

Palmitoylation of plakophilin is required for desmosome assembly.

Brett J. Roberts¹, Kristen E. Johnson¹, Kathleen P. McGuinn², Jintana Saowapa¹, Robert A Svoboda¹, My G. Mahoney² Keith R. Johnson^{1,3} and James K. Wahl III^{1#}

1. The University of Nebraska Medical Center, College of Dentistry, Department of Oral Biology, Lincoln, NE 68583;
2. Department of Dermatology and Cutaneous Biology, Thomas Jefferson University, Philadelphia, PA, 19107
3. Eppley Institute for Research in Cancer and Allied Diseases, Omaha, NE, 68198.

Key Words: desmosome, plakophilin, palmitoylation
Running title: Palmitoylation of desmosomal components

Corresponding author:
James K. Wahl III
The University of Nebraska Medical Center
College of Dentistry, Department of Oral Biology
Lincoln, NE, 68583-0740, USA
Fax: (402) 472-2551
Phone: (402) 472-1324
E-mail: jwahl@unmc.edu

Summary

Desmosomes are prominent adhesive junctions found in various epithelial tissues. The cytoplasmic domains of desmosomal cadherins interact with a host of desmosomal plaque proteins, including plakophilins, plakoglobin and desmoplakin, that in turn recruit the intermediate filament cytoskeleton to sites of cell-cell contact. While the individual components of the desmosome are known, mechanisms regulating the assembly of this junction are poorly understood. Protein palmitoylation is a posttranslational lipid modification that plays an important role in protein trafficking and function. Here, we demonstrate that multiple desmosomal components are palmitoylated *in vivo*. Pharmacologic inhibition of palmitoylation disrupts desmosome assembly at cell-cell borders. We mapped the site of plakophilin palmitoylation to a conserved cysteine residue present in the armadillo repeat domain. Mutation of this single cysteine residue prevents palmitoylation, disrupts plakophilin incorporation into the desmosomal plaque and prevents plakophilin-dependent desmosome assembly. Finally, plakophilin mutants unable to become palmitoylated act in a dominant-negative manner to disrupt proper localization of endogenous desmosome components and decrease desmosomal adhesion. Taken together, these data demonstrate that palmitoylation of desmosomal components is important for desmosome assembly and adhesion.

Introduction

Desmosomes are prominent cell-cell adhesive junctions found in epithelial and cardiac tissues and are widely thought to provide these tissues the ability to withstand mechanical stress (Brooke et al., 2012). Structurally, these adhesive structures link the intermediate filament cytoskeletal systems between adjacent cells and allow the cells of the tissue to function coordinately. Desmosomal cadherins (i.e. desmogleins and desmocollins) form the transmembrane core of the desmosome and these transmembrane proteins interact with a set of desmosomal plaque proteins to recruit the intermediate filament cytoskeleton to sites of cell-cell contact. Desmosomal plaque proteins include plakoglobin, desmoplakin and the plakophilins. Disruption of the expression or function of plaque proteins can have devastating effects on desmosome integrity and function (Gerull et al., 2004; McGrath et al., 1997; Ruiz et al., 1996).

Cells possess the ability to modulate adhesive strength between neighboring cells in response to extracellular cues. For example, keratinocytes acquire a motile phenotype during the

re-epithelialization phase of epidermal wound healing. During this process, cells decrease their adhesiveness with neighboring cells and migrate into the wound bed until the epithelial barrier is re-established (Thomason et al., 2012). When adhesive strength is altered or disrupted during tumorigenesis, tumor cells are believed to acquire the ability to detach from their normal neighbors and acquire the ability to migrate inappropriately. Altered desmosome assembly has been observed in several tumor types (Davies et al., 1999; Harada et al., 1996; Thomas and Speight, 2001). Additionally, It is likely that desmosomes are also responsive to extracellular cues and these signals should result in altered desmosome dynamics (Roberts et al., 2011). The mechanisms regulating desmosome assembly, stability and turnover during normal migratory events and tumorigenesis are poorly understood.

Protein palmitoylation is a reversible posttranslational modification whereby a 16-carbon fatty acid (palmitate) is linked to specific cysteine residues via a labile thioester linkage (reviewed in (Aicart-Ramos et al., 2011)). Palmitoylation regulates diverse protein activities including protein localization, activity and stability (Greaves and Chamberlain, 2011). Palmitoylation is thought to increase the association of substrate proteins with cellular membranes. Recent studies in yeast have identified the Asp-His-His-Cys (DHHC) family of proteins as palmitoyl acyltransferases (PATs) (Ohno et al., 2012). There are 23 evolutionarily conserved DHHC genes in mammals. The enzymes responsible for deacylation of protein targets are acyl protein thioesterases. Three cytosolic thioesterases (LYPLA1, LYPLA2 and LYPLAL1) have been identified to date (Sugimoto et al., 1996; Tomatis et al., 2010; Toyoda et al., 1999).

In the current study we have demonstrated that multiple desmosomal components are indeed palmitoylated in cultured cells. Additionally we have identified a single conserved cysteine residue in plakophilin-2 and plakophilin-3 that is the site of palmitoylation. Mutation of this cysteine residue results in decreased membrane targeting of plakophilin-2 and plakophilin-3 and the inability of mutant plakophilins to support de novo desmosome assembly in A431D cells. Finally, expression of mutant plakophilin-2 and plakophilin-3 in A431 weakens desmosomal adhesion compared to wild-type plakophilin-2 and plakophilin-3 and suggest the mutants act as dominant negatives with respect to cell adhesion. The data presented here suggest that palmitoylation of desmosomal components, and specifically plakophilins, plays an important role in regulation of junction assembly and adhesive strength.

Results

Desmosomal components are palmitoylated.

Recently, several studies have utilized large-scale proteomic screening strategies in an attempt to identify the landscape of palmitoylated proteins in cultured cells (Martin and Cravatt, 2009; Yang et al., 2010). These efforts have identified several desmosomal components as potential palmitoylated proteins (Yang et al., 2010). We set out to show that desmosomal proteins were indeed palmitoylated and to determine the effect of palmitoylation on desmosome assembly and function. We first chose to identify palmitoylated desmosomal components using an acyl-biotin exchange assay. Acyl-biotin exchange (ABE) is performed by selectively hydrolyzing thioester ester bonds followed by covalent tagging of the previously palmitoylated cysteine residues with biotin. Biotin-labeled proteins are captured by streptavidin pull-down and individual proteins are detected with specific antibodies (Wan et al., 2007). Streptavidin pull down revealed that the desmosomal plaque proteins (plakophilin-2, plakophilin-3 and plakoglobin) as well as desmosomal cadherins (desmogleins-2 and -3 and desmocollin-2) were indeed palmitoylated in A431 cells (Fig. 1A). Since two bands were detected in the blot for desmocollin-2, it is likely both desmocollin-2a and desmocollin-2b (Collins et al., 1991; Koch et al., 1991) are palmitoylated. In addition, we detected palmitoylation of plakophilin-2 using ABE in murine heart tissue (data not shown). The adherens junction components E-cadherin, β -catenin and α -catenin were found to not be palmitoylated and served as negative controls. Proteomics analysis (Yang et al., 2010) had previously suggested that desmoplakin was also palmitoylated however we were unable to detect desmoplakin palmitoylation in A431 cells. We chose to further investigate the role of palmitoylation of plakophilin on desmosome assembly and adhesion.

In order to further confirm the palmitoylation of plakophilins, we metabolically labeled A431 cells using the palmitic acid analog 17-ODYA (Martin and Cravatt, 2009). Proteins were immunoprecipitated from lysates of A431 cells that had been grown in medium containing 100 μ M 17-ODYA or control medium lacking 17-ODYA (DMSO). Biotin azide was covalently added to 17-ODYA by the Staudinger ligation and copper (I)-catalyzed azide-alkyne cycloaddition (click chemistry). Immunoprecipitated proteins were separated by SDS-PAGE and biotin-labeled proteins were detected by HRP-streptavidin blotting (Fig. 1B). Plakophilin-2 and plakophilin-3 were specifically labeled by 17-ODYA, while no biotin-labeled plakophilin-2

or plakophilin-3 was detected in cell lysate prepared from cells grown in control medium. Since A431 cells endogenously express plakophilin-2 and plakophilin-3 but not plakophilin-1, our studies here will focus on plakophilin-2 and plakophilin-3.

Inhibition of palmitoylation disrupts desmosome assembly.

Next we sought to investigate the effect of inhibiting global palmitoylation on desmosome assembly in A431 cells. 2-bromopalmitate (2-BP) is an irreversible inhibitor of protein-acyl transferases, responsible for palmitoylation of substrate proteins, and as a consequence, 2-BP treatment inhibits global palmitoylation in a non-selective manner (Davda et al., 2013). Immunoblot analysis of cell lysate prepared from A431 cells grown in 50 μ M 2-BP demonstrates there is no significant loss in expression of desmosomal components in 2-BP treated cells compared to control cells (Fig. 1C). Acyl-biotin exchange was used to demonstrate that 2-BP treatment resulted in a reduction in palmitoylation of plakophilin-2 and plakophilin-3 (Fig. 1D). Additionally, we examined the solubility of desmosomal components in buffer containing 0.5% Triton X-100. In cells treated with 2-BP, there was a significant shift from the insoluble pool to the soluble pool for plakophilin-2, plakophilin-3, plakoglobin and desmoglein-2. Solubility of desmocollin-2 was not significantly altered by 2-BP treatment (Fig 1E).

