 2 expression had no effect on the apical release of a nonglycosylated soluble protein whose nonpolarized secretion is unlikely to be signal mediated. Together, our results suggest a role for TGN pH in the efficient delivery of apical proteins.

Although we did not directly confirm that M 2 expression alters TGN pH, there is considerable indirect evidence to support this. M 2 has been demonstrated to function as an acid-activated proton channel in vivo and in vitro, and to alter the pH of a subset of acidified compartments in cells (Pinto et al., 1992; Schroeder et al., 1994; Wang et al., 1994; Chizhmakov et al., 1996; Shimbo et al., 1996; Henkel et al., 1999). M 2 slows TGN-to-PM delivery of newly synthesized proteins when expressed in nonpolarized cells, and the effects are blocked by the M 2 ion channel inhibitor AMT (Henkel and Weisz, 1998; Henkel et al., 1999). In addition, M 2 activity is normally required to prevent acid-dependent aggregation of the pH-sensitive fowl plague virus HA in the TGN; however, in the absence of active M 2, acidotropic agents such as chloroquine or...
ammonium chloride can substitute (Ciampor et al., 1992; Ohuchi et al., 1994; Takeuchi and Lamb, 1994). Finally, Grambas and Hay (1992) used conformation-sensitive antibodies to estimate the pH encountered by fowl plague virus HA during biosynthetic transport in MDCK cells; the pH of the Golgi complex in control cells was estimated to be ~5.6, and increased to ~6.0 in cells expressing active M2. However, because M2 has been demonstrated to transport other cations besides protons in vitro, albeit at very low efficiency (e.g., $10^{-5}$–$10^{-7}$-fold lower efficiency for sodium than for protons) (Chizhmakov et al., 1996; Shimbo et al., 1996), we cannot rule out the possibility that the effects we observed are due to altered Golgi ion composition rather than pH.

Our observations are consistent with earlier findings by Maitlin (1986) and Caplan et al. (1987), who observed decreased rates of delivery of apical membrane and secreted proteins, respectively, with no effect on their ultimate polarity in ammonium chloride-treated MDCK cells. We also compared the effect of M2 expression and of pH disruption using various global pH perturbants on the polarity of secretion of gp80, but found no effect of these treatments (data not shown). However, in our MDCK T23 cells, gp80 secretion was ~95% apical under all conditions tested; thus, the twofold increase in the ratio of apical to basolateral secretion in chloroquine-treated cells reported by Parczyk and Kondor-Koch (1989) would be difficult to detect. Interestingly, however, treatment with the V-ATPase inhibitor BafA1 resulted in general inhibition of apical and basolateral delivery of all proteins tested (data not shown). Together, the disparate observations using global pH perturbants reinforce the need to use selective pH perturbants, such as M2, in order to examine the role of pH in individual trafficking and sorting events.

A pical sorting has been proposed to occur by the recruitment of proteins into glycolipid-rich domains that are subsequently incorporated into apically destined vesicles. A lectin-like protein resident in these rafts, VIP36, has been proposed to function as a sorting receptor for both membrane and soluble proteins in the TGN (Fiedler et al., 1994; Fiedler and Simons, 1996); however, this protein was recently shown to be localized instead to earlier compartments of the secretory pathway (Fullekrug et al., 1999). An acidic TGN pH could be important for various steps in apical protein delivery, including recognition of apical sorting signals, recruitment of proteins into glycolipid rafts, incorporation of proteins or rafts into apically destined vesicles, vesicle formation or budding, and vesicle fusion. We considered the possibility that M2-mediated alkalinization of the TGN affects terminal glycosylation of itinerant proteins and thus disrupts carbohydrate-mediated recognition by a VIP36-like lectin. However, we could not detect any difference in the electrophoretic migration of HA or other proteins in M2-expressing cells compared with control cells, suggesting there was no gross alteration in glycosylation. Moreover, M2 expression had no effect on the mobility of the heavily glycosylated mucin-like protein MUC1 expressed in CHO cells (data not shown). In addition, the role for glycosylation in apical sorting appears to involve core residues as opposed to terminal residues that are added during intra-Golgi transport (Parczyk and Koch-Brandt, 1993; Wagner et al., 1995; Fiedler and Simons, 1996). Finally, M2 expression had no effect on the ultimate polarity of apical protein delivery to the apical surface, suggesting that recognition of sorting signals by the apical sorting machinery was not compromised.

Incorporation of proteins into glycolipid rafts is typically assessed by detergent insolubility, and has been demonstrated for both membrane and soluble apical proteins (Scheiffele et al., 1997; Keller and Simons, 1998). Cholesterol depletion or knockout of the proteolipid VIP17/MA1 disrupts lipid rafts, increases Triton X-100 solubility of HA, and results in decreased polarity of HA delivery to the apical surface (Keller and Simons, 1998; Cheong et al., 1999; Puertollano et al., 1999). By contrast, M2 expression did not affect Triton X-100 solubility or apical polarity of HA, suggesting that formation of glycolipid rafts is not inhibited by M2. This is consistent with the observation that apical proteins are incorporated into glycolipid rafts rela-
tively early during transit through the Golgi complex (Brown and Rose, 1992; Danielsen, 1995), i.e., during passage through nonacidified compartments that should be unaffected by M2 activity. Moreover, M2 itself is completely soluble in cold Triton X-100, suggesting that it is not incorporated into rafts.

