Coupling Assembly of the E-Cadherin/β-Catenin Complex to Efficient Endoplasmic Reticulum Exit and Basal-lateral Membrane Targeting of E-Cadherin in Polarized MDCK Cells

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Abstract. The E-cadherin/catenin complex regulates Ca\(^{2+}\)-dependent cell–cell adhesion and is localized to the basal-lateral membrane of polarized epithelial cells. Little is known about mechanisms of complex assembly or intracellular trafficking, or how these processes might ultimately regulate adhesion functions of the complex at the cell surface. The cytoplasmic domain of E-cadherin contains two putative basal-lateral sorting motifs, which are homologous to sorting signals in the low density lipoprotein receptor, but an alanine scan across tyrosine residues in these motifs did not affect the fidelity of newly synthesized E-cadherin delivery to the basal-lateral membrane of MDCK cells. Nevertheless, sorting signals are located in the cytoplasmic domain since a chimeric protein (GP2CAD1), comprising the extracellular domain of GP2 (an apical membrane protein) and the transmembrane and cytoplasmic domains of E-cadherin, was efficiently and specifically delivered to the basal-lateral membrane. Systematic deletion and recombination of specific regions of the cytoplasmic domain of GP2CAD1 resulted in delivery of <10% of these newly synthesized proteins to both apical and basal-lateral membrane domains. Significantly, >90% of each mutant protein was retained in the ER. None of these mutants formed a strong interaction with β-catenin, which normally occurs shortly after E-cadherin synthesis. In addition, a simple deletion mutation of E-cadherin that lacks β-catenin binding is also localized intracellularly. Thus, β-catenin binding to the whole cytoplasmic domain of E-cadherin correlates with efficient and targeted delivery of E-cadherin to the lateral plasma membrane. In this capacity, we suggest that β-catenin acts as a chauffeur, to facilitate transport of E-cadherin out of the ER and the plasma membrane.

Key words: polarity • epithelia • adhesion • protein targeting • membrane domains

Epithelial cells form barriers that separate the internal milieu from the outer environment of multicellular organisms, and vectorially transport ions and solutes between these compartments. To perform these functions, these cells form cell–cell contacts through cadherin adhesion proteins, establish tight seals between cell–cell contacts (tight junctions), and organize the plasma membrane into structurally and functionally distinct domains, termed apical and basal-lateral, that face these different compartments (Rodriguez-Boulan and Nelson, 1989).

Localization of transmembrane proteins to specific plasma membrane domains is achieved by protein sorting in the Golgi and subsequent delivery to specific membrane domains, and by selective retention of proteins in the plasma membrane (Nelson, 1992). Molecular mechanisms involved in protein sorting and delivery are poorly understood. To date, the only identified sorting signal for apical membrane proteins in MDCK cells is a glycosylphosphatidylinositol (GPI)\(^1\) linkage (Brown et al., 1989; Lisanti et al., 1989; for a recent review, see Nosjean et al., 1997). How the lipid anchor specifies apical domain-specific sorting and targeting in the TGN is not clear. It has been proposed that the GPI anchor enables the protein to enter glycosphingolipid clusters and, thereby, to be sorted to the apical membrane domain (Simons and Wandinger, 1990; Weimbs et al., 1997).

Several amino acid motifs have been identified that specify type-I transmembrane protein sorting in the TGN and delivery to the basal-lateral membrane (Rodriguez-

1. Abbreviations used in this paper: aa, amino acids; arm, armadillo; CYT, cytoplasmic; endo H, endoglycosidase H; GFP, green fluorescent protein; GPI, glycosylphosphatidylinositol; LDL, low density lipoprotein; TER, transepithelial electrical resistance; TM, transmembrane.
and assembly of the E-cadherin/E-cadherin sorting to the basal-lateral membrane domain. This prompted us to explore the relationship between E-cadherin synthesis, while E-cadherin mediates cell–cell adhesion by calcium-dependent homotypic interactions between E-cadherin extracellular domains on opposing membranes of contacting cells (Nagafuchi et al., 1987). However, strong adhesion requires linkage of the cytoplasmic domain of E-cadherin to the actin cytoskeleton (Nagafuchi and Takeichi, 1988). This linkage is mediated by direct binding of β-catenin to the cytoplasmic domain of E-cadherin (Aberle et al., 1994; Jou et al., 1995); the minimal stoichiometric complex with a cytosolic protein, is sorted and targeted to the basal-lateral membrane in a type-I membrane proteins studied (see above), E-cadherin probably after E-cadherin has reached the cell surface (Nagafuchi et al., 1991), and the di-leucine motif of Fc receptor (Hunziker and Fumey, 1994; Matter et al., 1994). It is noteworthy that these proteins are not known to associate with heterologous membrane protein binding partners or accessory proteins in the secretory pathway.

E-cadherin, a type-I single-span transmembrane protein, is an endogenous adhesion molecule of epithelial cells (Kemler, 1992). E-cadherin mediates cell–cell adhesion by calcium-dependent homotypic interactions between E-cadherin extracellular domains on opposing membranes of contacting cells (Nagafuchi et al., 1987). However, strong adhesion requires linkage of the cytoplasmic domain of E-cadherin to the actin cytoskeleton (Nagafuchi and Takeichi, 1988). This linkage is mediated by direct binding of β-catenin to the cytoplasmic domain of E-cadherin (Aberle et al., 1994; Jou et al., 1995); the minimal β-catenin binding site on E-cadherin is thought to be a 30–amino acid basic sequence in the middle of the cytoplasmic domain (Stappert and Kemler, 1994). In turn, β-catenin binds α-catenin (Aberle et al., 1994; Jou et al., 1995), which links the cadherin/catenin complex directly (Rimm et al., 1995) or indirectly (Knudsen et al., 1995) to the actin cytoskeleton. The stoichiometry of the E-cadherin/β-catenin/α-catenin complex is 1:1:1 (Ozawa and Kemler, 1992; Hinck et al., 1994a). Finally, evidence has accumulated that E-cadherin forms dimers through interactions between the extracellular and/or membrane proximal domains of adjacent proteins (Shapiro et al., 1995; Briecher et al., 1996; Nagar et al., 1996; Yap et al., 1998). In polarized MDCK cells, E-cadherin is localized to the lateral membrane (Le Bivic et al., 1990; Shore and Nelson, 1991), and newly synthesized E-cadherin is preferentially sorted in the Golgi and delivered directly to the basal-lateral membrane (Le Bivic et al., 1990). Mechanisms regulating assembly of the cadherin/catenin complex and targeting of E-cadherin to its site of function at the lateral membrane domain are unknown.