Next we examined the localization of desmosomal components in the presence of 2-BP. A431 cells expressing plakophilin-3/GFP (Roberts et al., 2011) were grown in the presence of 2-BP for 18 hours and the localization of plakophilin-3/GFP and other desmosomal components were examined. Immunofluorescence microscopy revealed a disruption in the localization of desmosomal components in A431 cells grown in medium containing 2-BP compared to control cells. As expected, plakophilin-3/GFP and endogenous desmoglein-2 were found to co-localize in a linear punctate staining pattern at cell-cell contact sites in DMSO treated control cells (Fig. 2A-C). In cells grown in medium containing 2-BP, plakophilin-3/GFP and desmoglein-2 co-localized however the pattern of desmosome localization was disrupted compared to control cells. The linear punctate array present in untreated cells was replaced in the 2-BP treated cells with larger aggregates of desmosomal components with increased space between punctate structures and some intracellular accumulation of signal. Cytoplasmic aggregates containing desmosomal components are observed throughout the 2-BP treated cultures. The nature of these structures is unclear however these structures do not co-localize with markers of the golgi

apparatus, lysosomes or the endocytic recycling compartment (data not shown). A similar staining pattern was observed for other desmosomal components, plakophilin-2 (Fig. 2M-R) and desmoplakin (Fig. 2S-X). E-cadherin localization Fig 2 (D-I) was not altered in cells grown in media containing 2-BP demonstrating that palmitoylation impacts desmosome junction assembly while adherens junction assembly is not significantly affected by treatment with 2-BP.

Inhibition of palmitoylation delays desmosome assembly in HaCat keratinocytes.

In order to investigate the role of palmitoylation during desmosome assembly we performed a calcium switch experiment using HaCat keratinocytes in the presence or absence of 2-BP. Cells were seeded on glass coverslips and grown in medium containing low calcium (0.050 mM calcium) until the culture reached approximately 75-80% confluence. Cells were grown overnight in low calcium containing medium with or without 50 mM 2-BP. Calcium was added to the medium to a final concentration of 1.8 mM and cells were processed for immunofluorescence microscopy after 2.5 hours in normal calcium conditions.

Junctional proteins are largely cytosolic when HaCat keratinocytes are grown in medium containing low calcium (Fig. 3 left panels). Adding calcium to the culture medium induced the redistribution of adhesive junction components to the plasma membrane, assembly of desmosomes and recruitment of E-cadherin (Fig. 3 middle panels). Cells pretreated with 2-bromopalmitate failed to efficiently recruit desmosomal components to the plasma membrane and as a result failed to assemble desmosomes after 2.5 hours (Fig. 3 right panels). In contrast, E-cadherin was recruited to sites of cell-cell contact in the presence of 2-BP. In fact, E-cadherin localization at cell borders was enhanced in HaCat cells treated with 2-BP. Overall, 2-BP treatment inhibited desmosome assembly and this inhibition was not due to a disruption of E-cadherin recruitment to the plasma membrane but rather was specific to events directing desmosome assembly.

A conserved cysteine in the plakophilin armadillo repeat domain is palmitoylated.

Examination of the amino acid sequence of the plakophilins revealed a conserved cysteine residue present in all three plakophilin isoforms (Fig. 4A) residing in the unstructured “loop” sequence between armadillo repeats 5 and 6 (Choi and Weis, 2005). Additionally, a recent proteomics dataset by Yang et al. (Yang et al., 2010) identified this conserved cysteine as

a potentially palmitoylated residue. In addition, based on a web based algorithm, these conserved cysteine residues are predicted to be palmitoylated (CCS Palm; (Ren et al., 2008)). To test these predictions, we generated myc-tagged plakophilin-2 with a serine residue in place of the conserved cysteine (C603S) and stably expressed this plakophilin-2 mutant protein in A431 cells. Additionally, we generated the corresponding mutant in plakophilin-3 (C569S). Mutation of these cysteine residues in plakophilin-2 and plakophilin-3 abolished palmitoylation of the tagged plakophilin construct while myc-tagged wild-type plakophilin-2 and plakophilin-3 were palmitoylated (Fig. 4C). These data show that plakophilins are palmitoylated on a single conserved cysteine residue present in an unstructured loop in the armadillo repeat domain.

Since A431 cells endogenously assemble desmosomes, we determined the localization of the myc-tagged plakophilin constructs in these cells. Exogenous wild-type plakophilin-2 (Fig 5A-C) and plakophilin-3 (supplementary figure S1) localized to cell borders and co-localized extensively with endogenous desmoplakin. In contrast, mutant plakophilin-2 (C603S) (Fig 5D-F) and plakophilin-3 (C569S) (Fig S1) did not efficiently localize to sites of cell-cell contact and are noticeably more cytoplasmic in their distribution. Interestingly expression of mutant plakophilins in A431 cells results in noticeable disruption in the localization of endogenously expressed desmosomal components. For example, desmoplakin is partially redistributed to cytosolic punctate structures in cells expressing plakophilin-2 C603S and plakophilin-3 C569S (compare Fig 5 B and E or Fig S1 B and E). Additionally, the localization of the desmosomal cadherins was also disrupted in cells expressing mutant plakophilins compared to cells expressing wild-type plakophilin-2 or plakophilin-3 (Fig 5 and S1 panels G-R). These data suggest that plakophilin-2 C603S and plakophilin-3 C569S act as dominant negatives with respect to localization of desmosomal components at sites of cell-cell contact. The mechanism of this dominant-negative effect is currently under investigation.

Additionally plakophilin-2 C603S and plakophilin-3 C569S were found to be more soluble in lysis buffer containing Triton X-100 compared to wild-type plakophilins expressed in A431 cells (Fig 6). While the localization of endogenous desmosomal components was altered in cells expressing mutant plakophilins, the Triton X-100 solubility of these proteins was unaltered. These data suggest that the mutant plakophilins affect desmosome localization rather than solubility of the desmosomal components. The nature of the intracellular clusters is not understood.

Palmitoylation of the plakophilins enhances their association with lipid raft domains.

Palmitoylation of cysteine residues is proposed to increase the association of modified proteins with lipid raft domains. Recent studies have demonstrated that desmosomal components are indeed associated with membrane micro domains enriched in lipid rafts components (Brennan et al., 2012; Resnik et al., 2011) and disruption of lipid rafts has effects on desmosome dynamics (Stahley et al., 2014). We examined the ability of myc-tagged wild-type plakophilins and plakophilin mutants to associate with lipid raft components by sucrose-gradient centrifugation. Cell lysates prepared from A431 cells expressing wild-type and mutant plakophilins were separated by sucrose-gradient centrifugation and the co-sedimentation of the myc-tagged plakophilins with desmoglein-2 and caveolin-1 was examined by immunoblot analysis. Desmoglein-2 was shown to associate with lipid rafts previously and in our lysates desmoglein-2 partitioned with the lipid raft component caveolin-1 in fractions 4 and 5 of our preparations (Fig. 6 C-E). Wild-type plakophilins were found to be present in fractions 4 and 5 indicating an association with lipid raft components. Plakophilin mutants (Pkp-2 C603S and Pkp-3 C569S) showed a decreased association with the lipid raft fractions compared to the wild-type plakophilins. These data suggest that lack of palmitoylation of the plakophilins results in decreased association with lipid raft domains but other interactions are likely to be involved in recruitment to lipid raft domains, possibly direct interactions with other endogenous desmosomal components present in A431 lipid rafts (e.g. desmosomal cadherins).

Plakophilin mutants fail to support desmosome assembly in A431D cells.

Previously, our laboratory characterized a cell culture system that allowed us to examine plakophilin-dependent assembly of desmosomes (Lewis et al., 1997; Wahl, 2005). A431D cells expressing E-cadherin (A431DE cells) assemble adherens junctions but lack the expression of an endogenous plakophilin and do not assemble desmosomal components at sites of cell-cell contact. Expression of plakophilin-2 fused at its carboxyl terminus to the estrogen receptor ligand-binding domain resulted in a plakophilin-2/ER fusion protein that can be “activated” by the addition of 4-hydroxytamoxifen (4OHT) to the culture medium. In the absence of 4OHT, plakophilin-2/ER was localized in the cytoplasm (Fig. 7A) and desmoplakin was cytosolic and not recruited to the plasma membrane (Fig. 7B). Addition of 4OHT to the culture medium resulted in the localization of plakophilin-2/ER to the plasma membrane (Fig. 7D) and

recruitment of desmoplakin to punctate structures at sites of cell-cell contact (Fig. 7E). In contrast to the wild-type protein, plakophilin-2 C603S/ER failed to efficiently localize to sites of cell-cell contact and recruitment of desmoplakin to the plasma membrane was impaired (Fig. 7G-I). Wild-type plakophilin-2/ER fusion protein becomes incorporated into a Triton X-100 insoluble fraction (pellet fraction) following 4OHT. However, the mutant plakophilin/ER fusion protein remained in the Triton X-100 soluble fraction indicating the inability of the mutant fusion protein to initiate desmosome assembly in A431DE cells (Fig. 7K).

