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Palmitoylation of the β4-Subunit Regulates Surface Expression of Large Conductance Calcium-activated Potassium Channel Splice Variants*

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Background: The role of post-translational modification of regulatory β-subunits in the control of large conductance potassium (BK) channels is largely unknown.

Results: β4-subunit palmitoylation controls surface trafficking of BK channel α-subunit splice variants.

Conclusion: Palmitoylation of β4 masks an α-subunit trafficking motif to control surface delivery.

Significance: Palmitoylation of regulatory subunits provides a dynamic mechanism to control surface trafficking of specific BK channel variants.

Regulatory β-subunits of large conductance calcium- and voltage-activated potassium (BK) channels play an important role in generating functional diversity and control of cell surface expression of the pore forming α-subunits. However, in contrast to α-subunits, the role of reversible post-translational modification of intracellular residues on β-subunit function is largely unknown. Here we demonstrate that the human β4-subunit is S-acylated (palmitoylated) on a juxtamembrane cysteine residue (Cys-193) in the intracellular C terminus of the regulatory β-subunit. β4-Subunit palmitoylation is important for cell surface expression and endoplasmic reticulum (ER) exit of the β4-subunit alone. Importantly, palmitoylated β4-subunits promote the ER exit and surface expression of the pore-forming α-subunit, whereas β4-subunits that cannot be palmitoylated do not increase ER exit or surface expression of α-subunits. Strikingly, however, this palmitoylation- and β4-dependent enhancement of α-subunit surface expression was only observed in α-subunits that contain a putative trafficking motif (…REVEDEC) at the very C terminus of the α-subunit. Engineering this trafficking motif to other C-terminal α-subunit splice variants results in α-subunits with reduced surface expression that can be rescued by palmitoylated, but not depalmitoylated, β4-subunits. Our data reveal a novel mechanism by which palmitoylated β4-subunit controls surface expression of BK channels through masking of a trafficking motif in the C terminus of the α-subunit. As palmitoylation is dynamic, this mechanism would allow precise control of specific splice variants to the cell surface. Our data provide new insights into how complex interplay between the repertoire of post-transcriptional and post-translational mechanisms controls cell surface expression of BK channels.

The pore-forming α-subunits of large conductance voltage- and calcium-activated potassium (BK) channels assemble with a number of accessory regulatory β- and γ-subunits (1, 2). These regulatory subunits provide a mechanism to increase the functional diversity of BK channels in different tissues by modifying their calcium and/or voltage sensitivity, channel kinetics, surface expression, or regulation by a range of signaling molecules and toxins. Indeed, loss of function of these regulatory subunits is associated with disruption of normal physiological processes ranging from control of vascular tone (3) to excretion of potassium from the kidney (4, 5) and neuronal excitability (6).

Thus, mechanisms that dynamically control the functional regulation of α-subunits by regulatory subunits represent important determinants of physiological control. Indeed, BK channels are dynamically regulated by a diverse range of reversible post-translational modifications. However, in contrast to the extensive post-translational modification of intracellular residues of the pore-forming α-subunit, reversible post-translational modification of regulatory subunits is very poorly characterized.

Increasing evidence supports an important role for the only reversible lipid post-translational modification of proteins, S-acylation (palmitoylation), as an important mechanism to control a wide diversity of ion channels, including BK channels (7). Here we demonstrate that the BK channel regulatory β4-subunit is S-acylated (palmitoylated) at a cysteine residue in the C terminus juxtaposed to the second transmembrane domain. Palmitoylation of the β4-subunit controls surface expression of BK channels and thus represents an important additional regulatory step in controlling BK channel properties and function.

