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The FAM Deubiquitylating Enzyme Localizes to Multiple Points of Protein Trafficking in Epithelia, where It Associates with E-cadherin and β-catenin

Rachael Z. Murray,*† Lachlan A. Jolly,* and Stephen A. Wood*†‡

*Child Health Research Institute, North Adelaide, SA 5006, Australia; and †Centre for the Molecular Genetics of Development, University of Adelaide, SA 5005, Australia

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Ubiquitylation is a necessary step in the endocytosis and lysosomal trafficking of many plasma membrane proteins and can also influence protein trafficking in the biosynthetic pathway. Although a molecular understanding of ubiquitylation in these processes is beginning to emerge, very little is known about the role deubiquitylation may play. Fat Facets in mouse (FAM) is substrate-specific deubiquitylating enzyme highly expressed in epithelia where it interacts with its substrate, β-catenin. Here we show, in the polarized intestinal epithelial cell line T84, FAM localized to multiple points of protein trafficking. FAM interacted with β-catenin and E-cadherin in T84 cells but only in subconfluent cultures. FAM extensively colocalized with β-catenin in cytoplasmic puncta but not at sites of cell-cell contact as well as immunoprecipitating with β-catenin and E-cadherin from a higher molecular weight complex (~500 kDa). At confluence FAM neither colocalized with, nor immunoprecipitated, β-catenin or E-cadherin, which were predominantly in a larger molecular weight complex (~2 MDa) at the cell surface. Overexpression of FAM in MCF-7 epithelial cells resulted in increased β-catenin levels, which localized to the plasma membrane. Expression of E-cadherin in L-cell fibroblasts resulted in the relocalization of FAM from the Golgi to cytoplasmic puncta. These data strongly suggest that FAM associates with E-cadherin and β-catenin during trafficking to the plasma membrane.

INTRODUCTION

Correct sorting of the E-cadherin cell-cell adhesion protein to the basolateral plasma membranes of epithelial cells is essential for polarization and maintenance of cell integrity and function. Sorting primarily occurs at the trans-Golgi network (TGN) and the route taken to the plasma membrane can either be direct, as observed in MDCKII cells, or indirect, as in hepatocytes (Maurice *et al.,* 1994) and intestinal epithelia (Le Bivic *et al.,* 1990; Matter *et al.,* 1990). The indirect route entails initial transport to either the basolateral or apical surface, before internalization and sorting via endosomes and reinsertion into the lateral membrane. A dileucine repeat in the cytoplasmic domain of E-cadherin is necessary and sufficient for targeting E-cadherin to the basolateral membrane (Miranda *et al.,* 2001). However, increased efficiency of E-cadherin delivery to the cell surface can be influenced by trans-acting factors, including the presence of the E-cadherin–binding protein β-catenin (Chen *et al.,* 1999).

Post-translational ubiquitylation can also influence protein trafficking (Katzmann *et al.,* 2002; Schnell and Hicke, 2003). In the yeast *Saccharomyces cerevisiae,* mono-ubiquitylation of cytoplasmic domains is necessary and sufficient for the internalization of plasma membrane proteins (Hicke and Riezman, 1996; Shih *et al.,* 2000) and has been suggested to be the primary endocytic signal for most, if not all, yeast proteins (Hicke, 2001). In cultured mammalian cells ligand-dependent ubiquitylation of cell surface receptors triggers their internalization and is a major mechanism of their downregulation (Katzmann *et al.,* 2002). In addition to regulating the initial internalization of membrane proteins, ubiquitin also determines sorting and hence protein fate at a number of points along the endocytic pathway such that if a protein remains ubiquitylated it is sorted to internal vesicles of the multivesicular bodies (MVB) and ultimately degraded in the lysosome (Katzmann *et al.,* 2002). Not surprisingly a number of ubiquitin ligases and cargo-sorting proteins containing ubiquitin-binding or -interacting motifs localize and function at these routing points of the endocytic pathway (Katzmann *et al.,* 2001, 2002; Wang *et al.,* 2001; Reggiori and Pelham, 2002).

Ubiquitylation can be reversed by deubiquitylating enzymes (DUBs), some of which display substrate specificity (Wilkinson, 2000). However, very little is known about the possible role of DUBs in protein trafficking. The *S. cerevisiae* DOA4 gene encodes a DUB that deubiquitylates several endocytosed membrane proteins (Chen and Davis, 2002; Dupre and Haguenauer-Tsapis, 2001; Springael *et al.,* 2002). DOA4 acts at the late endosome/prevacuolar compartment, removing ubiquitin from its substrates before their entrance into the lysosome and is necessary for the recycling of ubiquitin from this pool (Amerik *et al.,* 2000). Recently, the yeast Ubp3p DUB has been shown to be necessary for deubiquitylation of the COPII protein Sec23, to facilitate transport between the endoplasmic reticulum (ER) and the *cis*-Golgi (Cohen *et al.,* 2003). There is very little information, however,

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‡ Corresponding author. E-mail address: stephen.wood@adelaide.edu au.

Abbreviations used: DUB, deubiquitylating enzyme; UBP, ubiquitin-specific protease; TGN, trans-Golgi Network; ER, endoplasmic reticulum; MDCK, Madin-Darby canine kidney; MVB, multivesicular body.

about the involvement of DUBs in protein trafficking in mammalian cells. The murine mUBPY deubiquitylating enzyme interacts with the Hrs-binding protein Hbp, which, together with Hrs, is thought to play a regulatory role in endocytic trafficking of growth factor-receptor complexes through early endosomes. This suggests that mUBPY may play a regulatory role in growth factor-receptor complex degradation but this has not been directly tested (Kato *et al.*, 2000).

Fat facets in mouse (FAM, also known as Usp9X) is a substrate-specific, developmentally regulated UBP (Taya *et al.*, 1998, 1999; Kanai-Azuma *et al.*, 2000; Pantaleon *et al.*, 2001; Noma *et al.*, 2002). Two FAM substrates have been identified, both of which are involved in the establishment and maintenance of epithelial cell adhesion and polarity and cell signaling. FAM interacts with and stabilizes both AF-6 (Taya *et al.*, 1998) and β-catenin (Taya *et al.*, 1999) in vitro and in vivo. AF-6 is a peripheral component of tight junctions that binds to ZO-1 (Yamamoto *et al.*, 1997) and also binds the adherens junction proteins nectin and ponsin as well as activated Ras and Rap1a (Yamamoto *et al.*, 1997; Takahashi *et al.*, 1999; Boettner *et al.*, 2000). β-catenin, a member of the "armadillo" repeat family of proteins, has two essential roles in the epithelial cells. It is required for the maintenance of adherens junctions, where it binds E-cadherin connecting it to the actin cytoskeleton via α-catenin (Conacci-Sorrell *et al.*, 2002). β-catenin is also found in the nucleus, where it acts as a transcriptional coactivator of Wnt signaling genes through its interaction with members of the LEF/TCF family of transcription factors (Conacci-Sorrell *et al.*, 2002). When not bound to either E-cadherin or LEF/TCF the free cytoplasmic pool of β-catenin is rapidly degraded by the ubiquitin-proteasome pathway (Conacci-Sorrell *et al.*, 2002). In vivo depletion of FAM in preimplantation mouse embryos, by addition of antisense oligonucleotides, resulted in a parallel decrease in β-catenin. AF-6 levels were also initially reduced but returned to normal; however, the nascent protein was mis-localized to the apical surface of blastomeres (Pantaleon *et al.*, 2001).

Given the high levels of FAM expression in epithelia during development (Wood *et al.*, 1997; Kanai-Azuma *et al.*, 2000), the identification of β-catenin and AF-6 as substrates (Taya *et al.*, 1998, 1999) and the loss of blastomere adhesion after depletion of FAM (Pantaleon *et al.*, 2001), we decided to further investigate FAM function in epithelia.