Expression of mutant plakophilins disrupts cell-cell adhesion.

We examined the relative intercellular adhesive strength of A431 cells expressing myc-tagged plakophilin-2, myc-tagged plakophilin-3 and myc-tagged plakophilin mutants using the disperse adhesion assay (Calautti et al., 1998; Huen et al., 2002). In this assay, a decrease in the number of cell fragments following mild mechanical stress indicates increased intercellular adhesion. As expected, A431 cells expressing wild-type myc-tagged plakophilin-2 and plakophilin-3 conferred increased intercellular adhesion compared to parental A431 cells (Fig. 8). Others have previously shown that exogenous expression of plakophilin isoforms can increase intercellular adhesion (Roberts et al., 2013; Setzer et al., 2004; Wolf et al., 2013) In contrast, expression of the myc-tagged plakophilin palmitoylation mutants failed to increase intercellular adhesion in these cultures. In fact, expression of the plakophilin palmitoylation mutants in A431 cells resulted in decreased adhesion compared to parental A431 cells. Taken together with the observation that desmoplakin localization is also disrupted in A431 cells expressing plakophilin mutants (Fig. 5 and S1) these data suggest that the plakophilin isoforms that are unable to be palmitoylated function as dominant-negative proteins with respect to strength of desmosomal adhesion.

Discussion

In the present study we have demonstrated that several desmosomal components are palmitoylated *in vivo* uncovering a novel post-translational modification as well as a potential mechanism of regulating junction dynamics. Previously, several desmosomal components were identified as potential palmitoylated proteins in a large-scale proteomics screen of palmitoylated proteins in DU145 prostate cells (Yang et al., 2010). Given the potential for a high incidence of

“false positives” associated with large proteomic data sets, we set out to show that desmosomal proteins are palmitoylated and to determine the role of palmitoylation in desmosome dynamics.

We demonstrated that both the desmosomal cadherins (desmoglein-2 and -3 and desmocollin-2) and desmosomal plaque proteins are palmitoylated while the adherens junction constituents, E-cadherin, α -catenin, β -catenin and desmoplakin are not palmitoylated. Plakophilin-2 and plakophilin-3 each contain 8 cysteines. We mapped the site of palmitoylation in plakophilin-2 and plakophilin-3 to a conserved cysteine present in the armadillo repeat domain between armadillo repeats 5 and 6 (Choi and Weis, 2005). Recent studies have demonstrated that another p120 catenin family member is also palmitoylated. Delta-catenin was shown to be palmitoylated in cultured hippocampal neurons and disruption of palmitoylation of delta-catenin decreased the association of delta-catenin with N-cadherin. Interestingly these authors identified two cysteines (C960 and C961) that are palmitoylated by the palmitoyl-acyl transferase DHHC5 (Brigidi et al., 2014). These cysteines are distinct from the conserved cysteine we identified in the plakophilins.

Mutation of the conserved cysteine residue in plakophilin-2 and plakophilin-3 resulted in the inability of the plakophilins to become palmitoylated, disrupted their localization to the plasma membrane and interfered with their ability to initiate desmosome assembly in A431D cells. Preventing global palmitoylation by 2-BP resulted in an inhibition of desmosome assembly in a calcium switch assay. E-cadherin localization and AJ assembly were not disrupted following 2-BP incubation in HaCat cells suggesting that 2-BP does not simply disrupt global cell-cell adhesion. Together these data indicate that palmitoylation of the plakophilins is of particular importance during desmosome assembly but does not address the possibility that palmitoylation of desmosomal proteins also plays a role in desmosome maturation, stability or disassembly. Further studies will be required to address these possibilities.

Palmitoylation is a reversible post-translational modification resulting in the addition of 16 carbon palmitate to specific cysteine side chains through a thioester linkage. A family of palmitoyl transferases containing the conserved Cys-rich DHHC (Asp-His-His-Cys) domain (Fukata et al., 2004; Roth et al., 2002) are responsible for the addition of palmitate to substrate proteins while removal of palmitate is catalyzed by cytosolic thioesterases (LYPLA1, LYPLA2 and LYPLA1L) (Tian et al., 2012; Veit and Schmidt, 2001; Zeidman et al., 2009). The reversible nature of this particular modulation makes it an attractive mechanism that is capable of

regulating desmosome assembly, stability or even adhesive strength in epithelial cells. Currently efforts are underway in our laboratory to identify the palmitoyl transferases responsible for palmitoylation of the plakophilins as well as the other desmosomal components. Identification of the PAT responsible for modification of the desmosomal components will be necessary to understand the sequence of events in palmitoylation dependent desmosome assembly.

Several groups have demonstrated that palmitoylation of substrate proteins results in increased association with cellular membranes, including the plasma membrane (Resh, 2006). Furthermore palmitoylation is thought to play a role in targeting of proteins to membrane microdomains. Recent studies have demonstrated that desmosomal components are associated with lipid rafts. (Brennan et al., 2012; Resnik et al., 2011; Stahley et al., 2014). Here we have shown that plakophilin mutants that are unable to become palmitoylated show decreased association with lipid raft markers in sucrose gradient centrifugation. Association of desmoglein-2 with raft fractions in this assay was not affected by plakophilin palmitoylation. It is likely that palmitoylation of the desmosomal components increase the incorporation of these proteins into lipid rafts and ultimately into desmosomal plaques. Palmitoylation may assist in the packing of desmosomal components in the plane of the membrane to generate the characteristic electron dense plaque seen by electron microscopy. Characterization of the palmitoylation of additional desmosomal components should shed light on the role of lipid rafts on desmosome dynamics.

Based on the data presented here we propose that palmitoylation of the plakophilins (and possibly other desmosomal components) affects the ability of these proteins to interact with the membrane in an ordered manner and affect junction assembly. Our studies were unable to examine the effect of palmitoylation on desmosome disassembly or degradation of desmosomal components. The effect of palmitoylation on these processes should be addressed in the future. Inhibition of global palmitoylation (2-BP treatment) prevents desmosome assembly following calcium addition in HaCat cells while E-cadherin localization is unaffected by inhibition of palmitoylation (Figs 2 and 3). More specifically plakophilin2 C603S/ER is unable to initiate desmosome assembly in A431DE cells upon 4-hydroxytamoxifen addition (Fig. 7). Recent studies have demonstrated that lipid raft association is required desmosome assembly (Brennan et al., 2012; Resnik et al., 2011; Stahley et al., 2014). Palmitoylation is likely to influence the association of desmosomal components with this highly ordered membrane microdomain and thereby affect desmosome assembly.

Several interesting questions remain to be addressed. The PATs and thioesterases responsible for the addition and removal of palmitate from desmosomal components must be identified and their activity characterized with respect to desmosome dynamics. It will be important to know in which specific membrane compartment the PATs reside and at what subcellular compartment do the desmosomal components become palmitoylated.

Additionally, it is currently unknown how palmitoylation of the plakophilin-2 and plakophilin-3 armadillo repeat domains influences membrane association. Since no binding partners of the plakophilin armadillo repeat domain have been identified, it is unclear if palmitoylation alters protein-protein interaction or simply strengthens the association with membrane. Previous analysis of plakophilin-3 has shown plakophilin-3 interaction with desmosomal components is mediated by the amino terminal head domain. Interestingly expression of the plakophilin-3 amino terminal head domain alone is not sufficient for recruitment to the plasma membrane and expression of the armadillo repeat domain of plakophilin-3 is recruited to the plasma membrane (Bonne et al., 2003; Roberts et al., 2011). Together these data suggest that sequences in the head domain as well as the arm repeats are needed for proper localization and insertion into desmosomal complexes. Here we have demonstrated that a single cysteine to serine substitution in the armadillo repeat domain disrupts membrane localization in A431 cells. We recently characterized desmosome assembly in migrating epithelial cells and we determined that desmosomes initiate assembly in close proximity to actin filaments between cells near the leading edge (Roberts et al., 2011). Plakophilin-1 has previously been shown to localize to the actin cytoskeleton when it is overexpressed in HaCat keratinocytes (Hatzfeld et al., 2000). Like plakophilin-2 and -3, plakophilin-1 is also palmitoylated in cultured cells (data not shown). Palmitoylation of the plakophilins may influence the ability of these desmosomal components to interact with the actin cytoskeleton and initiate desmosome assembly.

Materials and Methods

Cell Culture: The A431 cervical squamous cell carcinoma cell line was obtained from ATCC (Manassas, VA) A431 and HaCat keratinocytes (Boukamp et al., 1988) (a kind gift from Dr. Pamela Jensen, University of Pennsylvania) were routinely grown in DMEM media (Sigma Chemical Co., St. Louis, MO.) supplemented with 10% fetal bovine serum (HyClone

Laboratories, Logan, UT). A431DE cells were previously described (Lewis et al., 1997; Wahl, 2005). Generation of retroviral particles and retroviral infection has been previously described (Roberts et al., 2011; Sobolik-Delmaire et al., 2007). Retrovirally infected cell populations were routinely grown in DMEM media containing 500 µg/mL G418 (Mediatech Inc., Herndon, VA.). For calcium switch experiments, HaCat cells were grown in DMEM medium lacking calcium supplemented with 10% dialyzed fetal bovine serum for at least 48 hours prior to the addition of 1.8 mM CaCl₂ and 50 µM 2-bromopalmitate.