We are interested in the relationship between intracellular trafficking of membrane proteins and cell–cell adhesion. Previous studies reported that β-catenin binds to the cytoplasmic domain of E-cadherin shortly after E-cadherin synthesis, while α-catenin joins the complex later, probably after E-cadherin has reached the cell surface (Ozawa et al., 1990; Hinck et al., 1994a). Thus, unlike other type-I membrane proteins studied (see above), E-cadherin is sorted and targeted to the basal-lateral membrane in a stoichiometric complex with a cytosolic protein, β-catenin. This prompted us to explore the relationship between E-cadherin sorting to the basal-lateral membrane domain and assembly of the E-cadherin/β-catenin complex. There are two regions of the cytoplasmic domain of E-cadherin which are similar in amino acid sequence to previously identified basal-lateral sorting signals of LDL-R (Matter et al., 1992), i.e., a sequence motif of Y-XXX, where X is an acidic amino acid residue. The first putative sorting signal in E-cadherin is immediately proximal to the transmembrane domain and the other is at the extreme COOH terminus, also similar to the locations of the two sorting signals in LDL-R cytoplasmic domain (see Fig. 1). We show that despite these similarities, mutations of tyrosine to alanine in those two potential basal-lateral sorting signals in E-cadherin do not affect sorting of newly synthesized mutant E-cadherin in MDCK cells. Further dissection of the cytoplasmic domain of E-cadherin using a chimeric protein approach revealed that E-cadherin exit from the ER and efficient sorting to the basal-lateral membrane are coupled to assembly of the E-cadherin/β-catenin complex shortly after E-cadherin synthesis.

Materials and Methods

Antibodies

Monoclonal antibody against rat GP2 has been described previously (Mays et al., 1995) and was a gift from Dr. Anson Lowe (Stanford University). Monoclonal antibody KT3 against SV-40 large T antigen (MacArthur and Walter, 1984) was a gift from Dr. Gernot Walter (University of California, San Diego). A monoclonal antibody against the cytoplasmic domain of cadherin has been described previously (Marrs et al., 1993). Monoclonal antibody against human CD7 (T3.3A1) was obtained from American Type Culture Collection.

Recombinant cDNA Construction

Due to the numerous recombinant cDNA constructs used in this study and that some constructs are derivatives in nature, construction details are not described for all constructs but are available upon request (E-mail: ethen@cmgm.stanford.edu). Individual constructs were confirmed by restriction mapping and DNA sequencing (PAN facility, Stanford University).

Plasmid for Expression of E-cad

U-GFP, a previously unpublished plasmid based on CD8 (Aruffo and Seed, 1987a,b), containing a fusion protein with the extracellular domain of canine E-cadherin joined with green fluorescent protein (GFP), was the starting material. The chimeric coding region is flanked by Hind3 and Not1 sites at the 5′ and 3′ end, respectively, with a Xho1 site as a linker (reading frame CTC-GAG, Leu-Glu) between the E-cadherin extracellular domain and GFP. The majority of the cadherin region (Hind3-Xho1, 2.1 kb) is derived from a cDNA clone (Hind3-Bgl2, 1.9 kb). The small remaining portion of the cadherin extracellular domain (Bgl2-Xho1, 0.2 kb) was from a PCR product. The GFP region was replaced with a pair of complimentary oligonucleotides encoding for the epitope tag of KT3 (amino acid sequence KPPTP-PPEIPET) and a stop codon, while retaining the Xho1 linker and the 3′-end Not1 site. The resulting plasmid is named U-SVLT1. The encoded soluble, KT3-tagged extracellular domain of canine E-cadherin is named E-cad

A PCR reaction was carried out to amplify the coding region of E-cadherin from the internal endogenous Bgl2 site to the end of the coding region (the stop codon was replaced with a Xho1 site), using canine E-cadherin cDNA (a gift from Dr. Lee Rubin, University College London, UK) as the template. Note that the PCR product contains a small part of the extracellular domain and the complete transmembrane and cytoplasmic domains of E-cadherin and, after restricting with Bgl2 and Xho1, was used to replace the Bgl2 and Xho1 portion of U-SVLT1, resulting in the plasmid U-SVLT2. Thus, U-SVLT2 encodes a complete canine E-cadherin fused with KT3 epitope tag through a Xho1 (Leu-Glu) linker. Further mutagenesis of the putative basal-lateral sorting signals was carried out by PCR reactions to amplify the region of the Bgl2/Xho1 of U-SVLT2, as detailed below.

Plasmids for Expression of E-cad BL1, BL2, and BL2.

Plasmid U-SVLT3, which encodes the mutant protein E-cadherin BL2 (Y→A mutations in BL2), was generated by PCR using the pair of oligonucleotides Cad BL-P6 (5′-CGC GGG CCA GAT CCT CCC CCC AAG ACA TCT CTT-3′; Bgl2 site is underlined) and Cad BL-P5 (5′-CGC GGG CTC GAG GTC GTC GTC GCC ACC GCC GCC CAT GTC GCC CAG CTT TCT-3′; Nacl site is underlined). Note that the mutations introduced were accompanied by the introduction of a Nacl site. The PCR product was used to replace the Bgl2 and Xho1 portion of U-SVLT2. Plasmid U-SVLT3, which encodes the mutant protein E-cadherin BL1 (Y→A mutations in BL1), was generated
by PCR from three reactions. A complimentary pair of oligonucleotides, Cad BL-P6 (sense) and Cad BL-P5 (antisense) (sense) and Cad BL-P2 (antisense, 5′-GGG CCC CTC GAG GTC GTC CTC GCC ACC ACC TCC-3′; XhoI site is underlined). The reaction products were mixed and served as the template for the third reaction with a pair of oligonucleotides, Cad BL-P6 (sense), and Cad BL-P2 (antisense). The PCR product was subcloned and replaced the Bgl2-XhoI portion of the U-SVLT2 to give rise to U-SVLT5.

The plasmid U-SVLT4 which encodes the chimeric protein GP2BL-P2 (antisense). The PCR product was subcloned and replaced the Bgl2-XhoI portion of the U-SVLT2 to give rise to U-SVLT5.