MATERIALS AND METHODS

Cell Culture

L-cells and MCF-7 cells were grown in DMEM (GIBCO, Rockville, MD) supplemented with 10% (vol/vol) heat-inactivated fetal calf serum in a humidified atmosphere of 5% (vol/vol) CO_2/air. T84 cells were cultured in a 1:1 mixture of DMEM (GIBCO) and Ham's F12 (GIBCO) medium supplemented with 5% heat-inactivated fetal calf serum in a humidified atmosphere of 5% (vol/vol) CO_2/air. Cells used in immunofluorescence experiments were plated on glass coverslips at a low density and allowed to grow to either subconfluence, where the cultures contained discrete islands of cells or to confluence for 10–14 days. To halt trafficking at the Golgi, cells were incubated at 15°C for 2 h, and in some experiments 10 μM cycloheximide was added to the media 30 min before incubation at 15°C to block protein synthesis. Where indicated cells were incubated in 1 μM brefeldin A (BFA) from penicillin brefeldianum (Sigma, St. Louis, MO) for 1 h to disrupt the Golgi.

Antibodies, Immunoprecipitation, and Western Analysis

Affinity-purified polyclonal anti-FAM rabbit antibody raised to the peptide sequence TATTRGSPVGGNDNQGQAPC were generated as described previously (Kanai-Azuma *et al.*, 2000). Antibodies to E-cadherin, β-catenin (mouse monoclonal), p120, AF6, GM130, Lamp1, and ZO-1 were purchased from BD Transduction Laboratories (Lexington, KY). Antibodies to myosin, β-catenin (rabbit polyclonal), β-tubulin, and anti-rabbit Cy3-conjugated antibody were purchased from Sigma. Anti-mouse Alexa 488–conjugated antibody was purchased from Molecular Probes (Eugene, OR). HRP-conjugated anti-mouse and anti-rabbit antibodies were purchased from Dako (Carpinteria, CA).

For immunoprecipitation cells were lysed in buffer A (50 mM Tris, pH 7.5, 1 mM EDTA, 50 mM NaCl, 0.5% Triton X-100 containing one protease inhibitor cocktail tablet per 10 ml; Complete, Mini; Roche, Indianapolis, IN), centrifuged to remove cell debris, and incubated with protein A agarose for 1 h to remove nonspecifically bound proteins. The resulting supernatant was then incubated with antibody bound to protein A agarose for 1 h, and then unbound proteins were washed away using buffer A, followed by a final wash in PBS. The Protein A agarose was then boiled in SDS sample buffer to elute the bound proteins.

For Western blot analysis, samples were separated by SDS-PAGE, and proteins were transferred onto nitrocellulose (Towbin *et al.*, 1979). Immunoblotting was performed using the ECL kit (Amersham Pharmacia Biotech, Piscataway, NJ) according to the manufacturer's instructions.

Plasmids and Transfections

The E-cadherin expression plasmid (PGK-E-cadherin-hygro) was a gift from Rolf Kemler (Max-Planck Institute for Immunobiology, Freiburg). The pDEST-FAM-V5 was derived by the insertion of FAM cDNA into pEFDEST51 (Invitrogen, Carlsbad, CA) by an LR Gateway reaction. Transient transfections were performed using DOTAP Liposomal Transfection Reagent (Roche) according to their instructions. Briefly, MCF-7 cells were grown to 60–70% confluence either in flasks or on glass coverslips and transfected with the amount of DNA indicated using the solutions provided. After 24 h the medium was changed and the cells grown for a additional 24 h and then either fixed with ethanol or scraped and lysed in buffer A, and the lysate used for subsequent experiments.

Mass Spectrometry Peptide Mass Fingerprinting

Proteins were resolved by SDS-PAGE and stained with Coomassie Blue R-250.

Individual bands were excised, destained, S-amidomethylated, and subjected to in-gel tryptic digestion essentially as described (Speicher *et al.*, 2000). Extracted tryptic peptides were resolved by reversed-phase HPLC using a 1 × 30 mm column packed with Zorbax C-18 Extend matrix (Agilent Technologies, Wilmington, DE) and introduced into a Q-TOF^2 mass spectrometer (Micromass, Manchester, UK) at 10 μl/min. The eluted peaks were analyzed and the monoisotopic masses of the peptides were determined. Lists of peptide masses were used to interrogate the nonredundant NCBI protein sequence database (version NCBInr.03.26.2002) using the programs MS-Fit (http://prospector.ucsf.edu/ucsfhtml4.0/msfit.htm) or MASCOT (http://www.matrixscience.com; Hanson Institute Protein Core Facility).

Separation of T84 Cell Lysates by Gel Filtration Chromatography

T84 cells were washed in ice-cold PBS and then lysed in 250 μl of buffer A. Cell extracts were centrifuged to remove cell debris and 200 μl of the cell lysate was separated by gel filtration. Gel filtration was carried out using a Superose 6 FPLC column (Pharmacia) equilibrated with buffer B (20 mM Tris, pH 7.5, 10% glycerol, and 100 mM NaCl). Fractions (1 ml) were collected.

Immunofluorescence Microscopy

Cells were fixed in 100% ethanol for 20 min at −20°C and then the ethanol was removed. Coverslips were either used immediately or stored at −20°C. Cells were washed in PBS and then blocked with blocking solution (1% BSA in PBS). Cells were incubated at room temperature, with primary antibody and then secondary antibody antibodies for 1 h each.

Images were captured using the Bio-Rad Radiance 2100 confocal microscope (Bio-Rad Microscience Ltd, UK). The dual labeled cells were imaged with two separate channels in a sequential setting. The image data were further analysis using the Confocal Assistant Software (Todd Clark Brelje, University of Minnesota).

T84 cells are columnar cells 20–30 μm in height. Data used throughout this article have been selected to most clearly show the results and may not contain the nuclei because of the height of the cells. Where relevant a section through the basolateral region and a section at the subapical/apical point are shown.

Detergent Solubilization of MCF-7 Epithelial Monolayers

The assessment of cytoskeleton associated β-catenin in MCF-7 cells transfected with pDEST-FAM-V5 was performed according to the protocol of Svastova *et al.* (2003).

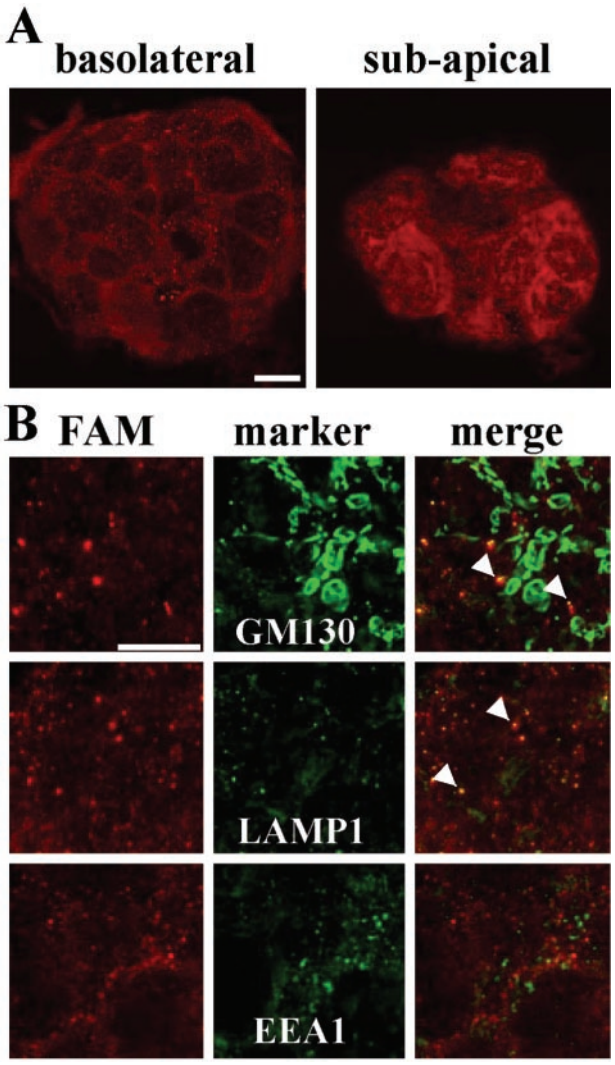

Figure 1. FAM localizes to sites of protein trafficking and sorting in T84 cells. (A) Individual confocal sections from the apical and basolateral regions of subconfluent T84 cells were immunolabeled with anti-FAM antibodies. FAM is found predominantly in vesicles present throughout the cytoplasm and close to or at the plasma membrane in the basolateral region of the cells. (B) Confocal sections from the basolateral region of subconfluent T84 cells were immunolabeled for FAM, GM130, LAMP1, or EEA1. FAM partially colocalizes in vesicles with the Golgi marker GM130 and the MVB marker LAMP1 but not with EEA1, an early endosome marker. Bar, 10 μm.