Antibodies: Monoclonal antibodies specific for plakophilin-3 (11F2) and plakophilin-2 (8H6) were generated as previously described (Hall et al., 2009; Johnson et al., 1993; Roberts et al., 2011; Wahl, 2002). Anti desmoplakin (20B6), anti desmoglein-2 (6D8), E-cadherin (4A2) and anti desmocollin-2/3 (7G6) were previously described (Bazzi et al., 2006; Nieman et al., 1999; Sobolik-Delmaire et al., 2007; Wahl et al., 1996). Rabbit anti desmoplakin (NW6) was a kind gift of Dr. Kathleen Green (Northwestern University, Chicago, IL.) Rabbit anti Caveolin-1 (N20) was obtained from Santa Cruz Biotechnology (Santa Cruz, CA.). Anti β-tubulin (E7) hybridoma was obtained from The Developmental Studies Hybridoma Bank (The University of Iowa, Iowa City, IA.) and hybridoma supernatant was generated. Rabbit anti-estrogen receptor was obtained from Sigma Chemical Co. (St. Louis, MO. Catalog #E0646) Generation of cell lysates, immunoblot analysis and immunofluorescence microscopy were performed as described previously (Roberts et al., 2011; Sobolik-Delmaire et al., 2007).

Detergent extraction: Cell lysates were prepared as previously described (Sobolik-Delmaire et al., 2006; Wahl et al., 2000). Triton X-100 soluble (s) and insoluble (p) fractions were isolated by first washing cell monolayers with 1x phosphate buffered saline. Cells grown in a T25 cm² flask were scraped into 1 mL of Triton X-100 containing buffer (10 mM Tris HCl; pH8.0, 0.5% Triton X-100 and 2 mM EDTA) and incubated on ice while shaking for 15 minutes. The insoluble material was collected by centrifugation for 15 minutes at 14,000 x g. The insoluble pellet was washed once with Triton X-100 lysis buffer prior to resuspension of the pellet in 1 mL of SDS containing buffer (10 mM Tris HCl; pH 8.0, 2% SDS, 2 mM EDTA). Lysates were prepared in Laemmli sample buffer and resolved by SDS-PAGE.

Generation of cDNA constructs: Human plakophilin-2a (NP_001005242) and plakophilin-3 (NP_009114) cDNA were previously described (Hall et al., 2009; Roberts et al., 2011).

Plakophilin-2 (pkp-2/ER) fused to the estrogen receptor ligand binding domain T2 variant (Feil

et al., 1997) was generated by standard procedures to remove the stop codon from each cDNA and add an XhoI restriction site. Plakophilin point mutations (pkp-2 C603S and pkp-3 C569S) were generated using QuikChange™ site directed mutagenesis kit (Stratagene/Agilent Technologies, Santa Clara, CA.). The modified cDNAs were completely sequenced and shown to have no unintended changes. Addition of a 2x c-myc epitope tag to the amino terminus was achieved by subcloning plakophilin cDNAs downstream of the cDNA encoding the epitope tag in a modified pSPUTK vector (Falcone and Andrews, 1991). The plakophilin cDNAs together with the c-myc epitope tag were subsequently subcloned into an LZRS retroviral expression vector. Plakophilin-3/GFP has been described previously (Roberts et al., 2011). cDNA constructs were cloned into vectors based upon LZRS (Ireton et al., 2002) which were transfected into Phoenix cells for the generation of retroviral particles.

Acyl biotin exchange: A431 cells were grown to 80-90% confluence and lysates were prepared as described by Wan et al. (Wan et al., 2007). Cells were harvested in lysis buffer containing 1% Triton X-100 or 0.5% Empigen BB (EMD Millipore, Darmstadt, Germany) (150 mM NaCl, 50 mM Tris HCl, pH 7.4, 1% Triton X-100 or 0.5% Empigen BB, 5 mM EDTA) containing 10 mM NEM (N-ethylmaleimide, Sigma) and were collected by scraping on ice and passed through a 25 gauge needle. Triton X-100 was used for most ABE experiments but Empigen BB was used to solubilize desmoplakin from A431 cell monolayers. Samples were chloroform-methanol precipitated and the pellet was allowed to air dry for 2-3 minutes. The pellet was re-suspended in 300 µL of 4% SDS buffer (4% sodium dodecyl sulfate, 50 mM Tris HCl, pH 7.4, 5 mM EDTA) and diluted four fold in lysis buffer containing 10 mM NEM. The samples are incubated at 4° C overnight with gentle agitation. NEM was removed by performing 3 sequential chloroform-methanol precipitations and following the last precipitation, the pellet was re-suspended in 100 µL of 4% SDS buffer. The sample was divided in two and one half was diluted five-fold with buffer containing 0.7 M hydroxylamine (+HA) (0.7 M hydroxylamine, 1 mM HPDP-biotin, 0.2% Triton X-100, 1 mM PMSF and 1x protease inhibitor cocktail (Sigma)) and the other sample was diluted five-fold with buffer lacking hydroxylamine (-HA). Samples were incubated at room temperature with gentle rocking for one hour. Samples were chloroform-methanol extracted three times and the final pellets were re-suspended in 240 µL 4% SDS buffer and diluted with 960 µL low-HPDP-biotin buffer (150 mM NaCl, 50 mM Tris HCl; pH7.4, 5 mM EDTA, 0.2 mM HPDP-biotin, 0.2% Triton X-100, 1 mM PMSF, 1x protease inhibitor cocktail).

Samples were incubated at room temperature with gentle agitation for one hour prior to three sequential chloroform-methanol precipitations. The final pellet was re-suspended in 75 μ L of 2% SDS buffer (2% SDS, 50 mM Tris HCl; pH 7.4, 5 mM EDTA) and samples were diluted to 0.1% SDS in lysis buffer containing 0.2% Triton X-100, 1x protease inhibitor cocktail and 1 mM PMSF. Protein concentrations were determined and equal amounts of protein were added to streptavidin agarose. Biotin-labeled proteins were captured on streptavidin agarose and non-specifically bound proteins were removed by washing the beads in lysis buffer containing 0.1% SDS and 0.2% Triton X-100. Captured proteins were boiled in 2x Laemmli sample buffer and resolved by SDS-PAGE.

Metabolic labeling and Acyl Biotin Exchange: For 17-ODYA metabolic labeling, A431 cells were grown to 80% confluence in 100 mm tissue culture dishes and were treated with 100 μ M 17-ODYA (17-octadecynoic acid; Cayman Chemical Co.) or DMSO vehicle (Sigma) for 48 hours (Zoltewicz et al., 2012). To facilitate dissolution of 17-ODYA in the medium 75 μ L of 20 mM 17-ODYA stock in DMSO (or DMSO only) mixed with 150 μ L 10% fatty acid free bovine serum albumin (Sigma) was added to 15 mL DMEM and the mixture vortexed prior to being added to cells. Cells were lysed in extraction buffer containing 0.5% Empigen BB detergent (10 mM Tris HCl, pH 8.0, 0.5% Empigen BB, 2 mM EDTA) and insoluble proteins were pelleted by centrifugation (14,000 x g for 15 min). Plakophilins were immunoprecipitated from Empigen BB soluble lysates and immune complexes were washed 3 times using TBST (10 mM Tris HCl, pH 8.0, 150 mM NaCl, 0.5% Tween-20). Immunoprecipitated proteins were eluted from the beads in 47 μ L elution buffer (50 mM HEPES, pH 7.4, 150 mM NaCl, 2% SDS). The Cu-catalyzed click reaction was performed as described in (Charron et al., 2009). Briefly, 47 μ L of eluted protein was added to 0.25 μ L 10 mM biotin azide (Invitrogen), 0.5 μ L 50 mM TCEP [Tris-(2-carboxyethyl)phosphine] hydrochloride (Sigma), 0.25 μ L 10 mM TBTA (Tris[(1-benzyl-1H-1,2,3-triazol-4-yl)methyl]amine) (Sigma) and 0.5 μ L 50 mM CuSO₄ (Sigma) for a total reaction volume of 50 μ L and the solution was incubated at room temperature for 1 hour. Samples were prepared in 1x Laemmli sample buffer containing 2-mercaptoethanol. Samples were not boiled prior to SDS-PAGE. Labeled proteins were separated by SDS-PAGE and biotin-labeled proteins were detected by blotting with HRP-labeled streptavidin (Jackson ImmunoResearch, West Grove, PA.)

Lipid raft fraction analysis. Cell lysates were prepared from A431 cell lines expressing wild-type or mutant plakophilins and analyzed by sucrose gradient centrifugation as previously described (McGuinn and Mahoney, 2014).

Dispase assays. Cells were grown to confluence in 6-well dishes and 24 hours post confluence the cell sheets were removed from the culture dish by incubating with dispase (Roche Applied Science, Indianapolis, IN.). Cell sheets were carefully transferred to 15 mL conical tubes and subjected to mechanical stress by inversion. Cell sheet fragments were counted, assays were performed in triplicate and the data are expressed as the average number of fragments/well.