The amount of HA released from the TGN in mechanically perforated cells was decreased in cells expressing active M2, suggesting that acidification is required for efficient apical protein export from the TGN. However, this result does not rule out additional functions for acidification in vesicle targeting to or fusion with the apical PM. Moreover, it cannot be determined from this assay whether the number of apically destined vesicles is affected by M2, or whether there is less apical cargo per vesicle. However, our observation that apical secretion of

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Figure 6. M2 does not affect apical secretion of hGH. MDCK cells stably expressing hGH were infected with A VM2rev or A VM2 and induced with 10 mM butyrate. Cells were starved, pulse labeled for 30 min, chased for 2 h at 19°C, then transferred to 37°C. AMT was included in all steps where indicated. The medium was collected and replaced at the indicated time points. At the end of the experiment, filters were solubilized, hGH was immunoprecipitated from all samples, and the kinetics of apical (a) and basolateral (b) secretion were quantitated. The total amount of hGH secreted by control filters (infected with A VM2rev) at the end of the time course was normalized to 100% to allow comparison between experiments; average secretion at the end of the chase period was 46.1 ± 9.8% of total hGH. The mean of six independent experiments is plotted. M2 expression had no effect on either apical or basolateral secretion of hGH.

Figure 7. M2 slows apical secretion of ghGH. (a) ghGH is secreted predominantly apically. Stable MDCK cells expressing ghGH were infected with A VT-A and A VM2rev and induced with 10 mM butyrate. The following day, cells were starved, radiolabeled for 30 min, then chased for the indicated periods. At each time point, the apical and basolateral medium were replaced and immunoprecipitated with anti-myc antibody. Approximately 85% of the secreted ghGH was released apically. (b and c) Secretion kinetics of ghGH. MDCK cells stably expressing ghGH were infected with A VM2rev or A VM2 and induced with 10 mM butyrate. Cells were starved, pulse labeled for 30 min, then chased for the indicated periods at 37°C. AMT was included in all steps where indicated. Samples were collected and analyzed as described in the legend to Fig. 6. The mean of seven experiments is shown. On average, 68.4 ± 5.9% of the total ghGH was secreted by the end of the chase. Kinetics of apical (b) and basolateral (c) secretion are shown. Statistical analysis of the raw data by paired t test revealed that M2 significantly affected apical secretion of ghGH relative to M2rev-expressing cells. Asterisk indicates P = 0.04; two asterisks indicate P = 0.02.
nonglycosylated hGH is unaffected by M2 expression suggests that M2 does not affect the overall volume of apically destined vesicles, and by inference, the number of apically destined vesicles formed.

We attempted to reconstitute budding of hGH-containing vesicles in mechanically perforated cells; however, in our hands, release of hGH was a TP-independent effect. We suspect that this is due to inefficient concentration of hGH in the TGN during the 19°C chase, as a TP-independent release of immature HA (compared with the sialylated form) has been observed previously (Bennett et al., 1988).

Thus, we cannot be certain that HA and hGH traffic to the apical surface in distinct vesicles. Therefore, we considered an alternative explanation for our results: that apically sorted cargo is delivered to the apical surface in distinct vesicles that do not contain hGH; and that budding of the former class of vesicles is selectively inhibited by M2. We do not favor this hypothesis, as it implies both that nonsorted cargo is actively excluded from apical vesicles (i.e., sorted, in a sense), and that a separate class of vesicles exists that is enriched in this nonsorted cargo. Because MDC cells do not secrete endogenous proteins in a non-polarized fashion, this seems an unlikely possibility.

Because the rate of delivery but not the overall polarity of delivery of proteins that are preferentially targeted to the apical surface was selectively inhibited, M2 may interfere with recruitment of presorted cargo into apically destined vesicles. Lin et al. (1998) have recently postulated a two-step mechanism for HA sorting in which the ability to enter glycolipid rafts is a prerequisite for recognition by the apical sorting machinery. Our data are consistent with a model in which M2 does not interfere with either of these steps, but rather with the subsequent incorporation of these rafts into forming vesicles. Efficient sorting into glycolipid rafts but inefficient recruitment of these lipid rafts into apical vesicles could result in the observed delay in apical transport with little to no effect on the steady state distribution of HA. However, the mechanism by which cargo loading could be disrupted by M2 activity is unknown. One possibility is that TGN acidification could be important in limiting the size of glycolipid rafts. Formation of large oligomeric complexes containing Golgi-resident proteins has been proposed to block their entry into intra-Golgi transport vesicles (Machamer, 1993; Nilsson et al., 1993; Weisz et al., 1993). Alternatively, acidic pH might be important for the recognition of signals that direct rafts to forming apical vesicles. Finally, acidification could play a role in the active recruitment of rafts into forming vesicles.

In summary, we have demonstrated that expression of active M2 interferes with release of newly synthesized apical but not basolateral proteins from the TGN. The effect of M2 is consistent with a role for TGN acidification in the recruitment of presorted apical proteins into forming vesicles. Future experiments will be directed towards further understanding the role of TGN pH in this step of protein sorting.

We are very grateful to Dr. Gerard A podaca for numerous helpful sugges-
tions, for extensive comments on the manuscript, and for the rabbit pR\r construct and anti-myc antibody. We also thank Dr. Keith M ostov for anti-secretory component antibody and Dr. Mark K rystal for BL-1743.

This work was supported by grants from the National Institutes of Health (RO1 DK 54407 to O.A. Weisz and RO1 DK 26012 to R.P. Hughey), the Cystic Fibrosis Foundation (to O.A. Weisz), and Dialysis Clinic, Inc.

Submitted: 22 July 1999
R evised: 16 December 1999
A ccepted: 30 December 1999

References