RESULTS

FAM Localizes to Points of Protein Trafficking

In the polarized intestinal cell line T84, FAM localizes to puncta of varying sizes throughout the cytoplasm from the nucleus to a point at or near the plasma membrane (Figures 1A and 2). Similar results were also obtained in Caco-2 intestinal epithelial cells (unpublished data). The vesicular FAM staining was present throughout the basolateral region of the cell but absent from the apical region, stopping at a point just below the localization of the tight junction protein ZO-1 at points of cell-cell contact. The number of FAM-associated puncta gradually increased toward the apical region of the cell (Figure 1A). To identify with which membrane-bound compartment(s) FAM was associated, cells were colabeled with antibodies specific for FAM and for proteins highly enriched in specific organelles. FAM partially colocalized with the Golgi apparatus marker GM130, with LAMP1, a marker of multivesicular bodies (MVBs) and the lysosome, but little, if any, colocalization was found with EEA1, an early endosome marker (Figure 1B) or the ER marker BiP (unpublished data). The majority of FAM puncta did not colocalize with any of the organelle markers, however, indicating that FAM localized to sites of protein sorting and trafficking in T84 cells.

Identification of Proteins Colocalizing with Vesicular FAM

In light of the fact that two of FAM's substrates, β-catenin and AF-6, are adhesion junction proteins, and hence need to be trafficked to the plasma membrane, we investigated whether these and other adhesion junction proteins colocalized with FAM in T84 cells. In subconfluent T84 cells FAM and β-catenin extensively colocalized in cytoplasmic vesicles throughout the basolateral region of the cell (Figure 2A). FAM did not however colocalize with β-catenin at the cell surface. This was observed in apical regions of subconfluent T84s as well as in confluent cells when all β-catenin was present at cell-cell contacts and there was no overlap with FAM that remained in cytoplasmic vesicles (Figure 2B). Vesicles containing FAM and AF-6 were also detected in the basolateral but not apical regions of subconfluent T84 cells (Figure 2A). Similar results were seen with other cell adhesion molecules including ZO-1, a tight junction protein, and $p120^{ctn}$, an adherens junction protein (Figure 2A).

Detection of FAM at a number of intracellular localizations raised the possibility that distinct populations of FAM exist in T84 cells, possibly in differing protein complexes. To begin the identification of FAM-associated proteins, we performed immunoprecipitation of whole T84 cell lysates and coimmunoprecipitated greater than 40 bands as visualized by Coomassie Blue staining (unpublished data). Eight predominant, high-molecular-weight bands (>100 kDa) were analyzed by MALDI-TOF mass spectometry. Seven of these were identified as either components of the cytoskeleton or motor proteins and included spectrins (nonerythrocyte alpha I and alpha II and beta), alpha 4 actinin, and nonmuscle myosin II and villin as well as a protein with no significant matches to sequences in the nonredundant NCBI protein sequence database (see MATERIALS AND METHODS). Given that these proteins are present in both cytoskeletal structures as well as sites of vesicular protein transport, we performed immunofluorescence to determine if, and where, these proteins colocalized with FAM. Alpha actinin is an actin-binding protein and localizes to both the actin cytoskeleton and vesicles (Pol *et al.*, 1997). Myosin II is a motor protein involved in actin cytoskeleton rearrangements at cellular extensions and also in the budding of a subpopulation of vesicles from the trans-Golgi network (TGN; Ikonen *et al.*, 1997; Allan *et al.*, 2002). In both instances FAM colocalized only with the punctate cytoplasmic staining (Figures 3, A and B), suggesting that the interaction of these proteins was also on vesicles.

FAM Associates with E-cadherin and β-catenin Complexes

To further investigate whether the colocalization of FAM and β-catenin reflected their presence in common complexes, the elution profile of FAM was determined using gel filtration chromatography to separate proteins and protein complexes by size followed by immunoblot anal-

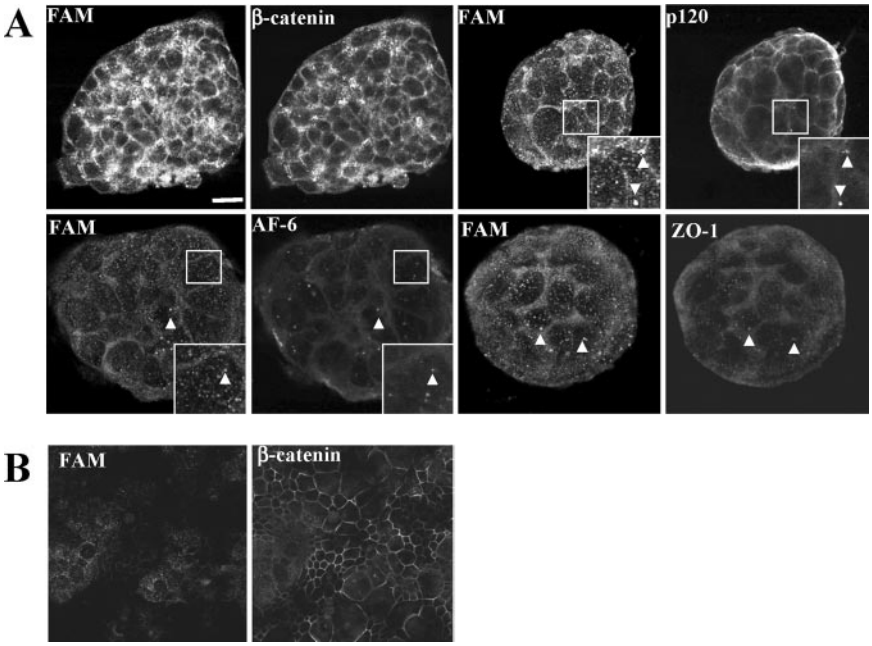

Figure 2. Colocalization of FAM with junction proteins in vesicles. (A) Individual confocal sections from basal regions of subconfluent T84 cells were coimmunolabeled for FAM and the cell adhesion proteins β-catenin, p120catenin, AF-6, and ZO-1. FAM extensively colocalized with the apical junction protein β-catenin found in vesicles in the basolateral region of subconfluent T84 cells and also, but to a lesser extent with p120catenin, AF-6, and ZO-1. Insets: boxed regions at a higher magnification; arrows: colocalizing puncta. The bar in the top panel is 10 μm. (B) Individual confocal sections from an apical region of confluent T84 cells were immunolabeled for FAM and β-catenin. FAM which remains cytoplasmic does not colocalize with β-catenin, which is found at sites of cell-cell contact.

ysis (Figures 4, A and B). FAM was present in at least two distinct complexes in both subconfluent and confluent T84 cells. Population I (PI) eluted around fractions 8–9 in the size range of 2 MDa, whereas population II (PII) peaked around fraction 13 (500 kDa), eluting over several fractions that vary in size from ~290 kDa, free FAM, to part of a complex of at least 400–700 kDa. Both populations have the potential to contain several FAM-associated complexes. The proportion of FAM located in the two populations did not vary from subconfluent to confluent cells (compare Figures 4, A and B). Lysates extracted from Caco-2 cells fractionated with a very similar elution profile (unpublished data). β-catenin coeluted in PI and PII, the majority eluting in PI (Figures 4, A and B); however, the ratio of β-catenin changed depending on cell confluence, such that the amount in PII is reduced in confluent T84 cells. Similar results were also seen for E-cadherin, such that little, if any, E-cadherin was present in PII at confluence (Figures 4, A and B). In addition, p120 catenin, which associates with the cadherin complex at the plasma membrane (Davis *et al.*, 2003), was also only detected in the large molecular weight complex in confluent T84 cells (Figure 4B).

Although proteins coelute this does not necessarily mean that they are in a complex together. Therefore to test whether β-catenin and E-cadherin were in a complex with FAM in either PI or PII, immunoprecipitation with anti-FAM antibodies was performed from fractions 8–9 and fractions 12–15, and the FAM-associated proteins were analyzed (Figure 4C). E-cadherin and β-catenin coimmunoprecipitated with FAM from PII but not PI despite the fact that the vast majority of β-catenin and E-cadherin was present in PI. The predicted size of an E-cadherin, β-catenin, and FAM complex (~500 kDa) is consistent with elution around fractions 13, suggesting that the FAM may be in a complex with these proteins alone. p120 catenin did not coimmunprecipitate with FAM, from either subor confluent T84 cells under the conditions used (unpublished data).