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dithiothreitol for 5 min. An equal volume of 100 mM citric acid buffer (pH 5.5) was added to the immunoprecipitates, and 1 U of endoglycosidase H (Boehringer Mannheim) was added and the sample was incubated at 37°C for 16 h. The processed samples were resolved by 10% SDS-PAGE and detected by fluorography.

Radioactive signals collected with a PhosphorImager were transferred directly to Adobe Photoshop, and radioactive signals collected with fluorescence were scanned from autoradiography film (Kodak) into Adobe Photoshop with a Hewlett-Packard ScanJet IIC scanner. The contrast of images was adjusted in Photoshop, the images were arranged and labeled for individual figures using Canvas 5 (Deneba Software). In some cases, samples containing apical or basal-lateral membrane biotinylated proteins were separated in gels with an empty lane between the sample lanes in order to avoid any cross contamination of protein samples. The empty, intervening lane was removed in Canvas 5 and the two sample lanes are shown side-by-side. The rearranged images were printed using a Tektronix dye sublimation printer. The printed images are representative of the original data.

**Size Exclusion Chromatography**

Preparation of samples and elution of extracted proteins of MDCK cells from Superox 6 column was performed using identical procedures as previously published (Stewart and Nelson, 1997). The collected fractions were resolved by 7.5% SDS-PAGE and proteins were transferred onto nitrocellulose membranes. The membranes were then probed with a monoclonal antibody against the extracellular domain of E-cadherin (Transduction Laboratories) or a monoclonal antibody against β-catenin (Transduction Laboratories). After incubation with horseradish peroxidase conjugated secondary antibody (Amersham), the signals were recorded using ECL reagent (Amersham) and autoradiography film (Kodak).

**Immunofluorescence Staining and Other Staining Methods**

For immunofluorescent staining of GP2 chimeric proteins, cells on collagen coated coverslips were fixed with 3.7% paraformaldehyde in 0.1 M phosphate buffer (pH 7.2) at room temperature, permeabilized with 0.5% Triton X-100 in PBS, and processed for immunofluorescence staining with monoclonal antibody against rat GP2. NBD-ceramide (Molecular Probes) staining of the Golgi apparatus performed on fixed MDCK cells as published previously (Pagano et al., 1989). Acridine orange staining of lysosomes in live MDCK cells on coverslips was performed by adding acridine orange (1 μg/ml Sigma Chemical Co.) to growth medium for 30 min at 37°C, followed by incubation in normal growth medium without acridine orange for 15 min. Then the coverslip was then mounted on a microscope slide with spacers to form a chamber for direct observation.

Fluorescent antibody-stained cells, NBD-ceramide-stained fixed cells, or acridine orange stained living cells were observed using a Zeiss Axioplan fluorescence microscope with a 63× objective and the appropriate filter sets. Note that for observation of acridine orange staining, the normal filter set for fluorescence microscopy was reconfigured by replacing the barrier filter with a long pass band filter (590 nm). Fluorescent images of stained cells were recorded using Kodak Tri-X film (see Fig. 5 A) or Kodak Ektachrome Elite II (ASA 400) film (see Fig. 5, B–D). Photographic images were then digitized with a slide scanner (Nikon) and resized using Adobe Photoshop. Images in Fig. 5 and Fig. 12 were arranged and labeled using Canvas 5 and printed from the computer file using a dye sublimation printer.

**Results**

**LDL-R-like Basal-lateral Sorting Motifs Are Not Responsible for Basal-lateral Sorting of E-Cadherin**

The primary structure of the cytoplasmic domain of E-cadherin contains two regions with amino acid sequences and spacing that are similar to previously identified basal-lateral sorting signals in the cytoplasmic domain of the LDL-R (Matter et al., 1992; see Fig. 1). We assessed whether these two motifs function as basal-lateral sorting determinants for E-cadherin. All tyrosine residues in each motif of canine E-cadherin were mutated into alanine in region 1 (BL1), or region 2 (BL2), or both (BL12); similar mutations in both motifs of LDL-R resulted in random sorting to the cell surface in MDCK cells (Matter et al., 1992). Each mutant was epitope-tagged with the SV-40 epitope (Shore and Nelson, 1991) and stably transfected into MDCK cells (Fig. 2). Clonally monolayers of cells were grown on Transwell™ filters for 16 h. The processed samples were resolved by 10% SDS-PAGE and proteins were transferred onto nitrocellulose membranes. The membranes were then probed with a monoclonal antibody to the epitope tag.

Greater than 95% of newly synthesized mutant E-cadherin, lacking tyrosine residues in either region 1 (BL1), or region 2 (BL2), or both (BL12) was delivered to the basal-lateral domain of MDCK cells with an efficiency and fidelity similar to those of endogenous E-cadherin (Fig. 2). This result indicates that the basal-lateral sorting determinant(s) of E-cadherin are different from those of LDL-R. To further dissect basal-lateral sorting determinants in E-cadherin, we next examined the overall localization of the basal-lateral sorting determinant in the whole molecule.

A secreted form of E-cadherin (E-cadsol), in which the transmembrane (TM) and cytoplasmic (CYT) domains had been deleted, was expressed stably in MDCK cells (Fig. 2). Delivery of newly synthesized E-cadsol to different membrane domains was detected by sampling apical and basal-lateral medium for 35S-Met/Cys labeled E-cadsol. Note that E-cadsol was efficiently secreted into the culture medium, did not associate with the cell surface of MDCK cells, and did not disrupt TER (Y.-T. Chen, unpublished result). As shown in Fig. 2, newly synthesized E-cadsol was secreted equally into the medium of both apical and basal-lateral compartments of the Transwell™ filter. We conclude that the extracellular domain of E-cadherin does not carry signals that specify E-cadherin sorting or delivery to the basal-lateral membrane.
Basal-lateral Sorting Activity Resides in the Cytoplasmic Domain of E-Cadherin

To locate the basal-lateral sorting signal(s) in E-cadherin, we constructed a chimeric protein comprising the transmembrane and specific regions of the cytoplasmic domain of E-cadherin fused to the extracellular domain of GP2, a highly glycosylated protein of zymogen granules in pancreatic exocrine cells (Hoops and Rindler, 1991). Normally, GP2 is attached to the membrane via a GPI anchor, and is delivered exclusively to the apical domain of MDCK clone II/G cells (Mays et al., 1995). A deletion mutant of GP2 that lacked the GPI modification signal (Fig. 3A, GP2ΔGPI) was expressed in MDCK cells. As shown in Fig. 3A, newly synthesized GP2ΔGPI was secreted equally into both the apical and basal-lateral medium. This result confirms that GP2 sorting to the apical membrane requires the GPI-anchor (see Mays et al., 1995), and reveals that the extracellular domain of GP2 does not contain specific sorting signals for the basal-lateral membrane.