EXPERIMENTAL PROCEDURES

Expression Constructs

Full-length BK channel ZERO α-subunit splice variants (coding sequence starts and ends in amino acids MDA . . . . DEC, respectively, also referred to as MDA-DEC (see Fig. 4A)) with
either an N-terminal FLAG tag (FLAG-ZERO) or an N-terminal FLAG and C-terminal HA tag (FLAG-ZERO-HA) in pcDNA3.1 were described previously (8). To generate FLAG-tagged splice variants differing in the N or C termini, a construct with coding sequence starting and ending MAN...ERL (generous gift of Dr. Jon Lippiat, University of Leeds (9)) was first subcloned into pcDNA3.1 using Nhel and NotI. An N-terminal FLAG tag was generated by PCR amplification using forward and reverse primers, forward 5’-ACGGTACCATGGGTTATGCAGACTTTAGCTC-3’ and reverse 5’-CTCTGACCATCGCTGCCAAGAGCTTGCG-3’, and the subsequent amplicon was ligated into the pcDNA3.1 using KpnI and PpuMI. To generate the MDA-ERL variant, an N-terminal KpnI and PpuMI fragment from FLAG-ZERO (MDA-DEC) was subcloned into the MAN-ERL backbone. To engineer the C-terminal heptapeptide REVEDEC from the ZERO (MDA-DEC) variant into the MAN-ERL variant to generate MAN-REVEDEC, the last 7 residues of MAN-ERL were swapped with REVEDEC using PCR primers, forward 5’-GTC TCT CCC TAG TGT TGG-3’ and reverse 5’-CCTAGTCAATTACATCTCTCAATTCTCTTTTCCTGTTCCTCCCAGG-3’, and the subsequent amplicon was ligated into a PacI and XbaI backbone from MAN-ERL.

To generate site-directed mutants and epitope-tagged constructs of the β4-subunit, a human construct (generous gift of Dr. Jon Lippiat, University of Leeds (9)) was used as template and subcloned into pcDNA3.1. The palmitoylation-deficient mutant C193A was generated using: forward 5’-CTGGT-TCTGACCATGCTGCTGCCAAGAGCTTGCG-3’, and reverse 5’-ACGGCACAAGCTCTTGGCAGCGATGGTCAGGA-3’, and the subsequent amplicon was TOPO-cloned, digested with NheI and XbaI fragment ligated into the pcDNA3.1 using KpnI and PpuMI. To generate the MDA-ERL variant, an N-terminal KpnI and PpuMI fragment from FLAG-ZERO (MDA-DEC) was subcloned into the MAN-ERL backbone. To engineer the C-terminal heptapeptide REVEDEC from the ZERO (MDA-DEC) variant into the MAN-ERL variant to generate MAN-REVEDEC, the last 7 residues of MAN-ERL were swapped with REVEDEC using PCR primers, forward 5’-GTC TCT CCC TAG TGT TGG-3’ and reverse 5’-CCTAGTCAATTACATCTCTCAATTCTCTTTTCCTGTTCCTCCCAGG-3’, and the subsequent amplicon was ligated into a PacI and XbaI backbone from MAN-ERL.

β4-Subunit Palmitoylation Controls BK Channel Trafficking

Cell Culture, Transfection, and Imaging

HEK293 cells and N2a neurons were maintained in DMEM with 10% FCS. For imaging experiments, cells were plated on poly-D-lysine-coated glass in 6-well cluster plates at 15–20% confluency, and 24 h later, they were transfected with the respective plasmids using ExGen 500 and used 48 h after transfection. For N2a cells, they were differentiated for 48 h after transfection in DMEM containing 1% BSA.