FAM Localizes to the Golgi Independently of β-catenin T84 Cells

β-catenin associates with E-cadherin at the ER before the dimer is transported to the Golgi and ultimately the plasma membrane (Chen *et al.*, 1999). Given FAM's interaction with β-catenin in T84 as well as others cells (Taya *et al.*, 1998, 1999), we wanted to determine if FAM's localization to the Golgi was dependent on β-catenin. First, cells were treated with BFA, which disrupts Golgi architecture (Lippincott-Schwartz *et al.*, 1989). This treatment resulted in the severe disruption of FAM localization throughout the entire cell (Figure 5A). To further analyze FAM's association with the Golgi, trafficking was halted at the pre-Golgi stage by incubation of cells at 15°C (Saraste and Kuismanen, 1984). After incubation at 15°C for 2 h a much greater proportion of FAM was found localized at the Golgi than in cells grown under normal conditions (compare Figures 5B and 1B). However, this localization at the Golgi was independent of β-catenin, which was not present at the Golgi (Figure 5C). The lack of β-catenin at the Golgi was anticipated as the cells were treated with 10 μM cycloheximide, a translation inhibitor, for 30 min before incubation of the cells at 15°C for 2 h. Therefore nascent proteins of the secretory pathway, including E-cadherin and associated β-catenin, would have trafficked beyond the Golgi.

Expression of E-cadherin in Cadherin-negative Fibroblasts Redistributes FAM from the Golgi to Cytoplasmic Vesicles

Although FAM localized to the Golgi independently of E-cadherin and β-catenin, we wanted to determine if the E-cadherin–β-catenin complex could nevertheless influence FAM's localization in the cell. Therefore, we investigated the localization of FAM in L-cell fibroblasts, a cadherin-negative cell line, in the presence or absence of E-cadherin. In the absence of E-cadherin, free cytoplasmic β-catenin is rapidly degraded by the ubiquitin-proteasome system (Aberle *et al.*, 1997; Kitagawa *et al.*, 1999) and consequently L-cells have low levels of β-catenin protein. The majority of FAM local-

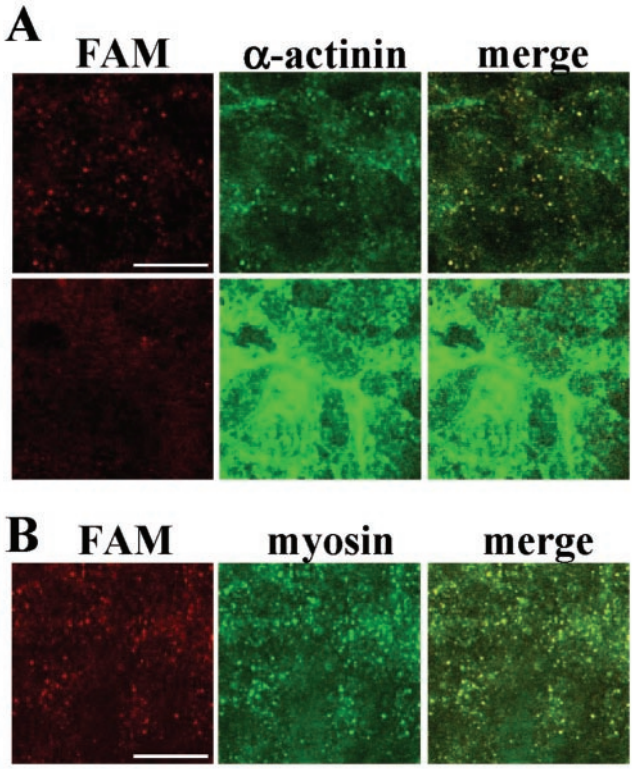

Figure 3. FAM localizes with punctate forms of α-actinin and myosin in T84 cells. (A) Individual confocal sections from both the apical and basolateral region of T84 cells were immunolabeled for FAM and α-actinin. FAM partially colocalizes with α-actinin in vesicles but not with that found at the plasma membrane. (B) Individual confocal sections from the basolateral region of subconfluent T84 cells were immunolabeled for FAM and myosin. FAM and myosin partially colocalize in basolateral cytoplasmic vesicles.

ized to the Golgi in L-cells but low levels were also detected in cytoplasmic puncta (Figure 6A), confirming FAM's association with the Golgi in the absence of β-catenin.

We generated stably transfected L-cell lines expressing exogenous E-cadherin. This resulted in changes to cell morphology, with the cells becoming more epithelial-like. The localization of FAM was also clearly altered with the majority of FAM localized to vesicles in the cytoplasm rather than to the Golgi (Figure 6B). In some cells punctate FAM staining was detected predominantly in submembranous regions below sites of cell-cell contact (Figure 6B). This alteration in FAM localization was not due to changes in overall cellular FAM levels (Figure 6C). FAM was found to be associated with E-cadherin in these cells (Figure 6D).

Overexpression of FAM in MCF-7 Epithelial Cells Increases the Level of β-catenin at the Plasma Membrane

Finally, we wanted to determine if FAM could influence β-catenin levels and/or intracellular localization. To this end we overexpressed V5 epitope-tagged full-length FAM in polarized MCF-7 epithelial cells, which express both β-catenin and E-cadherin (Zhu *et al.*, 2001) and are more amenable to transient transfection than T84 cells. Expression of exogenous FAM resulted in increased levels of β-catenin, E-cadherin, and p120 catenin (Figure 7A). These increases appeared to be correlated with the level of exogenous FAM expressed (Figure 7A, compare lanes 2 and 3). To determine where β-catenin was localized in cells expressing exogenous FAM, immunofluorescence was performed. There was no colocalization of β-catenin and FAM in transfected cells as detected by the V5 epitope (Figure 7B) with β-catenin predominantly at the plasma membrane and FAM in cytoplasmic vesicles. β-catenin was not detected in the nucleus in any transfected cells. This suggested that FAM increased β-catenin in stable cadherin-catenin adhesion complexes at sites of cell-cell contact. Similar results were observed in HEK293T cells (unpublished data). Functional cadherin-catenin adhesion complexes are bound to the cytoskeleton

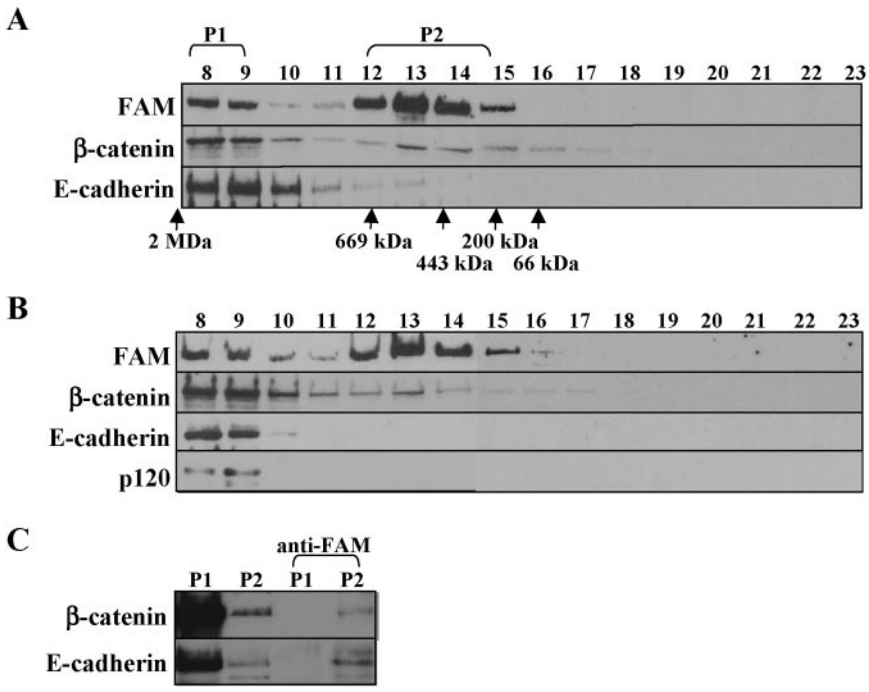

Figure 4. Two populations of FAM exist in T84 cells, one containing a proportion of cellular E-cadherin and β-catenin. (A and B) Subconfluent and confluent, respectively, T84 cell lysates were separated by gel filtration chromatography using a Superose 6 column. Fractions were immunoblotted with anti- FAM, E-cadherin, β-catenin, and p120catenin antibodies. FAM elutes as at least two distinct populations in both subconfluent and confluent T84 cells, both of which elute with β-catenin, although the proportion of β-catenin eluting with PII is reduced in confluent cells. (C) Proteins eluted in PI (fractions 8–9) and PII (fractions 12–15) were immunoblotted, either before or after immunoprecipitaion with anti-FAM antibodies, with antibodies against FAM, β-catenin, and E-cadherin. Both β-catenin and E-cadherin associate with FAM in a complex of ~500 kDa but not with the larger FAM complex(es).