GP2ΔGPI was fused to the TM and CYT of E-cadherin, producing the chimeric protein GP2CAD1 (Fig. 3B). Significantly, >95% of newly synthesized GP2CAD1 was preferentially delivered to the basal-lateral domain, which represents an efficiency and fidelity of delivery similar to that of endogenous E-cadherin. We conclude the transmembrane and cytoplasmic domains of E-cadherin contain a basal-lateral sorting signal(s).

Figure 2. Delivery of newly synthesized KT3 tagged E-cadherin mutants to the basal-lateral membrane domain, and secretion of E-cadΔcd into both apical and basal-lateral media. The diagram shows schematically the structure of each mutant constructs. The scale shows the number of amino acid residues in the cytoplasmic domain (CYT), the extracellular domain is not drawn to the same scale. To examine plasma membrane delivery, cells expressing E-cadherin (E-cad), or tyrosine to alanine substitution mutants (E-cad BL1, BL2, and BL12) were grown on Transwell™ filters for 7 d, labeled with 35S-Met/Cys for 1 h, cell surface biotinylated on either the apical (Ap) or basal-lateral (Bl) membrane, and then processed for immunoprecipitation using the specified antibodies (mAb KT3 against epitope tag, or 3G8 against the extracellular domain of canine E-cadherin) followed by immobilized avidin. Secretion of E-cadΔcd was assessed in confluent cell monolayers grown on Transwell™ filters by sampling the apical and basal-lateral media for 35S-Met/Cys protein.

Figure 3. Dominant basal-lateral sorting activity of E-cadherin is located in the transmembrane/ cytoplasmic domains. (A) GPI modification is the sole determinant for targeting GP2 to the apical membrane. GP2 has been shown previously to be preferentially delivered to the apical domain of MDCK clone II/G cells (Mays et al., 1995). Diagrams show schematically the structure of GP2 lacking the GPI modification signal (GP2ΔGPI). GP2ΔGPI delivery was determined as described for E-cadΔcd (see Fig. 1 legend, and Materials and Methods). (B) Newly synthesized GP2CAD1, labeled for 1 h, is sorted to the basal-lateral membrane domain, similar to endogenous E-cadherin. Diagrams show schematically the structure of GP2CAD1 compared with E-cadherin. GP2CAD1 delivery to the cell surface was assessed by 35S-Met/Cys labeling and cell surface biotinylation of the apical (Ap) or the basal-lateral (Bl) membrane domain. Note that the autoradiogram showing the E-cadherin targeting is the same as that shown in Fig. 2, and is included here for comparison.
Systematic Deletions of E-Cadherin Cytoplasmic Domain Result in Retarded Exit from ER and Random Delivery of GP2/Cadherin Chimera to the Apical and Basal-lateral Cell Surface

To map in detail the basal-lateral sorting domain of E-cadherin, a series of chimeric proteins were created in which GP2D GPI was used as the extracellular domain (reporter) fused to the transmembrane domain and specific regions of the cytoplasmic domain of E-cadherin (Fig. 4). Each mutant was designed to explore whether distinct features/activities of the cytoplasmic domain, such as binding to β-catenin and individual putative sorting signals, could be separated from each other.

In general, two types of deletion mutants were constructed. The first type involved the introduction of simple truncations in the cytoplasmic domain: GP2CAD2 contained amino acids (aa) 1–33 of the cytoplasmic domain, and ended at the COOH terminus of the first putative basal-lateral sorting signal (BL1); GP2CAD4 only contained the first 4 aa of the cytoplasmic domain, and ended just before the start of the previously defined minimal β-catenin binding domain (see Introduction); GP2CAD7 contained aa 1–129 of the cytoplasmic domain, and ended at the COOH terminus of the minimal β-catenin binding domain (aa 100–129); GP2CAD8 contained aa 1–115 of the cytoplasmic domain, and ended in the middle of the minimal β-catenin binding domain; GP2CAD10 contained almost all of the cytoplasmic domain except the COOH-terminal three acidic amino acids (EDD). The second type of mutants were loop-out mutants in which two halves of the cytoplasmic domain were joined after an intervening sequence had been deleted: GP2CAD3 contained a deletion of aa 83–129 of the cytoplasmic domain (minimal β-catenin binding domain is aa 100–129); GP2CAD5 contained aa 83–129 of the cytoplasmic domain; GP2CAD9 contained aa 1–33 and aa 83–129 of the cytoplasmic domain. Rather unexpectedly, none of the mutants (GP2CAD1–GP2CAD10) gave distinct sorting patterns compared with endogenous E-cadherin or GP2CAD1 (Fig. 4). In all cases, mutant proteins were delivered equally to both apical and basal-lateral membranes. Note that the relative amounts of each chimera delivered to either the apical (Ap) or basal-lateral (Bl) membrane domains was not determined (ND) for GP2CAD2, 4, and 6, because these proteins completely lacked the minimal β-catenin binding domain.