Statistical analysis. For all experiments, error bars represent standard deviation of the mean, and data was compared using two-tailed Student's t-test assuming unequal variances. Statistical significance was assumed when $p < 0.05$. $p < 0.05$ is represented by * and $p < 0.01$ is represented by **

Acknowledgements

This project was supported by grants from the National Institute of General Medical Sciences (P20GM103489; J.K.W. and K.R.J.) and National Institute of Arthritis and Musculoskeletal and Skin Diseases (R01AR056067; MGM) from the National Institute of Health. K. R.J. and J.K.W. receive royalties from the sale of some of the antibodies used in these studies.

Figure Legends

Figure 1. Desmosomal components are palmitoylated. A) A431 cell lysates were prepared and acyl-biotin exchange was performed to identify palmitoylated proteins. Lysates were split in two and processed with (+) and without (-) hydroxylamine (HA). After the final streptavidin-agarose pull-down, the captured proteins were resolved by SDS-PAGE and individual desmosomal and adherens junction components were detected by immunoblot analysis. B) A431 cells were grown in medium with or without 100 μ M 17-ODYA for 48 hours. Plakophilin-2 and plakophilin-3 were immunoprecipitated from cell lysates and HRP-biotin was added to labeled cells using the Cu-catalyzed click reaction. Immunoprecipitations with no immunoprecipitating antibody (No Aby) served as negative controls. Immunoprecipitates were resolved by SDS-PAGE and labeled proteins were detected by HRP-streptavidin or isoform anti-plakophilin antibodies. C) Cell lysates were prepared from A431 cells grown in the presence or absence of 50 μ M 2-BP for 18

hours and immunoblot analysis was performed to examine the levels of plakophilin-2 (Pkp-2), plakophilin-3 (Pkp-3), plakoglobin (Pg), desmoplakin (Dp), desmocollin-2 (Dsc-2) and desmoglein-2 (Dsg-2). Beta-tubulin was used as a loading control. D) Acyl-biotin exchange demonstrated that plakophilin-2 and plakophilin-3 are palmitoylated in the absence of 2-BP and palmitoylation is decreased in A431 cells grown in medium containing 50 μ M 2-BP. E) Triton X-100 insoluble (p) and soluble (s) fractions were prepared from control A431 cultures (DMSO) or from A431 cells grown in media containing 50 μ M 2-BP. Immunoblot analysis determined there was a significant increase in the soluble fraction of plakophilin-2, plakophilin-3, plakoglobin and desmoglein-2 in 2-BP treated cultures. Desmocollin-2 Triton X-100 solubility was unchanged following 2-BP treatment.

Figure 2. Inhibition of palmitoylation by 2-bromopalmitate alters desmosomal component localization at cell borders. A431 cells expressing plakophilin-3/GFP were grown on glass coverslips in medium containing 50 μ M 2-BP or DMSO as a negative control (18 hours). Cells were fixed and immunostained with antibodies specific for desmoglein-2 (Dsg2) (panels A-F), E-cadherin (E-Cad) (panels G-L), plakophilin-2 (Pkp-2) (panels M-R) and desmoplakin (DP) (panels S-X). Inhibition of palmitoylation has little effect on the localization of E-cadherin while the localization of desmosomal components is disrupted at cell-cell borders. The bar in panel A represents 10 μ m.

Figure 3. Inhibition of palmitoylation disrupts calcium induced desmosome assembly in HaCat keratinocytes. HaCat keratinocytes were grown on glass coverslips in medium containing low calcium (left panels) in the absence (middle panels) or the presence of 50 μ M 2-bromopalmitate (right panels) overnight. Calcium was added (1.8 mM final concentration) to the medium for 2.5 hours and cells were processed for immunofluorescence microscopy using antibodies indicated. Average fluorescence intensity was determined using Slidebook5 image software by measuring a segment of equal length and width across 30 individual cell borders for each treatment. Blue lines are the average fluorescence intensity for control cultures and red lines represent fluorescence intensity in 2-bromopalmitate treated cell cultures. The bar in panel A represents 10 μ m.

Figure 4. A conserved cysteine in plakophilins is palmitoylated. A) Sequence alignment of plakophilin-1 (NP_001005337), plakophilin-2 (NP_001005242) and plakophilin-3 (NP_009114) shows similarity in the sequences surrounding the conserved cysteine residue. B) Immunoblot analysis of cell lysates prepared from control A431 cells, A431 cells expressing myc-tagged wild-type plakophilin-2 (myc-Pkp-2), myc-tagged plakophilin-2 C603S (myc-Pkp-2 C603S), myc-tagged wild-type plakophilin-3 (myc-Pkp-3) and myc-tagged plakophilin-3 C569S (myc-Pkp-3 C569S). Lysates were blotted with anti-myc, anti-plakophilin-2 or anti-plakophilin-3. Exogenous proteins were expressed at levels similar to those of the endogenous plakophilins, and the myc-tagged proteins were all expressed at similar levels to one another. Anti-tubulin is shown as a loading control. C) Acyl-biotin exchange demonstrates that plakophilin-2 C603S and plakophilin-3 C569S are not palmitoylated while wild-type plakophilin-2 and plakophilin-3 are palmitoylated.

Figure 5. Palmitoylation defective plakophilin-2 disrupts endogenous desmosomal component localization. A431 cells expressing wild-type plakophilin-2 (panels A-C, G-I and M-O) or plakophilin-2 C603S (panels D-F, J-L, and P-R) were grown on glass coverslips, fixed and immunostained using antibodies recognizing the myc epitope tag (panels A and D), desmocollin-2 (panels G and J) and desmoglein-2 (panels M and P). Desmoplakin co-localization is shown in panels B, E, H, K, N and Q. The bar in panel A represents 10 μ m.

Figure 6. Plakophilin mutants display altered Triton X-100 solubility and lipid raft association compared to wild-type plakophilin. A) Triton X-100 insoluble (P) and soluble fractions (S) were prepared from A431 cells expressing wild-type plakophilin-2, plakophilin-2 C603S, wild-type plakophilin-3 and plakophilin-3 C569S. Immunoblot analysis was performed using antibodies recognizing the myc epitope tag, plakoglobin, desmoglein-2 and desmocollin-2/3. B) Immunoblot analysis was performed in triplicate and quantification of the signal was determined using a LiCor Odyssey Imaging system. Myc-tagged plakophilin-2 C603S and myc-tagged plakophilin-3 C569S were found to be more soluble compared to myc-tagged wild-type plakophilin-2 and -3. Triton X-100 solubility of endogenous plakoglobin, desmoglein-2 and desmocollin-2/3 was not altered by the expression of mutant plakophilin-2 or plakophilin-3. (* p-value < 0.05). C and D) Cell lysates were prepared from A431 cells expressing myc-tagged wild-

type plakophilin-2 and myc-tagged plakophilin-2 C603S (C) and myc-tagged wild-type plakophilin-3 and myc-tagged plakophilin-3 C569S (D). Lysates were subjected to sucrose density centrifugation and one mL fractions were collected and immunoblot analysis was performed with the indicated antibodies. Fractions 4 and 5 (underlined) are enriched in the lipid raft component cavelolin-1 and endogenous desmoglein-2 and wild-type plakophilin-2 and wild-type plakophilin-3. E) The ratio of myc positive signal to the desmoglein-2 positive signal present in fractions 4 and 5 is shown graphically. The ratio of Plakophilin-2 C603S and plakophilin-3 C569S to the corresponding desmoglein-2 signal are reduced in fractions 4 and 5 compared to the wild-type plakophilins.

Figure 7. Plakophilin-2 C603S fails to efficiently initiate desmosome assembly in A431DE cells. In the absence of 4-hydroxytamoxifen (4OHT) neither plakophilin-2/ER nor desmoplakin localize to cell borders (panels A-C). Addition of 100 nM 4OHT to the medium for 18 hours results in plakophilin-2/ER localization at cell borders and the recruitment of desmoplakin (panels D-F). In contrast to the wild-type protein, plakophilin-2 C603S/ER did not efficiently localize to cell borders and desmoplakin was not efficiently recruited (anti ER; panels G-I). (J) Immunoblot analysis of A431DE cells expressing plakophilin-2/ER (Pkp-2/ER) or plakophilin-2 C603S/ER demonstrates equivalent expression of the plakophilin-2 fusion proteins. Anti β -tubulin is included as a loading control (K) A431DE cells expressing plakophilin-2/ER or plakophilin-2 C603S/ER were grown in medium containing 100 nM 4OHT for 18 hours. Triton X-100 soluble (S) and Triton X-100 insoluble pellet (P) fractions were prepared and immunoblotted with antibodies specific for plakophilin-2. Samples were prepared in triplicate and data were collected using LiCor Odyssey near-infrared imaging. (** p-value < 0.01).

Figure 8. Expression of plakophilin palmitoylation mutants disrupts desmosomal adhesion.