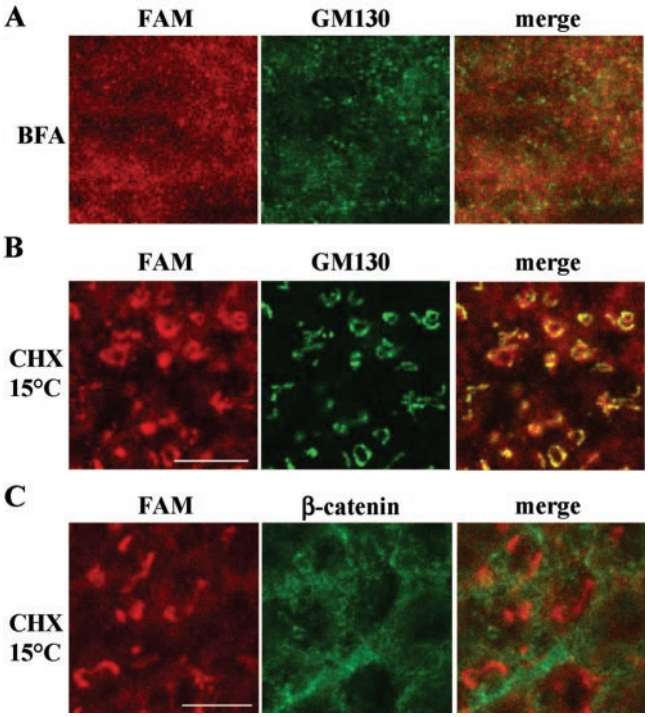

Figure 5. Disrupting the Golgi alters FAM localization, whereas halting traffic at the Golgi in T84 cells localizes FAM to the Golgi. (A) T84 cells were incubated with 1 μM brefeldin A for 1 h at 37°C to disrupt the Golgi. Individual confocal sections were immunostained for FAM and GM130. FAM localization is altered when the Golgi is disrupted. (B and C) Individual T84 cells were incubated with 10 μM cycloheximide for 30 min at 37°C to deplete protein production before incubation at 15°C for 2 h to halt trafficking at the Golgi. Individual confocal sections from the basolateral region of T84 cells were immunostained for FAM, GM130, and β-catenin. A dramatic increase in the proportion FAM localizing with GM130 is seen when trafficking is halted at the Golgi but this is independent of β-catenin, which did not colocalize with GM130.

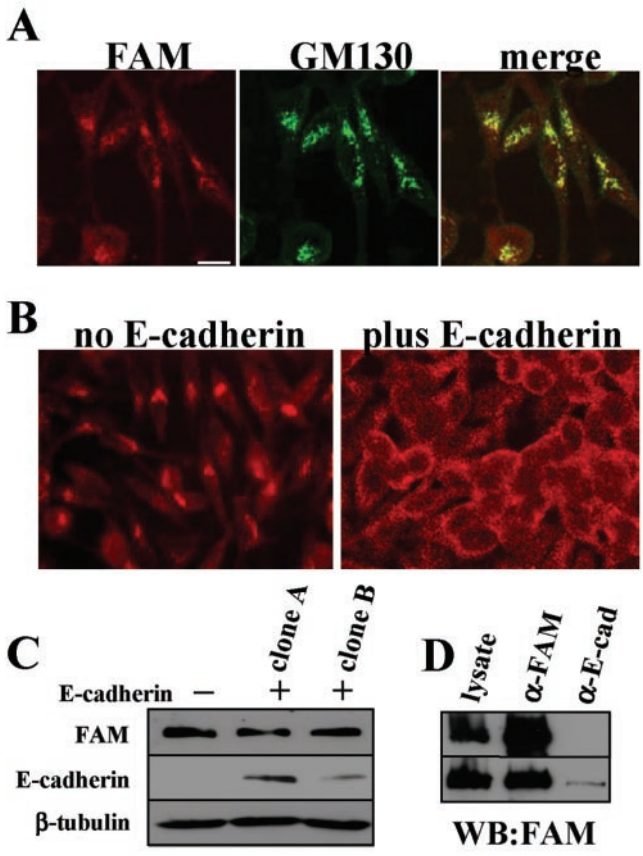

Figure 6. Exogenous E-cadherin in L-cell fibroblasts redistributes FAM from the Golgi to vesicles in the cytoplasm. (A) Individual confocal sections of L-cells, which have no E-cadherin, were immunostained for FAM and GM130. In the absence of E-cadherin FAM localizes to the Golgi. (B) Individual confocal sections of L-cells stably transfected with full-length E-cadherin were immunostained with anti-FAM antibodies. FAM relocalizes from the Golgi to vesicles after the addition of E-cadherin to L-cells. (C) L-cells stably transfected with full-length E-cadherin were lysed and immunoblotted with antibodies against FAM, E-cadherin, and β-tubulin. Expression of E-cadherin does not increase the level of FAM. (D) Lysates from untransfected (top row) and E-cadherin–expressing clone A (bottom row) were immunoprecipitated with antibodies against FAM or E-cadherin before Western analysis with FAM antibodies. FAM associates with E-cadherin in L-cells after the addition of exogenous E-cadherin.

and hence insoluble in Triton X-100, whereas a membrane-inserted E-cadherin–β-catenin complex not involved in cell adhesion is Triton X-100 soluble (Svastova *et al.*, 2003). Therefore to directly assess whether the FAM-induced increase in β-catenin, E-cadherin, and p120 catenin levels was due to increased adhesion complexes, the proportion of β-catenin in Triton X-100–soluble and –insoluble fractions was determined. At subconfluence a higher proportion of β-catenin in the soluble fraction in untransfected cells was observed (Figure 7C). The presence of exogenous FAM, however, resulted in a higher proportion of β-catenin in the insoluble fraction (Figure 7C), although FAM was found entirely in the soluble fraction, indicating that FAM itself is not associated with mature adhesion complexes. Together these data indicate that FAM facilitates the transport of the cadherin-catenin complex to the plasma membrane.

DISCUSSION

FAM Localizes at Sites of Protein Trafficking

Here we demonstrate that the FAM deubiquitylating enzyme localizes to sites of protein trafficking and/or sorting in epithelia and fibroblasts. These included the Golgi and late endosomes and/or lysosomes as well as cytoplasmic vesicles but not EEA1-positive early endosomes nor the ER. The Golgi apparatus was the predominant site of FAM localization in L-cell fibroblasts (Figure 6) and HEK293T cells (unpublished data). In addition, blocking protein trafficking at the Golgi in T84 cells resulted in most of FAM colocalizing with the Golgi marker GM130 (Figure 5B), suggesting that the majority, if not all, FAM associates with the Golgi at some point. Similarly, disruption of endocytosis also resulted in dramatic relocalization of all FAM throughout the cell (unpublished data). This suggests that in T84 cells FAM is not statically resident at particular subcellular localizations and raises the possibility that it may remain associated with vesicles as they traverse between different compartments.