To examine the subcellular location of each chimeric protein, cells were grown on glass coverslips and processed for immunofluorescence. An anti-GP2 antibody was used to examine the distributions of the GP2CAD chimeras, and to distinguish them from endogenous E-cadherin (Fig. 5). Immunofluorescence (IF) revealed plasma membrane (PM) staining for E-cadherin and GP2CAD1 while all other chimeric proteins (GP2CAD2–10) gave an intracellular reticular staining pattern consistent with localization in the endoplasmic reticulum (ER). Examples of staining are given in Fig. 5. 1 h labeling with 35S-Met/Cys and cell surface biotinylation show delivery of newly synthesized chimeric protein to both apical (Ap) and basal-lateral (Bl) membrane domains. β-catenin binding to GP2CAD1 and derived mutant proteins was assessed by steady state 35S-Met/Cys labeling for 24 h and immunoprecipitation using anti-GP2 antibody. Examples of immunoprecipitates of GP2CAD1, 3, 7, 8, and 10 are given in Fig. 9. Catenin binding was not determined (ND) for GP2CAD2, 4, and 6, because these proteins completely lacked the minimal β-catenin binding domain (see text).
The sensitivity of GP2CAD10 to endo H digestion, we con-
nates. It is likely that this protein band represents a small
minor protein with a slower electrophoretic mobility was
of the major GP2CAD10 protein band. Note that the elec-
were stained for GP2CAD10. The reticular pattern of
were very similar to that of the ER resident protein
were incubated by immunofluorescence staining. Reticular
staining of GP2CAD10 (B) is distinct from cell surface staining
GP2CAD10 staining (Fig. 5 B), and other GP2CAD mu-
tants was retained in the ER, we examined the sensitivity
GP2CAD10 expression in MDCK cells (Fig. 5 C; Pagano et al., 1989), and lysosomes re-
were stained for GP2CAD10. The reticular pattern of
GP2CAD10 to digestion by endoglycosidase H (endo
GP2CAD10 and GP2CAD1 (or endogenous E-cadherin)
reached the cell surface. Note that the percentage of protein detected by cell surface
GP2CAD10 delivered to the cell surface was considerably
and chased in DMEM containing an excess of nonradioac-
were stained for GP2CAD1. Golgi staining (C), and lysosomal staining
(endo H). GP2CAD10 expressed MDCK cells; (C)
were incubated with 35S-Met/Cys for 24 h, ex-
and chased in DMEM containing an excess of nonradioac-
tive Met/Cys for 40 min. At the end of the chase period, ei-
the Golgi revealed by NBD-ceramide staining of fixed
tants (Fig. 5 C; Pagano et al., 1989), and lysosomes re-
were labeled live cells with acridine orange (Fig. 5 D; Palmgren, 1991). Thus, the majority of GP2CAD10 is
most likely localized to the ER.

To confirm biochemically that GP2CAD1 deletion mu-
tants were retained in the ER, we examined the sensitivity
GP2CAD10 to digestion by endoglycosidase H (endo
GP2CAD10 MDCK cells were incubated with 35S-Met/Cys for 24 h to label proteins to steady state. Total
cell lysates were prepared, and GP2CAD10 was immuno-
precipitated with anti-GP2 antibody and then subjected to
endo H digestion. As shown in Fig. 6, endo H digestion re-
sulted in a significant increase in electrophoretic mobility
of the major GP2CAD10 protein band. Note that the elec-

high mannose carbohydrate chains and had not undergone
further processing consistent with its location in the ER.

Truncations of E-Cadherin Cytoplasmic Domain Result
in both Reduced Cell Surface Delivery and Random
Sorting to Plasma Membrane Domains

The difference in staining patterns of GP2CAD1 and
GP2CAD10 (Fig. 5) might reflect differences in the effi-
ciency of protein passage through the secretory pathway.
Therefore, we compared the kinetics of cell surface deliv-
ery of newly synthesized GP2CAD1, GP2CAD10, and
endogenous E-cadherin (Fig. 7). MDCK cells stably express-
ging GP2CAD1 or GP2CAD10 were grown on Transwell™
filters for 7 d, pulse labeled with 35S-Met/Cys for 20 min,
and chased in DMEM containing an excess of nonradioac-
tive Met/Cys for 40 min. At the end of the chase period, ei-
ther whole cell lysates were collected, or cells were treated
with the plasma membrane-impermeant biotinylating
agent NHS-SS-biotin before lysis. Cell lysates were immu-
noprecipitated with antibody specific to rat GP2; biotin-
ylated proteins were further precipitated with immobilized
avidin. Identical experiments were performed with paren-
tal MDCK cells to examine the kinetics of endogenous
E-cadherin delivery to the plasma membrane.

As shown in Fig. 7 A, 25.9 ± 1.3% of newly synthesized
endogenous E-cadherin, 23.0 ± 1.8% of GP2CAD1, and
6.8 ± 3.1% of GP2CAD10 reached the cell surface. Note
that the percentage of protein detected by cell surface
biotinylation represented only the fraction of newly syn-
thesized protein delivered from the ER to the plasma
membrane in the 40-min chase period. Thus, the amount
of GP2CAD1 delivered to the cell surface was similar to
that of endogenous E-cadherin, while the amount of
GP2CAD10 delivered to the cell surface was considerably
lower than that of either GP2CAD1 or E-cadherin.

The difference in the amount of cell surface delivery of
GP2CAD10 and GP2CAD1 (or endogenous E-cadherin)
was also reflected in the steady state distribution of these
proteins (Fig. 7 B). GP2CAD1 and GP2CAD10 expressing
cells were labeled with 35S-Met/Cys to steady state for
24 h. Parallel cultures were either extracted immediately,
or biotinylated on both apical and basal-lateral mem-
branes. Biotinylated and non-biotinylated proteins were
resolved by SDS-PAGE and detected by
fluorography. Only a small fraction (~10%) of GP2CAD10
marked with asterisk) does not display an increase in electro-
phoretic mobility upon endo H treatment. Numbers at the left show molecular mass in kD.
of the total GP2CAD1 extracted from cells. In contrast, the amount of biotinylated GP2CAD10 was ~7% of the total amount of GP2CAD10. Since the extracellular domain of GP2CAD1 and GP2CAD10 were identical, the difference in the amount of cell surface exposed proteins is unlikely to be due to a difference in the efficiency of protein biotinylation. We conclude that GP2CAD1 rapidly and efficiently exits the ER and is delivered to the basal-lateral membrane. In contrast, ~90% of GP2CAD10 re-

Effects of aLLN and Chloroquine on GP2CAD1 and GP2CAD10 Degradation

The data presented above show that nearly all of GP2CAD10 is retained in the ER, whereas nearly all GP2CAD1 is localized in the plasma membrane. It is generally acknowledged that misfolded secretory proteins retained in the ER are degraded through the proteasome pathway (for a recent review, see Coux et al., 1996). To examine degradative pathways, cells were pulse-labeled with 35S-Met/Cys for 15 min and then chased in an excess of nonradioactive Met/Cys for 225 min in the presence of either chloroquine phosphate (a lysosome inhibitor) or N-acetyl-Leu-Leu-norleucinal (aLLN, a 26S proteasome inhibitor). As shown in Fig. 8 (upper panels), 70% of newly synthesized GP2CAD1 remained at the end of the chase period in the presence of chloroquine, compared with 40% in its absence. By comparison, ~50% of GP2CAD10 remained in the presence of chloroquine compared with 42% in its absence. In the presence of aLLN (Fig. 8, bottom panels), 82% of GP2CAD1 remained compared with 50% in its absence; 83% of GP2CAD10 remained in the presence of aLLN, compared with 60% in its absence. These results show that chloroquine phosphate suppressed degradation of both GP2CAD1 and GP2CAD10 but the effect on GP2CAD1 was greater. On the other hand, aLLN had a more inhibitory effect on the degradation of GP2CAD10 than did chloroquine, while both aLLN and chloroquine suppressed the degradation of GP2CAD1.