Dispase adhesion assays were performed to examine the relative strength of desmosomal adhesion in parental A431 cells (panel A) and in A431 cells expressing myc-tagged plakophilin-2 (panel B), myc-tagged plakophilin-2 C603S (panel C), myc-tagged plakophilin-3 (panel D), and myc-tagged plakophilin-3 C569S (panel E). Panels A-E depicts representative examples of cell sheet fragmentation counted in the dispase assay. Dispase assays were performed in triplicate and quantification of the dispase assay is depicted in panel F (* p-value < 0.05).

References:

- Aicart-Ramos, C., Valero, R. A. and Rodriguez-Crespo, I.** (2011). Protein palmitoylation and subcellular trafficking. *Biochim Biophys Acta* **1808**, 2981-94.
- Bazzi, H., Getz, A., Mahoney, M. G., Ishida-Yamamoto, A., Langbein, L., Wahl, J. K., 3rd and Christiano, A. M.** (2006). Desmoglein 4 is expressed in highly differentiated keratinocytes and trichocytes in human epidermis and hair follicle. *Differentiation* **74**, 129-40.
- Bonne, S., Gilbert, B., Hatzfeld, M., Chen, X., Green, K. J. and van Roy, F.** (2003). Defining desmosomal plakophilin-3 interactions. *J Cell Biol* **161**, 403-16.
- Boukamp, P., Petrussevska, R. T., Breitkreutz, D., Hornung, J., Markham, A. and Fusenig, N. E.** (1988). Normal keratinization in a spontaneously immortalized aneuploid human keratinocyte cell line. *J Cell Biol* **106**, 761-71.
- Brennan, D., Peltonen, S., Dowling, A., Medhat, W., Green, K. J., Wahl, J. K., 3rd, Del Galdo, F. and Mahoney, M. G.** (2012). A role for caveolin-1 in desmoglein binding and desmosome dynamics. *Oncogene* **31**, 1636-48.
- Brigidi, G. S., Sun, Y., Beccano-Kelly, D., Pitman, K., Mobasser, M., Borgland, S. L., Milnerwood, A. J. and Bamji, S. X.** (2014). Palmitoylation of delta-catenin by DHHC5 mediates activity-induced synapse plasticity. *Nat Neurosci* **17**, 522-32.
- Brooke, M. A., Nitoiu, D. and Kelsell, D. P.** (2012). Cell-cell connectivity: desmosomes and disease. *J Pathol* **226**, 158-71.
- Calautti, E., Cabodi, S., Stein, P. L., Hatzfeld, M., Kedersha, N. and Paolo Dotto, G.** (1998). Tyrosine phosphorylation and src family kinases control keratinocyte cell-cell adhesion. *J Cell Biol* **141**, 1449-65.
- Charron, G., Zhang, M. M., Yount, J. S., Wilson, J., Raghavan, A. S., Shamir, E. and Hang, H. C.** (2009). Robust fluorescent detection of protein fatty-acylation with chemical reporters. *J Am Chem Soc* **131**, 4967-75.
- Choi, H. J. and Weis, W. I.** (2005). Structure of the armadillo repeat domain of plakophilin 1. *J Mol Biol* **346**, 367-76.
- Collins, J. E., Legan, P. K., Kenny, T. P., MacGarvie, J., Holton, J. L. and Garrod, D. R.** (1991). Cloning and sequence analysis of desmosomal glycoproteins 2 and 3 (desmocollins): cadherin-like desmosomal adhesion molecules with heterogeneous cytoplasmic domains. *J Cell Biol* **113**, 381-91.
- Davda, D., El Azzouny, M. A., Tom, C. T., Hernandez, J. L., Majmudar, J. D., Kennedy, R. T. and Martin, B. R.** (2013). Profiling targets of the irreversible palmitoylation inhibitor 2-bromopalmitate. *ACS Chem Biol* **8**, 1912-7.
- Davies, E. L., Gee, J. M., Cochrane, R. A., Jiang, W. G., Sharma, A. K., Nicholson, R. I. and Mansel, R. E.** (1999). The immunohistochemical expression of desmoplakin and its role in vivo in the progression and metastasis of breast cancer. *Eur J Cancer* **35**, 902-7.
- Falcone, D. and Andrews, D. W.** (1991). Both the 5' untranslated region and the sequences surrounding the start site contribute to efficient initiation of translation in vitro. *Mol Cell Biol* **11**, 2656-64.
- Feil, R., Wagner, J., Metzger, D. and Chambon, P.** (1997). Regulation of Cre recombinase activity by mutated estrogen receptor ligand-binding domains. *Biochem Biophys Res Commun* **237**, 752-7.
- Fukata, M., Fukata, Y., Adesnik, H., Nicoll, R. A. and Brecht, D. S.** (2004). Identification of PSD-95 palmitoylating enzymes. *Neuron* **44**, 987-96.

- Gerull, B., Heuser, A., Wichter, T., Paul, M., Basson, C. T., McDermott, D. A., Lerman, B. B., Markowitz, S. M., Ellinor, P. T., MacRae, C. A. et al.** (2004). Mutations in the desmosomal protein plakophilin-2 are common in arrhythmogenic right ventricular cardiomyopathy. *Nat Genet* **36**, 1162-4.
- Greaves, J. and Chamberlain, L. H.** (2011). DHHC palmitoyl transferases: substrate interactions and (patho)physiology. *Trends Biochem Sci* **36**, 245-53.
- Hall, C., Li, S., Li, H., Creason, V. and Wahl, J. K.** (2009). Arrhythmogenic right ventricular cardiomyopathy plakophilin-2 mutations disrupt desmosome assembly and stability. *Cell Commun Adhes* **16**, 15-27.
- Harada, H., Iwatsuki, K., Ohtsuka, M., Han, G. W. and Kaneko, F.** (1996). Abnormal desmoglein expression by squamous cell carcinoma cells. *Acta Derm Venereol* **76**, 417-20.
- Hatzfeld, M., Haffner, C., Schulze, K. and Vinzens, U.** (2000). The function of plakophilin 1 in desmosome assembly and actin filament organization. *J Cell Biol* **149**, 209-22.
- Huen, A. C., Park, J. K., Godsel, L. M., Chen, X., Bannon, L. J., Amargo, E. V., Hudson, T. Y., Mongiu, A. K., Leigh, I. M., Kelsell, D. P. et al.** (2002). Intermediate filament-membrane attachments function synergistically with actin-dependent contacts to regulate intercellular adhesive strength. *J Cell Biol* **159**, 1005-17.
- Ireton, R. C., Davis, M. A., van Hengel, J., Mariner, D. J., Barnes, K., Thoreson, M. A., Anastasiadis, P. Z., Matrisian, L., Bundy, L. M., Sealy, L. et al.** (2002). A novel role for p120 catenin in E-cadherin function. *J Cell Biol* **159**, 465-76.
- Johnson, K. R., Lewis, J. E., Li, D., Wahl, J., Soler, A. P., Knudsen, K. A. and Wheelock, M. J.** (1993). P- and E-cadherin are in separate complexes in cells expressing both cadherins. *Exp Cell Res* **207**, 252-60.
- Koch, P. J., Goldschmidt, M. D., Walsh, M. J., Zimbelmann, R., Schmelz, M. and Franke, W. W.** (1991). Amino acid sequence of bovine muzzle epithelial desmocollin derived from cloned cDNA: a novel subtype of desmosomal cadherins. *Differentiation* **47**, 29-36.
- Lewis, J. E., Wahl, J. K., 3rd, Sass, K. M., Jensen, P. J., Johnson, K. R. and Wheelock, M. J.** (1997). Cross-talk between adherens junctions and desmosomes depends on plakoglobin. *J Cell Biol* **136**, 919-34.
- Martin, B. R. and Cravatt, B. F.** (2009). Large-scale profiling of protein palmitoylation in mammalian cells. *Nat Methods* **6**, 135-8.
- McGrath, J. A., McMillan, J. R., Shemanko, C. S., Runswick, S. K., Leigh, I. M., Lane, E. B., Garrod, D. R. and Eady, R. A.** (1997). Mutations in the plakophilin 1 gene result in ectodermal dysplasia/skin fragility syndrome. *Nat Genet* **17**, 240-4.
- McGuinn, K. P. and Mahoney, M. G.** (2014). Lipid Rafts and Detergent-Resistant Membranes in Epithelial Keratinocytes. *Methods Mol Biol*.
- Nieman, M. T., Kim, J. B., Johnson, K. R. and Wheelock, M. J.** (1999). Mechanism of extracellular domain-deleted dominant negative cadherins. *J Cell Sci* **112 (Pt 10)**, 1621-32.
- Ohno, Y., Kashio, A., Ogata, R., Ishitomi, A., Yamazaki, Y. and Kihara, A.** (2012). Analysis of substrate specificity of human DHHC protein acyltransferases using a yeast expression system. *Mol Biol Cell* **23**, 4543-51.
- Ren, J., Wen, L., Gao, X., Jin, C., Xue, Y. and Yao, X.** (2008). CSS-Palm 2.0: an updated software for palmitoylation sites prediction. *Protein Eng Des Sel* **21**, 639-44.
- Resh, M. D.** (2006). Palmitoylation of ligands, receptors, and intracellular signaling molecules. *Sci STKE* **2006**, re14.
- Resnik, N., Sepcic, K., Plemenitas, A., Windoffer, R., Leube, R. and Veranic, P.** (2011). Desmosome assembly and cell-cell adhesion are membrane raft-dependent processes. *J Biol Chem* **286**, 1499-507.