That ubiquitin plays a role in the regulation of protein trafficking is now well established although not fully understood (Katzmann *et al.*, 2002; Schnell and Hicke, 2003). The ubiquitylation status of endocytosed proteins determines

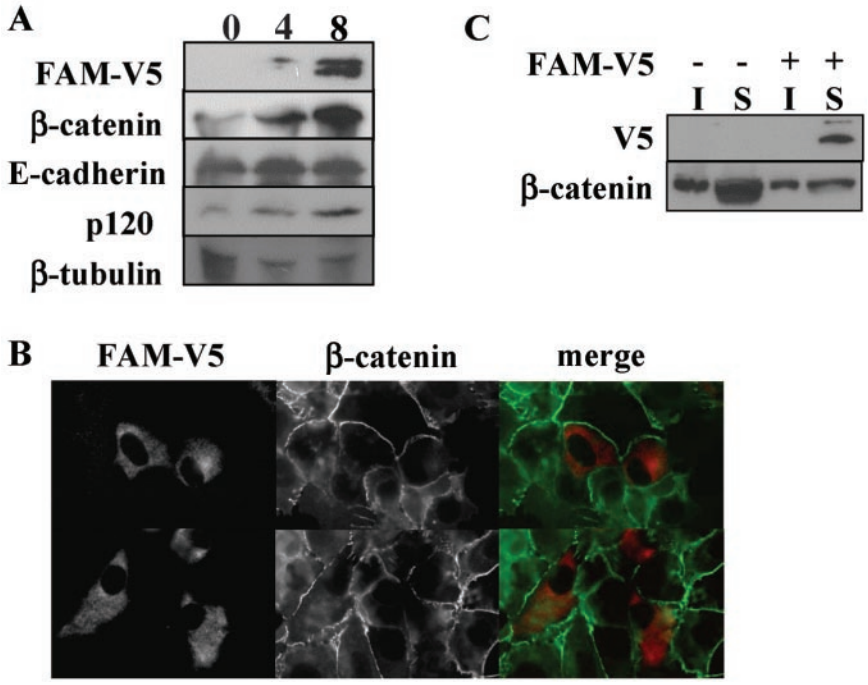

Figure 7. Overexpression of FAM in MCF-7 cells increases the level of β-catenin at the plasma membrane. (A) MCF-7 cells were analyzed for adhesion protein expression 48 h after transient transfection with 0, 4, or 8 μg of pDEST-FAM-V5. V5 epitope was detected in both transfected populations (4 μg lane clearly visible on longer exposure). When compared with the β-tubulin loading control, the level of all adhesion proteins was increased in the presence of exogenous FAM. β-catenin and p120catenin appeared to show a grade response to the different levels of FAM-V5. (B) Confluent MCF-7 cells were analyzed for the localization of exogenous FAM as detected by the V5 epitope, and β-catenin. FAM-V5 and β-catenin did not colocalize, with FAM predominantly in cytoplasmic vesicles and β-catenin concentrated at the plasma membrane. Only 10–20% of the cells appeared to have been transfected. (C) Soluble and insoluble fractions of β-catenin in subconfluent MCF-7 cells transiently transfected with pDEST-FAM-V5. Although exogenous FAM is exclusively localized to the soluble fraction, it results in a higher proportion of β-catenin in the insoluble fraction.

their fates en route to the lysosome. If the protein remains ubiquitylated, it is sequestered into internal vesicles of multivesicular bodies and hence is delivered into the lysosome (Katzmann *et al.,* 2002). A number of ubiquitin ligases and ubiquitin-interacting proteins regulating these processes have been identified suggesting a networking or scaffolding role for ubiquitin in forming protein trafficking complexes (Schnell and Hicke, 2003). The yeast deubiquitylating enzyme Doa4 functions at the late endosome/prevacuolar compartment to facilitate the recycling of ubiquitin from substrates as they are sorted into internal vesicles. Although FAM and Doa4p both localize to late stages of the endocytic pathway, they are not homologues. They share little sequence similarity beyond their ubiquitin-specific protease motifs, and Doa4 (Ubp4p) was unable to functionally replace FAM's homologue in *Drosophila* Fat Facets (Faf), whereas Fam could (Wu *et al.,* 1999; Chen *et al.,* 2000). The identification of liquid facets, the *Drosophila* homologue of epsin, as a critical substrate of Faf during photoreceptor development further implicates the Fat Facets deubiquitylating enzymes in the regulation of protein trafficking (Chen *et al.,* 2002). Genetic studies have also established that Faf facilitates endocytosis (Cadavid *et al.,* 2000).

FAM's localization at the Golgi apparatus raises the possibility that it may also play a role in regulating trafficking in the biosynthetic pathway. Targeting of proteins in the biosynthetic pathway can also be influenced by ubiquitylation, especially at the TGN. Monoubiquitylation of the yeast permease Gap1 results in transport to the plasma membrane, whereas polyubiquitylation targets it to the vacuole, a process regulated by the ubiquitin ligase Rsp5 and the ubiquitin ligase adaptors BUL1 and BUL2 (Helliwell *et al.,* 2001). The role of deubiquitylating proteins in this process, however, is unknown. FAM's colocalization with and immunoprecipitation of vesicular myosin II suggests that it may be involved in the trafficking of a subset of vesicles targeted to basolateral domains as they bud from the TGN (Musch *et al.,* 1997; Allan *et al.,* 2002). FAM is the first DUB to be shown to be localized to the Golgi apparatus and may be involved in regulating protein trafficking by antagonizing the function of ubiquitin ligases such as Rsp5 (Wang *et al.,* 2001; Kaminska *et al.,* 2002). Recently a function for the yeast Ubp3 in mediating COPII vesicle traffic between the ER and *cis*-Golgi has been proposed (Cohen *et al.,* 2003). However, although Ubp3p's substrate Sec23 functions in this region, Ubp3's interaction with Sec23 at this cellular location was not demonstrated (Cohen *et al.,* 2003).

Interestingly, the localization of FAM in polarized T84 epithelial cells differs from that observed in MDCK cells where it tightly localizes to sites of cell-cell contact (Taya *et al.,* 1998). The differences reported may be due to the different targeting mechanisms used by the two epithelia. MDCK cells directly target cargo to the basolateral membrane from the TGN. However intestinal epithelial cells, such as T84 use an indirect route involving a series of membrane insertions and recycling between the plasma membrane and sorting endosomes (Mostov *et al.,* 2000). In T84 cells, therefore, FAM may have a shorter resident time at sites of cell-cell contact. Alternatively the differences may reflect that the antibodies used were raised to different FAM epitopes. However, FAM has also been detected in a vesicular staining pattern in other epithelia, including the polarized trophectoderm cells of preimplantation mouse embryos (Pantaleon *et al.,* 2001) and in both primary and cultured (HaCaT) keratinocytes (S.A.W., unpublished observations).

Association of FAM with the E-cadherin–β-catenin Complex during Trafficking

We have shown previously that FAM interacts with and stabilizes the cell adhesion–associated and signaling molecules β-catenin and AF-6 (Taya *et al.,* 1998, 1999). In T84 cells FAM colocalized with a number of cell adhesion–associated proteins, including β-catenin, AF-6, α-actinin, ZO-1, and p120 catenin. Colocalization was only seen in the cytoplasmic puncta with all these proteins and not at sites of cell-cell contact although some punctate staining was evident just beneath the plasma membrane. The most extensive colocal-

ization observed was with the FAM substrate β-catenin in subconfluent cells (Figure 2A).

In epithelia, β-catenin associates with the cytoplasmic domain of E-cadherin at the ER (Chen *et al.*, 1999) before the complex is transported through the Golgi apparatus and to the basolateral plasma membrane. Although we have previously speculated that in preimplantation mouse embryos FAM stabilizes cytoplasmic β-catenin (Pantaleon *et al.*, 2001), several of the data presented here indicate that FAM can also associate with another pool of β-catenin, namely the E-cadherin– and vesicle-associated form in transit to or from the plasma membrane. First, as mentioned above, FAM only colocalized with the punctate staining of β-catenin in subconfluent cells (Figure 2A), whereas in confluent cells FAM did not colocalize at sites of cell-cell contact nor did the proteins immunoprecipitate. In subconfluent cells the adhesion junctions are unstable, undergoing constant rearrangement and insertion of new cadherin-catenin complexes (Le *et al.*, 1999), whereas at confluence cadherin complexes are stable and contain many more associated proteins.

Second, the coimmunoprecipitation of FAM with β-catenin and E-cadherin from the smaller fractions of PII only and failure to detect FAM at sites of cell-cell contact suggests that FAM does not associate with mature E-cadherin–β-catenin adhesion complexes. The size of fractions from PII are consistent with a complex containing FAM and β-catenin and E-cadherin alone, although the broad range of molecular weights covered in the complex does not preclude the presence of a small number of other proteins. The majority of E-cadherin and β-catenin was in PI, which contains higher molecular weight complexes in the order of 2 MDa, which are most probably stable cell adhesion complexes at the plasma membrane. The presence of p120catenin in PI only and the failure of FAM to immunoprecipitate with p120catenin supports the argument that FAM does not associate with mature cadherin adhesion complexes. In addition E-cadherin is not present in PII in confluent cells when there is decreased transport of E-cadherin out to PM and little recycling (Le *et al.*, 1999). Interestingly in no instances did FAM immunoprecipitation pull-down β-catenin and not E-cadherin also, even though some β-catenin was detected in PII in confluent cells and E-cadherin was not. This suggests that in T84 cells FAM associates with the E-cadherin–β-catenin complex alone.