Quantitative cell surface labeling of N-terminal FLAG epitope-tagged BK channel α-subunits in nonpermeabilized cells was performed using mouse monoclonal anti-FLAG M2 antibody (Sigma, 50 µg/µl) and secondary anti-mouse Alexa Fluor 543 (Invitrogen, 1:1000). Cells were then fixed in 4% paraformaldehyde for 30 min, permeabilized with 3% Triton X-100 for 10 min, and blocked with phosphate-buffered saline containing 3% bovine serum albumin plus 0.05% Tween 20 for 1 h. For total BK channel expression, either the intracellular C-terminal HA epitope tag was probed with anti-HA polyclonal rabbit antibody (Zymed Laboratories Inc. 1:500) followed by Alexa Fluor 488 (Molecular Probes, 1:1000) or the FLAG tag was probed with anti-FLAG antibody with anti-mouse Alexa Fluor 488 (1:1000). To detect β4-subunits, two approaches were used. For β4-subunits lacking an epitope tag, we used a mouse monoclonal antibody targeted to an extracellular epitope of β4 (NeuroMab clone L18A/3). In nonpermeabilized and permeabilized conditions, primary antibody dilutions were 1:300 and 1:1200, respectively, with anti-mouse secondary Alexa Fluor 488 or Alexa Fluor 543. For β4-subunits with a Myc epitope tag, the extracellular Myc C tag was detected using rabbit anti-MyC (Immune Systems) at 1:300 and anti-rabbit secondary antibody conjugated to either Alexa Fluor 488 or Alexa Fluor 647 prior to fixation and permeabilization. Total β4-subunit expression (MyC) was determined following cell fixation and permeabilization as above by probing with rabbit anti-MyC (Immune Systems) at 1:1000 and anti-rabbit secondary antibody conjugated to either Alexa Fluor 488 or Alexa Fluor 647 (1:1000) as appropriate. Cells were mounted in Mowiol and dried at room temperature in the dark overnight before image acquisition.

Confocal images were acquired on a Zeiss LSM510 laser scanning microscope, using a 63× oil Plan Apochromat (NA = 1.4) objective lens, on Nyquist sampling rates in multitracking mode to minimize channel crosstalk. Three-dimensional image stacks were deconvolved using Huygens (Scientific Volume Imaging), and cell surface expression of full-length channels was determined by quantitative immunofluorescence by calculating the surface (FLAG) to total channel protein (−HA or intracellular FLAG) ratio using ImageJ (National Institutes of Health). For co-localization experiments with endoplasmic reticulum (ER),2 co-localization was assayed by co-transfection of the channel subunits with pdsRed-ER (Clontech). Confocal images were acquired and deconvolved as above, and Pearson’s correlation coefficient (R) was determined using ImageJ (National Institutes of Health) with an R value of +1 indicating 100% co-localization.

2 The abbreviations used are: ER, endoplasmic reticulum; ANOVA, analysis of variance; acyl-RAC, S-acylation by resins-assisted capture; HEDTA, N-(2-hydroxyethyl)ethylenediaminetriacetic acid; TM2, transmembrane domain 2.
β4-Subunit Palmitoylation Controls BK Channel Trafficking

Palmitoylation Assays and Western Blotting

CSS-Palm Prediction—We exploited the published web-based CSS-Palm palmitoylation algorithm v3.0 (10) to predict cysteine residues within the entire coding sequence of the murine and human β4-subunits with prediction set to the highest cut off.

[3H]Palmitic Acid Incorporation—Transfected HEK293 cells were incubated in DMEM containing 10 mg/ml fatty acid free BSA for 30 min at 37 °C before incubation with 0.25 mCi/ml [3H]palmitic acid (PerkinElmer Life Sciences) for 4 h at 37 °C essentially as described (11, 12). Cells were lysed in 150 mM NaCl, 50 mM Tris-Cl, 1% Triton X-100, pH 8.0, and centrifuged, and channel fusion proteins were captured using magnetic microbeads (μMACSTM epitope tag isolation kits, Miltenyi Biotec). Following extensive washing, captured proteins were eluted, separated by SDS-PAGE, transferred to nitrocellulose membranes, dried, and exposed to light-sensitive film at −80 °C using a KODAK BioMax TranScreen LE (Amersham Biosciences). The same membrane was then reprobed with either an anti-β4 antibody (NeuroMab L18A/3) or an anti-Myc tag as appropriate.