E-Cadherin Binding to β-Catenin Is Coupled to Efficient ER Exit and Basal-lateral Membrane Delivery

The GP2CAD1 mutants were designed to test whether binding of β-catenin to the cytoplasmic domain of E-cadherin and basal-lateral membrane delivery could be separated from each other. GP2CAD1, GP2CAD5, GP2CAD7, GP2CAD9, and GP2CAD10 (see Fig. 4) were predicted to bind β-catenin since they contained at least as
83–129 of the cytoplasmic domain of E-cadherin which covers the previously defined minimal β-catenin binding domain (aa 100–129; Stappert and Kemler, 1994).

The GP2CAD1/catenin complex was coimmunoprecipitated with GP2 antibody and subjected to a high stringency wash in buffer containing 0.1% SDS, 1% sodium deoxycholate, and 1 M NaCl (High Stringency Wash Buffer, see Materials and Methods). Note that under this wash condition the stoichiometry of the coimmunoprecipitated complex of GP2CAD1/β-catenin/α-catenin was ~1:1:1 (Fig. 9), similar to that of the endogenous E-cadherin/ catenin complex (Ozawa and Kemler, 1992; Hinck et al., 1994a; see also Fig. 10). Surprisingly, we found that neither GP2CAD10 nor GP2CAD7 bound catenins under these conditions (Fig. 9), although both chimeras contained the previously mapped minimal β-catenin binding domain of E-cadherin (see Fig. 4). Similar results were obtained with GP2CAD5 and GP2CAD9 (Y.-T. Chen, unpublished results). Catenins were not coimmunoprecipitated in a complex with either GP2CAD8 (Fig. 9) in which the COOH-terminal half of the β-catenin binding domain had been deleted, or GP2CAD3 (Fig. 9) in which the β-catenin binding domain had been completely deleted. Overall, there is a strong correlation between lack of β-catenin binding to the cytoplasmic domain of E-cadherin, and retention of the majority of each GP2CAD1 mutant in the ER. Note that Fig. 9 also reveals a difference in the apparent molecular mass of GP2CAD1 and all other GP2CAD mutants. It is likely that this is due to differences in complex carbohydrate modifications between the proteins. GP2 is known to undergo extensive N-linked glycosylation (Hoops and Rindler, 1991). We show here that GP2CAD1 is efficiently delivered to cell surface and, thereby, receives extensive carbohydrate modifications during trafficking through the secretory pathway. In contrast, all other GP2CAD mutants are retained in the ER and, therefore, do not undergo complex carbohydrate modifications.

We also examined β-catenin binding to E-cadherin mutants in which putative basal-lateral sorting motifs has been mutated (Tyr→Ala), and an E-cadherin chimera formed with another protein, human CD7. Stable MDCK cell lines expressing E-cadherin BL1, E-cadherin BL2, or E-cadherin BL12 were labeled with 35S-Met/Cys to steady state for 24 h, and mutant proteins were immunoprecipitated with the monoclonal antibody KT3 under the stringent wash conditions used above. All three Tyr-to-Ala mutants of E-cadherin (BL1, BL2, and BL12) bound β-catenin and α-catenin under high stringency wash conditions (Fig. 10); note that these mutants were rapidly exported from the ER and sorted efficiently and specifically to the basal-lateral membrane (Fig. 2).

We placed the putative minimal β-catenin binding domain (aa 83–129, BB1) of E-cadherin cytoplasmic domain on the COOH terminus of an unrelated type-I transmembrane protein, human CD7. The resulting chimeric protein (CD7BB1) bound α-catenin and β-catenin, whereas CD7 did not (Fig. 11; note that aliquots of the sample were resolved by either 7.5% or 10% SDS-PAGE in order to obtain better separation of α-catenin/β-catenin and CD7/CD7BB1, respectively). However, quantification of the amounts of α- and β-catenins bound to CD7BB1 revealed that the stoichiometry of CD7BB1/β-catenin/α-catenin was 5:1:0.8 when normalized to the number of Met and Cys residues in CD7BB1 and catenins; this compared with the ratio of ~1:1:1 for E-cadherin/β-catenin/α-catenin or GP2CAD1/β-catenin/α-catenin (see above). Most of CD7 and CD7BB1 was localized at the cell surface (Y.-T. Chen, unpublished results); presumably, the cytoplasmic domain of CD7 in the CD7BB1 chimera contains signal(s) for its entry into the secretory pathway regardless of whether β-catenin is bound or not. Trafficking patterns of CD7 and CD7BB1 were similar in polarized MDCK cells. Approximately 60% of the cell surface delivery of both proteins was to the basal-lateral membrane (Y.-T. Chen, unpublished results). We conclude that a domain containing aa 83–129 is a transportable β-catenin binding domain in E-cadherin, but the binding strength of β-catenin/E-cadherin, based on high stringency washes, is much lower than that of β-catenin bound to the complete cytoplasmic domain of E-cadherin. Neither the BB1 domain alone nor β-catenin binding, per se, specifies protein delivery to the basal-lateral membrane.
We also expressed a truncated E-cadherin, E-cad8 (Fig. 12), containing the complete extracellular and transmembrane domains, and cytoplasmic domain up to aa 115 (i.e., a deletion of aa 116–151 of the cytoplasmic domain), which is identical to the COOH-terminal deletion in GP2CAD8 (see Fig. 4). This deletion covers the minimal β-catenin binding site (Stappert and Kemler, 1994), and β-catenin is not immunoprecipitated in a complex with E-cad8 (data not shown) as reported previously (Stappert and Kemler, 1994). E-cad8 was epitope tagged at its COOH terminus with the KT3 epitope tag, which enabled us to distinguish its distribution in cells expressing endogenous E-cadherin. In confluent monolayers of MDCK cells, in which cell–cell contacts are clear (Fig. 12 B), E-cad8 is not apparent at cell–cell contacts but is localized to intracellular compartments. The staining patterns comprise bright, punctate structures that are present, although less abundant in cells expressing GP2CAD10 (Fig. 5 B), and a diffuse cytoplasmic staining also similar to that of GP2CAD10 (Fig. 5 B).