In addition, introduction of E-cadherin into L-cells resulted in the relocation of a large fraction of FAM to vesicular structures in the cytoplasm (Figure 6B) strongly arguing that FAM is associated with the trafficking of E-cadherin–β-catenin complexes. Reciprocally, increased expression of FAM in MCF-7 cells, which are polarized epithelia expressing both β-catenin and E-cadherin, resulted in an increase in β-catenin, E-cadherin, and p120 catenin levels (Figure 7A) The increased β-catenin localized at the plasma membrane and not in the nucleus (Figure 7, B and C) as occurs in the presence of Wnt signaling (Hecht and Kemler, 2000). These data indicate that FAM's effect are on the cadherin-catenin adhesion complex and not on stabilization of free cytoplasmic β-catenin. The fact that FAM was found entirely in the soluble fraction and not in the adhesion complexes suggests that its primary role is to facilitate transport of the complex to the plasma membrane. This raises the interesting possibility that FAM and E-cadherin can simultaneously bind the armadillo repeats of β-catenin (Taya *et al.*, 1999; Huber *et al.*, 2001; Shapiro, 2001).

Two types of vesicles would be expected to contain β-catenin in subconfluent epithelia: those of the biosynthetic pathway as well as endocytic vesicles. The colocalization of FAM with virtually all basolateral β-catenin vesicles suggest that it is associated, at least in part, with β-catenin as it traffics toward the plasma membrane. This is supported by FAM's colocalization with myosin II, which labels vesicles as they bud form the TGN (Ikonen *et al.*, 1997).

We propose that FAM is a deubiquitylating enzyme associated with intracellular protein trafficking. In epithelial cells it appears that FAM may regulate the trafficking of both tight and adherens junction–associated proteins including AF-6, ZO-1, and the E-cadherin–β-catenin dimer. Both β-catenin and E-cadherin are known to be ubiquitylated. The cytoplasmic tail of E-cadherin is unstructured in the absence of bound β-catenin (Huber *et al.*, 2001). It also contains PEST sequences, which overlap with the β-catenin–binding sites, and so E-cadherin uncomplexed is degraded at the ER in a ubiquitin-dependent manner (Chen *et al.*, 1999). E-cadherin at the plasma membrane can also be ubiquitylated by the ubiquitin ligase, Hakai, in response to Src kinase (Fujita *et al.*, 2002). The ubiquitylation of β-catenin has been well characterized but has generally been thought to be restricted to the free cytoplasmic pool. However, Hakai activation also results in the ubiquitylation of β-catenin at the plasma membrane (Fujita *et al.*, 2002).

The data here show that the mammalian-deubiquitylating enzyme FAM plays a role in the trafficking of β-catenin and E-cadherin in epithelia. The data also suggest that this occurs in part, as the E-cadherin–β-catenin complex moves through the biosynthetic pathway. This may reflect a wider role for FAM in regulating the trafficking of other adhesion junction proteins, including another FAM substrate, AF-6. Whether FAM's function as a deubiquitylating enzyme is important in these processes requires further investigation.

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REFERENCES

Aberle, H., Bauer, A., Stappert, J., Kispert, A., and Kemler, R. (1997). b-catenin is a target for the ubiquitin-proteasome pathway. EMBO J. *16,* 3797–3804.

Allan, V.J., Thompson, H.M., and McNiven, M.A. (2002). Motoring around the Golgi. Nat. Cell Biol. *4,* E236–E242.

Amerik, A.Y., Nowak, J., Swaminathan, S., and Hochstrasser, M. (2000). The Doa4 deubiquitinating enzyme is functionally linked to the vacuolar protein-sorting and endocytic pathways. Mol. Biol. Cell *11,* 3365–3380.

Boettner, B., Govek, E.-E., Cross, J., and Van Aelst, L. (2000). The junctional multidomain protein AF-6 is a binding partner of the Rap1A GTPase and associates with the actin cytoskeletal regulator profilin. Proc. Natl. Acad. Sci. USA *97,* 9064–9069.

Cadavid, A.L.M., Ginzel, A., and Fischer, J.A. (2000). The function of the *Drosophila* Fat facets deubiquitinating enzyme in limiting photoreceptor cell number is intimately associated with endocytosis. Development *127,* 1727–1736.

Chen, L., and Davis, N.G. (2002). Ubiquitin-independent entry into the yeast recycling pathway. Traffic *3,* 110–123.

Chen, X., Overstreet, E., Wood, S.A., and Fischer, J.A. (2000). On the conservation of function of the *Drosophila* Fat facets deubiquitinating enzyme and Fam, its mouse homolog. Dev. Genet. Evol. *210,* 603–610.

Chen, X., Zhang, B., and Fischer, J.A. (2002). A specific protein substrate for a deubiquitinating enzyme: liquid facets is the substrate of Fat facets. Genes Dev. *16,* 289–294.

Chen, Y.-T., Stewart, D.B., and Nelson, W.J. (1999). Coupling assembly of the E-cadherin/beta-catenin complex to efficient enoplasmic reticulum exit and basal-lateral membrane targeting of E-cadherin in polarized MDCK cells. J. Cell Biol. *144,* 687–699.

Cohen, M., Stutz, F., Belgareh, N., Haguenauer-Tsapis, R., and Dargemont, C. (2003). Ubp3 requires a cofactor, Bre5, to specifically de-ubiquitinate the COPII protein, Sec23. Nat. Cell Biol. *5,* 661–667.

Conacci-Sorrell, M., Zhurinsky, J. and Ben-Ze'ev, A. (2002) The cadherin-catenin adhesion system in signaling and cancer. J. Clin. Invest. *109,* 987–991.

Davis, M.A., Ireton, R.C., and Reynolds, A.B. (2003). A core function for p120-catenin in cadherin turnover. J. Cell Biol. *163,* 525–534.

Dupre, S. and Haguenauer-Tsapis, R. (2001) Deubiquitination step in the endocytic pathway of yeast plasma membrane proteins: crucial role of Doa4p ubiquitin isopeptidase. Mol. Cell. Biol. *21,* 4482–4494.

Fujita, Y., Krause, G., Scheffner, M., Zechner, D., Leddy, H.E.M., Behrens, J., Sommer, T., and Birchmeier, W. (2002). Hakai, a c-Cbl-like protein, ubiquitinates and induces endocytosis of the E-cadherin complex. Nat. Cell Biol. *4,* 222–231.

Hecht, A., and Kemler, R. (2000). Curbing the nuclear activities of beta-catenin. Control over Wnt target gene expression. EMBO Rep. *1,* 24–28.

Helliwell, S.B., Losko, S., and Kaiser, C.A. (2001). Components of a ubiquitin ligase complex specify polyubiquitination and intracellular trafficking of the general amino acid permease. J. Cell Biol. *153,* 649–662.

Hicke, L. (2001). Protein regulation by monoubiquitin. Nat. Rev. Mol. Cell. Biol. *2,* 195–201.

Hicke, L., and Riezman, H. (1996). Ubiquitiniation of a yeast plasma membrane receptor signals its ligand-stimulated endocytosis. Cell *84,* 277–287.

Huber, A.H., Stewart, D.B., Laurents, D.V., Nelson, W.J., and Weis, W.I. (2001). The cadherin cytoplasmic domain is unstructured in the absence of b-catenin. A possible mechanism for regulating cadherin turnover. J. Biol. Chem. *276,* 12301–12309.

Ikonen, E., de Almeid, J.B., Fath, K.R., Burgess, D.R., Ashman, K., Simons, K., and Stow, J.L. (1997). Myosin II is associated with Golgi membranes: identification of p200 as nonmuscle myosin II on Golgi-derived vesicles. J. Cell Sci. *110,* 2155–2164.