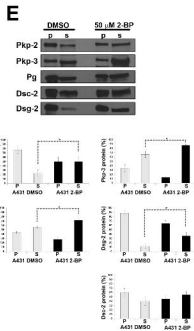
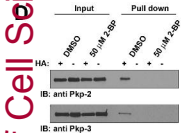
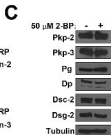
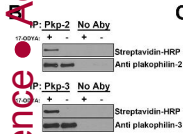
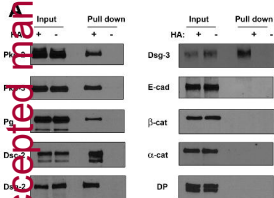
- Roberts, B. J., Pashaj, A., Johnson, K. R. and Wahl, J. K., 3rd.** (2011). Desmosome dynamics in migrating epithelial cells requires the actin cytoskeleton. *Exp Cell Res* **317**, 2814-22.
- Roberts, B. J., Reddy, R. and Wahl, J. K., 3rd.** (2013). Stratifin (14-3-3 sigma) Limits Plakophilin-3 Exchange with the Desmosomal Plaque. *PLoS One* **8**, e77012.
- Roth, A. F., Feng, Y., Chen, L. and Davis, N. G.** (2002). The yeast DHHC cysteine-rich domain protein Akr1p is a palmitoyl transferase. *J Cell Biol* **159**, 23-8.
- Ruiz, P., Brinkmann, V., Ledermann, B., Behrend, M., Grund, C., Thalhammer, C., Vogel, F., Birchmeier, C., Gunthert, U., Franke, W. W. et al.** (1996). Targeted mutation of plakoglobin in mice reveals essential functions of desmosomes in the embryonic heart. *J Cell Biol* **135**, 215-25.
- Setzer, S. V., Calkins, C. C., Garner, J., Summers, S., Green, K. J. and Kowalczyk, A. P.** (2004). Comparative analysis of armadillo family proteins in the regulation of a431 epithelial cell junction assembly, adhesion and migration. *J Invest Dermatol* **123**, 426-33.
- Sobolik-Delmaire, T., Katafiasz, D., Keim, S. A., Mahoney, M. G. and Wahl, J. K., 3rd.** (2007). Decreased plakophilin-1 expression promotes increased motility in head and neck squamous cell carcinoma cells. *Cell Commun Adhes* **14**, 99-109.
- Sobolik-Delmaire, T., Katafiasz, D. and Wahl, J. K., 3rd.** (2006). Carboxyl terminus of Plakophilin-1 recruits it to plasma membrane, whereas amino terminus recruits desmoplakin and promotes desmosome assembly. *J Biol Chem* **281**, 16962-70.
- Stahley, S. N., Saito, M., Faundez, V., Koval, M., Mattheyses, A. L. and Kowalczyk, A. P.** (2014). Desmosome assembly and disassembly are membrane raft-dependent. *PLoS One* **9**, e87809.
- Sugimoto, H., Hayashi, H. and Yamashita, S.** (1996). Purification, cDNA cloning, and regulation of lysophospholipase from rat liver. *J Biol Chem* **271**, 7705-11.
- Thomas, G. J. and Speight, P. M.** (2001). Cell adhesion molecules and oral cancer. *Crit Rev Oral Biol Med* **12**, 479-98.
- Thomason, H. A., Cooper, N. H., Ansell, D. M., Chiu, M., Merrit, A. J., Hardman, M. J. and Garrod, D. R.** (2012). Direct evidence that PKC α positively regulates wound re-epithelialization: correlation with changes in desmosomal adhesiveness. *J Pathol*.
- Tian, L., McClafferty, H., Knaus, H. G., Ruth, P. and Shipston, M. J.** (2012). Distinct acyl protein transferases and thioesterases control surface expression of calcium-activated potassium channels. *J Biol Chem* **287**, 14718-25.
- Tomatis, V. M., Trenchi, A., Gomez, G. A. and Daniotti, J. L.** (2010). Acyl-protein thioesterase 2 catalyzes the deacylation of peripheral membrane-associated GAP-43. *PLoS One* **5**, e15045.
- Toyoda, T., Sugimoto, H. and Yamashita, S.** (1999). Sequence, expression in Escherichia coli, and characterization of lysophospholipase II. *Biochim Biophys Acta* **1437**, 182-93.
- Veit, M. and Schmidt, M. F.** (2001). Enzymatic depalmitoylation of viral glycoproteins with acyl-protein thioesterase 1 in vitro. *Virology* **288**, 89-95.
- Wahl, J. K., 3rd.** (2002). Generation of monoclonal antibodies specific for desmoglein family members. *Hybrid Hybridomics* **21**, 37-44.
- Wahl, J. K., 3rd.** (2005). A role for plakophilin-1 in the initiation of desmosome assembly. *J Cell Biochem*.
- Wahl, J. K., Sacco, P. A., McGranahan-Sadler, T. M., Sauppe, L. M., Wheelock, M. J. and Johnson, K. R.** (1996). Plakoglobin domains that define its association with the desmosomal cadherins and the classical cadherins: identification of unique and shared domains. *J Cell Sci* **109 (Pt 5)**, 1143-54.
- Wahl, J. K. r., Nieset, J. E., Sacco-Bubulya, P. A., Sadler, T. M., Johnson, K. R. and Wheelock, M. J.** (2000). The amino- and carboxyl-terminal tails of (beta)-catenin reduce its affinity for desmoglein 2. *J Cell Sci* **113 (Pt 10)**, 1737-45.
- Wan, J., Roth, A. F., Bailey, A. O. and Davis, N. G.** (2007). Palmitoylated proteins: purification and identification. *Nat Protoc* **2**, 1573-84.

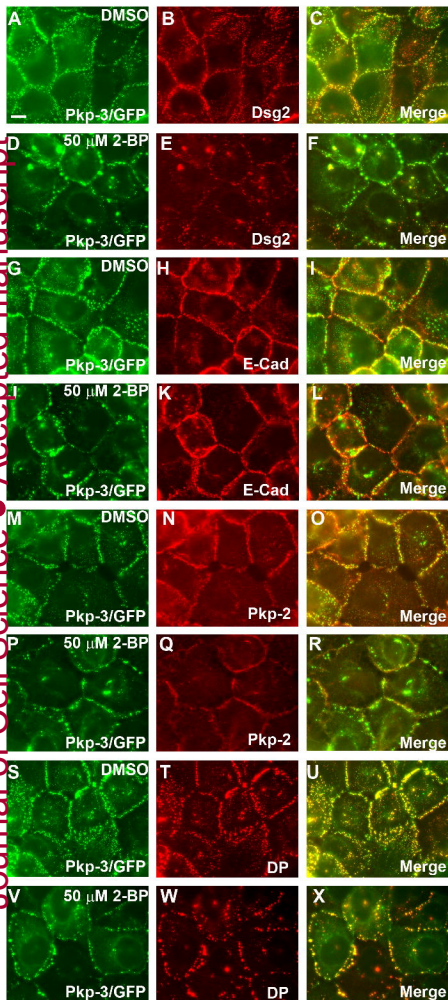
Wolf, A., Rietscher, K., Glass, M., Huttelmaier, S., Schutkowski, M., Ihling, C., Sinz, A., Wingenfeld, A., Mun, A. and Hatzfeld, M. (2013). Insulin signaling via Akt2 switches plakophilin 1 function from stabilizing cell adhesion to promoting cell proliferation. *J Cell Sci* **126**, 1832-44.

Yang, W., Di Vizio, D., Kirchner, M., Steen, H. and Freeman, M. R. (2010). Proteome scale characterization of human S-acylated proteins in lipid raft-enriched and non-raft membranes. *Mol Cell Proteomics* **9**, 54-70.