The extracellular and membrane proximal cytoplasmic domains of cadherin have been proposed to be involved in dimer formation (Shapiro et al., 1995; Nagar et al., 1996; Brieher et al., 1996; Yap et al., 1998). To test whether E-cad8 interacted with endogenous E-cadherin, we separated proteins extracted from MDCK cells expressing E-cad8 using a Superose 6 size exclusion column. Endogenous E-cadherin eluted in fractions 13–16 (Fig. 12 C, see legend for details), as shown previously (Stewart and Nelson, 1997). However, E-cad8 eluted in fractions 16–19 in a profile distinctively different from that of endogenous E-cadherin (Fig. 12 C). Note that E-cad8 has an apparent molecular mass smaller than that of full-length E-cadherin, which is consistent with the cytoplasmic domain deletion. A protein band with an apparent molecular mass greater than that of the full-length E-cadherin probably represents the precursor form of E-cad8 (Ozawa and Kemler, 1990). We also found an enrichment of higher molecular mass precursor forms of three other E-cadherin cytoplasmic domain deletion mutants when expressed in MDCK cells (data not shown).

Discussion

How membrane proteins are sorted and delivered to different plasma membrane domains in polarized epithelial cells is an important question. However, to date most studies have focused on single proteins that do not form a complex with subunit membrane or cytosolic proteins during their transit through the secretory pathway. Although these studies have identified several types of intrinsic basal-lateral sorting signals in the cytoplasmic domain of a
E-cadherin is different from other type-I single-span transmembrane protein that have been used to study sorting signals, since it forms a 1:1:1 stoichiometric complex with two cytosolic proteins, β-catenin and α-catenin (Ozawa and Kemler, 1992). Significantly, previous studies implied that assembly of the E-cadherin/β-catenin complex occurs in the very early stage of trafficking (Ozawa and Kemler, 1992; Hinck et al., 1994a; this study). Therefore, E-cadherin must be sorted to the basolateral membrane in a complex with β-catenin. Amino acid sequences in the cytoplasmic domain of E-cadherin that are superficially similar to recently described ER exit (Nishimura and Balch, 1997) and basolateral sorting signals (Matter et al., 1992) in other proteins do not have these functions in E-cadherin. Instead, assembly of the E-cadherin/β-catenin complex is the obligatory step in efficient export from the ER, and subsequent delivery of E-cadherin to the basolateral membrane of polarized MDCK cells.

Defining the β-Catenin Binding Site in E-Cadherin

To examine domains of E-cadherin important in its sorting to the basolateral membrane domain, we used a chimeric protein approach. The chimera was composed of the extracellular domain of GP2, which is normally attached to the membrane through a GPI-anchor, fused to the transmembrane and cytoplasmic domains of E-cadherin (GP2-CAD1). The extracellular domain of GP2, when expressed without a membrane anchor, was secreted equally from both apical and basolateral membranes, showing that this domain does not contain specific membrane sorting signals. Using a similar approach, we showed that the extracellular domain of E-cadherin does not contain signals that specify sorting to the basolateral membrane. The chimeric protein GP2CAD1, however, was delivered directly to the basolateral membrane domain with a rate, efficiency and fidelity similar to that of endogenous E-cadherin.

GP2CAD1 also formed a complex with α- and β-catenin with a stoichiometry of ~1:1:1 that was resistant to disruption with a high stringency buffer containing 0.1% SDS, 1% deoxycholate and 1 M NaCl, similar to E-cadherin. The design of truncation mutants of GP2CAD1 used to examine sorting signals in the cytoplasmic domain of E-cadherin took into account a previously defined minimal β-catenin binding domain that had been mapped to a region of 30 aa, corresponding to aa 100–129 (Stappert and Kemler, 1994). However, we found that β-catenin did not bind, under these stringent conditions, to a slightly longer region containing this minimal β-catenin binding domain, aa 83–129, if regions of the cytoplasmic domain around it had been deleted (e.g., GP2CAD5, 7, 9, and 10).

We tested whether this difference between our results and those of Stappert and Kemler (1994) reflected the difference in the cell types used to express these mutants (L cells, MDCK cells), GP2CAD1, 6, 7, 8, and 10 were transiently transfected into L cells and HEK293 cells. By immunofluorescence in both cell types, GP2CAD1 was localized to the cell surface, whereas GP2CAD6, 7, 8, and 10 were predominantly localized to the ER (Y.-T. Chen, unpublished results), similar to their locations in MDCK cells (summarized in Fig. 4). Another reason for the difference in results might be the methods used to assess the stoichiometry of β-catenin binding to this minimal binding site on E-cadherin. However, Stappert and Kemler (1994), did not quantitate the stoichiometry of the complex formed between β-catenin and the minimal β-catenin binding domain (aa 100–129). We found that β-catenin bound to a chimeric protein composed of CD7 and aa 83–129 of the E-cadherin cytoplasmic domain (CD7BB1), but the stoichiometry of the coimmunoprecipitated complex was ~5:1 after a high stringency wash. Recently, Finnemann et al. (1997) reported the expression of three COOH-terminal deletion mutants of Xenopus XB/U-cadherin in L cells. A deletion of the most COOH-terminal 19 amino acids, which would contain the minimal β-catenin binding domain intact, bound β-catenin but the adhesion function of the truncated cadherin was interpreted to be “dramatically altered.” We note that biochemical data presented in the same paper (Fig. 3 in Finnemann et al., 1997) revealed a decrease in the avidity of β-catenin binding to the mutant cadherin. Interestingly, confocal microscopy of L cells expressing XB/U-cadherin revealed that full-length protein localized to cell–cell contacts, whereas the truncation mutant had a distinctly different location and appeared to have a punctate distribution. In conclusion, it seems likely that β-catenin binds to a minimal domain of E-cadherin comprising aa 100–129, but the interaction is considerably weaker than binding of β-catenin to the whole cytoplasmic domain of E-cadherin. Reduced binding of the cytoplasmic domain of cadherin to β-catenin leads to intracellular retention and reduced cell surface expression of cadherin.