Kaminska, J., Gajewska, B., Hopper, A.K., and Zoladek, T. (2002). Rsp5p, a new link between the actin cytoskeleton and endocytosis in the yeast Saccharomyces cerevisiae. Mol. Cell. Biol. *22,* 6946–6948.

Kanai-Azuma, M., Mattick, J.S., Kaibuchi, K., and Wood, S.A. (2000). Co-localization of FAM and AF-6, the mammalian homologues of *Drosophila faf* and *canoe*, in mouse eye development. Mech. Dev. *91,* 383–386.

Kato, M., Miyazawa, K., and Kitamura, N. (2000). A deubiquitinating enzyme UBPY interacts with the Src homology 3 domain of Hrs-binding protein via a novel binding motif PX(V/I)(D/N)RXXKP. J. Biol. Chem. *275,* 37481–37487.

Katzmann, D.J., Babst, M., and Emr, S.D. (2001). Ubiquitin-dependent sorting into the multivesicular pathway requires the function of a conserved endosomal protein sorting complex, ESCRT-I. Cell *106,* 145–155.

Katzmann, D.J., Odorizzi, G., and Emr, S.D. (2002). Receptor downregulation and multivesicular-body sorting. Nat. Rev. Mol. Cell. Biol. *3,* 893–905.

Kitagawa, M. *et al.* (1999). An F-box, FWD1, mediates ubiquitin-dependent proteolysis of b-catenin. EMBO J. *18,* 2401–2410.

Le Bivic, A., Quaroni, A., Nichols, B., and Rodriguez-Boulan, E. (1990). Biogenetic pathways of plasma membrane proteins in Caco-2, a human intestinal epithelial cell line. J. Cell Biol. *111,* 1351–1361.

Le, T.L., Yap, A.S., and Stow, J.L. (1999). Recycling of E-cadherin: a potential mechanism for regulating cadherin dynamics. J. Cell Biol. *146,* 219–232.

Lippincott-Schwartz, J., Yuan, L.C., Bonifacino, J.S., and Klausner, R.D. (1989). Rapid redistribution of Golgi proteins into the ER in cells treated with brefeldin A: evidence for membrane cycling from Golgi to ER. Cell *56,* 801–813.

Matter, K., Brauchbar, M., Bucher, K., and Hauri, H.P. (1990). Sorting of endogenous plasma membrane proteins occurs from two sites in cultured human intestinal epithelial cells (Caco-2). Cell *60,* 429–437.

Maurice, M., Schell, M.J., Lardeux, B., and Hubbard, A.L. (1994). Biosynthesis and intracellular transport of a bile canalicular plasma membrane protein: studies in vivo and in the perfused rat liver. Hepatology *19,* 648–655.

Miranda, K.C., Khromykh, T., Christy, P., Le, T.L., Gottardi, C.J., Yap, A.S., Stow, J.L., and Teasdale, R.D. (2001). A dileucine motif targets E-cadherin to the basolateral cell surface in Madin-Darby canine kidney and LLC-PK1 epithelial cells. J. Biol. Chem. *276,* 22565–22572.

Mostov, K.E., Verges, M., and Altschuler, Y. (2000). Membrane traffic in polarized epithelial cells. Curr. Opin. Cell Biol. *12,* 483–490.

Musch, A., Cohen, D., and Rodriguez-Boulan, E. (1997). Myosin II is involved in the production of constitutive transport vesicles from the TGN. J. Cell Biol. *138,* 291–306.

Noma, T., Kanai, Y., Kanai-Azuma, M., Ishii, M., Fujisawa, M., Kurohmaru, M., Kawakami, H., Wood, S.A., and Hayashi, Y. (2002). Stage- and sex-dependent expressions of Usp9x, an X-linked mouse ortholog of *Drsosphila* Fat Facets, during gonadal development and oogenesis in mice. Mech. Dev. *119,* 1–5.

Pantaleon, M., Kanai-Azuma, M., Mattick, J.S., Kaibuchi, K., Kaye, P.L., and Wood, S.A. (2001). FAM deubiquitylating enzyme is essential for preimplantation mouse embryo development. Mech. Dev. *109,* 151–160.

Pol, A., Ortega, D., and Enrich, C. (1997). Identification of cytoskeleton-associated proteins in isolated rat liver endosomes. Biochem. J. *327,* 741–746.

Reggiori, F., and Pelham, H.R.B. (2002). A transmembrane ubiquitin ligase required to sort membrane proteins into multivesicular bodies. Nat. Cell Biol. *4,* 117–123.

Saraste, J., and Kuismanen, E. (1984). Pre- and post-Golgi vacuoles operate in the transport of Semliki Forest virus membrane glycoproteins to the cell surface. Cell *38,* 535–549.

Schnell, J. D. and Hicke, L. (2003) Non-traditional functions of ubiquitin and ubiquitin-binding proteins. J. Biol. Chem. epub Ms R300018200.

Shapiro, L. (2001). beta-catenin and its multiple partners: promiscuity explained. Nat. Struct. Biol. *8,* 484–487.

Shih, S.C., Sloper-Mould, K.E., and Hicke, L. (2000). Monoubiquitin carries a novel internalization signal that is appended to activated receptors. EMBO J. *19,* 187–198.

Speicher, K.D., Kolbas, O., Harper, S., and Speicher, D.W. (2000). Systematic analysis of peptide recoveries from in-gel digestions for protein identifications in proteome studies. J. Biomol. Tech. *11,* 74–86.

Springael, J.Y., Nikko, E., Andre, B., and Marini, A.M. (2002). Yeast Npi3/Bro1 is involved in ubiquitin-dependent control of permease trafficking. FEBS Lett. *517,* 103–109.

Svastova, E., Zilka, N., Zat'ovicova, M., Gibadulinova, A., Ciampor, F., Pastorek, J., and Pastorekova, S. (2003). Carbonic anhydrase IX. reduces E-cadherin-mediated adhesion of MDCK cells via interaction with beta-catenin. Exp. Cell Res. *290,* 332–345.

Takahashi, K. *et al.* (1999). Nectin/PRR: an immunoglobulin-like cell adhesion molecule recruited to cadherin-based adherens junctions through interaction with Afadin, a PDZ domain-containing protein. J. Cell Biol. *145,* 539–549.

Taya, S., Yamamoto, T., Kanai-Azuma, M., Wood, S.A., and Kaibuchi, K. (1999). The deubiquitinating enzyme Fam interacts with and stabilizes b-catenin. Genes Cells *4,* 757–767.

Taya, S. *et al.* (1998). The Ras target AF-6 is a substrate of the fam deubiquitinating enzyme. J. Cell Biol., *142,* 1053–1062.

Towbin, H., Staehelin, T., and Gordon, J. (1979). Electrophoretic transfer of proteins from polyacrylamide gels to nitrocellulose sheets: procedure and some applications. Proc. Natl. Acad. Sci. USA *76,* 4350–4354.

Wang, G., McCaffery, J.M., Wendland, B., Dupre, S., Haguenauer-Tsapis, R., and Huibregtse, J.M. (2001). Localization of the Rsp5p ubiquitin-protein ligase at multiple sites within the endocytic pathway. Mol. Cell. Biol. *21,* 3564–3575.

Wilkinson, K.D. (2000). Ubiquitination and deubiquitination: targeting of proteins for degradation by the proteasome. Semin. Cell Dev. Biol. *11,* 141–148.

Wood, S.A., Pascoe, W.S., Ru, K., Yamada, T., Hirchenhain, J., Kemler, R., and Mattick, J.S. (1997). Cloning and expression analysis of a novel mouse gene with sequence similarity to the *Drosophila fat facets* gene. Mech. Dev. *63,* 29–38.

Wu, Z., Li, Q., Fortini, M.E., and Fischer, J.A. (1999). Genetic analysis of the role of the *Drosophila fat facets* gene in the ubiquitin pathway. Dev. Genet. *25,* 312–320.

Yamamoto, K., Harada, N., Kano, K., Taya, S., Canaani, E., Matsuura, Y., Mizoguchi, A., Ide, C., and Kaibuchi, K. (1997). The Ras target AF-6 interacts with ZO-1 and serves as a peripheral component of tight junctions in epithelial cells. J. Cell Biol. *139,* 785–795.

Zhu, W., Leber, B., and Andrews, D.W. (2001). Cytoplasmic O-glycosylation prevents cell surface transport of E-cadherin during apoptosis. EMBO J. *20,* 5999–6007.