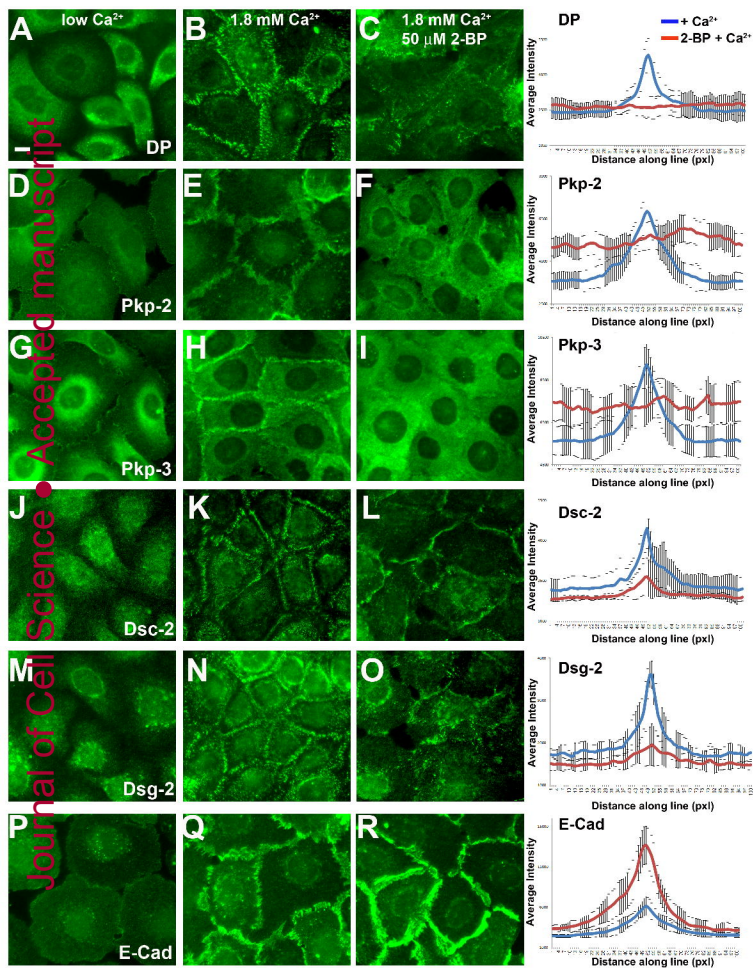
Zeidman, R., Jackson, C. S. and Magee, A. I. (2009). Protein acyl thioesterases (Review). *Mol Membr Biol* **26**, 32-41.

Zoltewicz, S. J., Lee, S., Chittoor, V. G., Freeland, S. M., Rangaraju, S., Zacharias, D. A. and Notterpek, L. (2012). The palmitoylation state of PMP22 modulates epithelial cell morphology and migration. *ASN Neuro* **4**, 409-21.





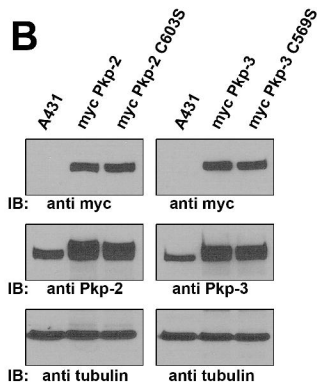
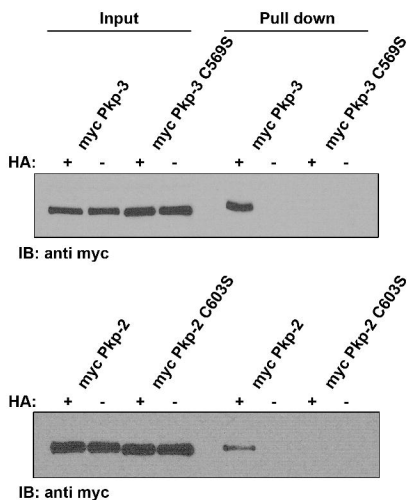
Roberts et al.
Figure 2



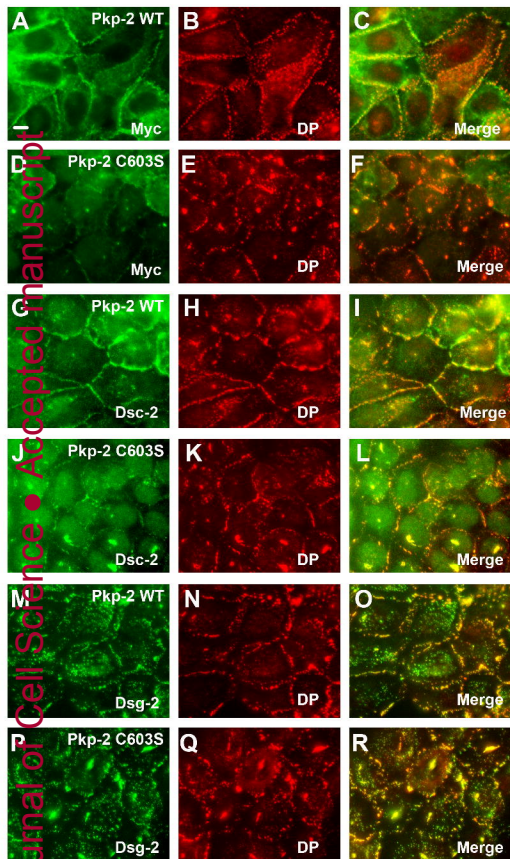
Roberts et al.
Figure 3

A

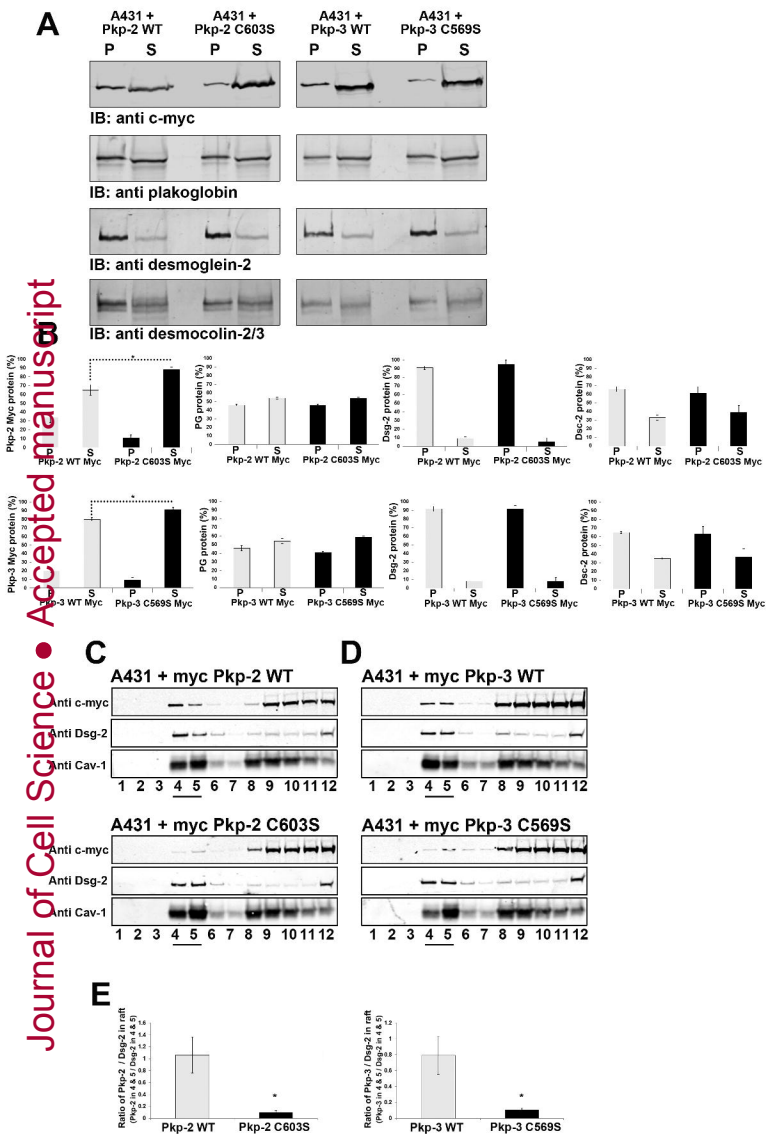
Pkp-1 487 KSSTGCFSNKSDK 499
 Pkp-2 598 NKSIGCFGSRSRK 610
 Pkp-3 564 GEMVGCFTPQSRR 576

B**C**

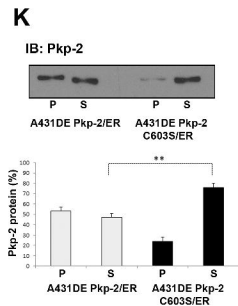
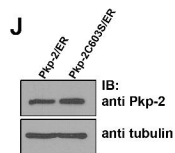
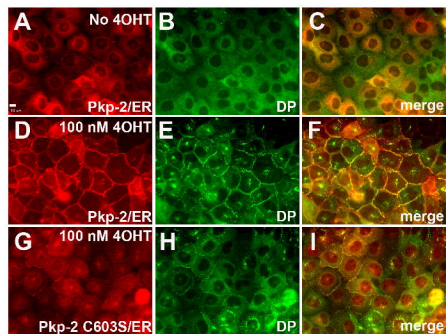
Roberts et al.
Figure 4



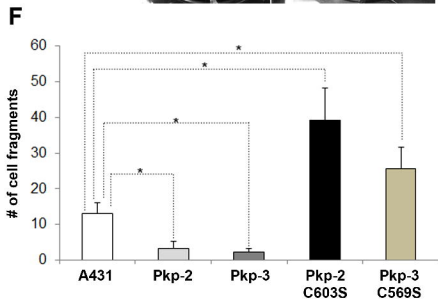
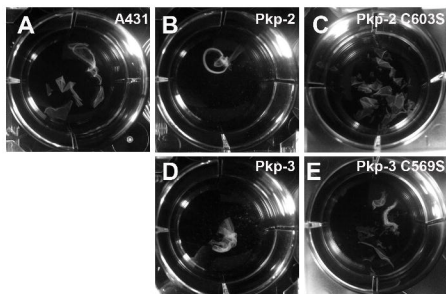
Roberts et al.
Figure 5



Roberts et al.
Figure 6



Roberts et al.
Figure 7



Roberts et al.
Figure 8