The cadherin-binding domain in β-catenin lies within the armadillo (arm) repeats of β-catenin (Hulsken et al., 1994). The crystal structure of the arm repeats revealed a rigid cylindrical super-helix of helices that form a groove lined with positively-charged amino acids (Huber et al., 1997). The length of this groove could potentially accommodate a fully extended peptide of aa 25–30, or a longer peptide with local secondary structures; note that the minimal β-catenin binding site on E-cadherin is 29 aa and has a pI of 3.1 (see Huber et al., 1997). Although structural analysis of the E-cadherin/β-catenin cocrystal is required to define the interaction in detail, our recent analysis has revealed that the cytoplasmic domain of E-cadherin is protected from proteolysis when it has formed a 1:1 stoichiometric complex with the β-catenin arm repeats (Huber, A., D.B. Stewart, W.J. Nelson, and W. Weis, in preparation). This result is compatible with the view formed from the present studies of β-catenin binding to GP2CAD1 deletion mutants in which most of the cytoplasmic domain of E-cadherin, including the previously mapped minimal β-catenin binding domain, interacts with β-catenin.

β-Catenin/E-Cadherin Binding Is Coupled to Efficient Exit of E-Cadherin from the ER

Using a combination of results obtained by cell surface biotinylation, sensitivity to endoglycosidase H digestion, immunoprecipitation, and immunofluorescence we have shown that GP2CAD1 bound β-catenin and >90% en-
tered the secretory pathway to the basal-lateral membrane. However, GP2CAD1 deletion mutants did not bind α- or β-catenin and >90% remained in the ER. Previous studies indicated that newly synthesized E-cadherin binds β-catenin soon after its synthesis, and that α-catenin binds to the complex when E-cadherin arrives at the cell surface (Ozawa and Kemler, 1992; Hinck et al., 1994a). Thus, formation of the E-cadherin/β-catenin complex correlates with efficient exit of E-cadherin from the ER.

It is possible that E-cadherin has a specific ER export signal that is deleted from the GP2CAD1 mutants. Recently, it was reported that the COOH-terminal acidic residues of VSV-G protein are involved in efficient exit of VSV-G protein from ER (Nishimura and Balch, 1997), and that deletion of the most COOH-terminal two valine residues of proTGFα resulted in the ER accumulation of the protein (Briley et al., 1997). It has been suggested that COOH-terminal acidic amino acid residues constitute an ER export signal (Nishimura and Balch, 1997). In this regard, it is striking that our results showed that a deletion of the COOH-terminal three acidic amino acids of GP2-CAD1 resulted in the accumulation of the protein (GP2-CAD10) in the ER. However, our data are not consistent with the possibility that these, or other acidic amino acids at the COOH terminus constitute a minimal ER exit signal. Internal deletions of the cytoplasmic domain of E-cadherin (e.g., GP2CAD3) resulted in retention of the protein in the ER, even though COOH-terminal acidic amino acids were intact. In general, we cannot separate the roles of different regions/motifs as ER export signals from the dominant requirement for high affinity binding of β-catenin to the whole cytoplasmic domain of E-cadherin. It seems more likely that the complex of E-cadherin/β-catenin presents a conformation or motif in the cytoplasmic domain of E-cadherin that allows efficient export of the complex from the ER. Definitive proof of this mechanism will require the expression of E-cadherin in a cell line lacking both β-catenin and plakoglobin. ER retention of GP2CAD1 proteins containing a truncated cytoplasmic domain is likely to be a consequence of missfolding, due to inhibition of β-catenin binding (see Fig. 9). These misfolded proteins are targeted subsequently for degradation in either lysosomes or the 26S proteasome (Fig. 8). Finally, our analysis of the distribution of the simple deletion mutant E-cad8 (Fig. 12), which was not a chimeric protein, showed that this mutant was also localized intracellularly. E-cad8 did not form a complex with endogenous E-cadherin despite an intact extracellular and membrane proximal cytoplasmic domain, which have been identified as potential sites for dimer formation (Shapiro et al., 1995; Nagar et al., 1996; Brieher et al., 1996; Yap et al., 1998). Thus, E-cadherin dimerization may not occur in the absence of β-catenin binding, or is dependent on E-cadherin leaving the ER or arriving at the plasma membrane.

**β-Catenin Binding to E-Cadherin and Delivery of E-Cadherin to Sites of Function in the Basal-lateral Membrane Domain of the Cell Surface**

Previous studies have emphasized that sorting of transmembrane proteins to either the apical or basal-lateral membrane occurs in the TGN (Matter and Mellman, 1994). For example, early studies showed that influenza virus HA and VSV-G protein appeared together in vesicles and membrane compartments until the TGN where they appeared to be segregated into separate vesicle populations (Fuller et al., 1985). Our data show that complex formation between E-cadherin cytoplasmic domain and β-catenin in the ER is not only coupled to efficient export of E-cadherin but also direct delivery of E-cadherin to the basal-lateral membrane. Note that in the absence of complex formation with β-catenin, a small amount (<10%) of GP2CAD1 deletion mutants leaked out of the ER and were then delivered randomly to both the apical and basal-lateral membranes. As in the case of ER export, we suggest that binding of β-catenin to E-cadherin induces a conformational change in the cytoplasmic domain of E-cadherin that reveals a sorting determinant(s) that is recognized by the basal-lateral sorting machinery. Thus, β-catenin may function as a chauffeur to facilitate E-cadherin transport through the secretory pathway. At present, we cannot rule out an alternative possibility that β-catenin itself contains basal-lateral membrane targeting information, and that this information is recognized by the sorting machinery for delivery of the E-cadherin/β-catenin complex to the basal-lateral membrane.

That binding of β-catenin to the cytoplasmic domain of E-cadherin plays an essential role in the efficient delivery of E-cadherin to the cell surface raises the interesting possibility that ER exit is a potential regulatory point for E-cadherin function. For example, limited availability of β-catenin for binding to E-cadherin, or post-translational modifications to β-catenin that reduce the affinity of E-cadherin/β-catenin binding might lead to the retention of un-complexed E-cadherin in the ER. Since the half-life of E-cadherin is quite short (<5 h in MDCK cells; Shore and Nelson, 1991), retention of newly synthesized E-cadherin in the ER would quickly result in reduced cell surface expression of E-cadherin and, consequently, reduced cell–cell adhesion. We note that β-catenin is a component of the Wnt/Wingless signaling pathway in which regulation of β-catenin levels is critical (Cadigan and Nusse, 1997). Significantly, there is evidence that changes in β-catenin levels leads to changes in steady state and cell surface levels of cadherins, and increased cadherin-mediated cell–cell adhesion (Bradley et al., 1993; Hinck et al., 1994b; Yanagawa et al., 1997). These effects on cadherin could be mediated by the availability of β-catenin for binding to cadherin in the ER, which regulates cadherin entry into the secretory pathway and, therefore, the amount of cadherin available for adhesion functions at the cell surface.

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