Acyl-RAC of Mouse Cerebellum—Acyl-RAC of mouse cerebellum was performed with a modification of the acyl-RAC method described by Forrester et al. (13). Briefly, cerebellar from mice aged 8–12 weeks were rapidly isolated and immediately homogenized with a Dounce on ice in lysis buffer containing 25 mM NaCl, 25 mM HEPES, 1 mM EDTA at pH 7.5 essentially as described (11, 12). Cells were lysed in 150 mM NaCl, 50 mM Tris-Cl, 1% Triton X-100, pH 8.0, and centrifuged, and channel fusion proteins were captured using magnetic microbeads (μMACSTM epitope tag isolation kits, Miltenyi Biotec). Following extensive washing, captured proteins were eluted, separated by SDS-PAGE, transferred to nitrocellulose membranes, dried, and exposed to light-sensitive film at −80 °C using a KODAK BioMax TranScreen LE (Amersham Biosciences). The same membrane was then reprobed with either an anti-β4 antibody (NeuroMab L18A/3) or an anti-Myc tag as appropriate.

Electrophysiology

Macropatch recordings were performed using the inside-out patch clamp configuration at room temperature essentially as described (14). Briefly, the extracellular recording solution was composed of 140 mM KMeSO3, 2 mM KCl, 20 mM HEPES, 2 mM MgCl2, pH 7.3. The internal solution was composed of 140 mM KMeSO3, 2 mM KCl, 20 mM HEPES, 5 mM HEDTA, pH 7.3, with CaCl2 added to give a free Ca2+ concentration of 10 μM. Voltage protocols and acquisition were controlled using an Axopatch 200B amplifier and Digidata 1440A using pCLAMP10. Conductance-voltage (G/V) relationships were constructed from tail currents recorded using test pulses from −100 to 120 mV followed by a step to a negative voltage (~80 mV), and V0.5,max was determined from Boltzmann fits of the normalized G/V curves. Activation and deactivation time constants were determined by fitting to an exponential function.

Statistical Analysis

All data are presented as means ± S.E. with N = number of independent experiments and n = number of individual cells analyzed in imaging assays. Data were analyzed by ANOVA with post hoc Dunnett’s test with significance set at p < 0.05.

RESULTS

β4 Is Palmitoylated at a Juxtamembrane C-terminal Cysteine Residue—Using the CSS-Palm v3.0 palmitoylation prediction algorithm at high threshold (10), we identified a single predicted cysteine residue (Cys-193, CSS-Palm prediction score = 1.67; Fig. 1A), highly conserved across species, that is juxtaposed to transmembrane domain 2 (TM2) in the intracellular C terminus of the human β4-subunit (gene name KCNMB4). To test whether β4-subunits are palmitoylated, we took two approaches. Firstly, the β4-subunit was transiently expressed in HEK293 cells that were metabolically labeled with [3H]palmitate. Immunoprecipitation of the β4-subunits revealed robust incorporation of [3H]palmitate into β4-subunits (Fig. 1B). Mutation of the predicted palmitoylated cysteine residue Cys-193 to alanine (C193A) abolished [3H]palmitate incorporation without affecting protein expression of the mutated C193A β4-subunit (Fig. 1B). Secondly, using acyl-RAC (13) that allows determination of hydroxylamine-sensitive thioester bonds that couple S-acylated cysteine residues to their cognate lipid, we identified β4-subunit S-acylation in native mouse brain (Fig. 1C).

β4-Subunit Palmitoylation Controls Surface Expression and ER Exit—In many proteins, S-acylation controls trafficking and surface delivery of transmembrane proteins. To examine whether palmitoylation of β4-subunits affects their surface expression and trafficking per se, we undertook quantitative immunofluorescence assays. Using an antibody that recognizes an extracellular epitope expression of the WT β4-subunit in HEK cells revealed no significant surface expression (Fig. 1E) and predominant intracellular retention in the ER in agreement with previous studies (15). The C193A palmitoylation-deficient mutant had no significant effect on β4-subunit expression or localization (Fig. 1E). To improve the sensitivity of β4-subunit detection at the cell surface expression, we also engineered a β4-subunit with a Myc tag (Mycβ4) in the extracellular domain between transmembrane domains 1 and 2. Probing for the Mycβ4 tag revealed low, but detectable, levels of β4-subunit surface expression, with predominant intracellular ER retention, and surface expression was abolished below the limit of detection with the C193A mutant.

β4-Subunits are retained in the ER by a putative ER retention signal (KKXX) in the C terminus of the subunit (15). Thus, to improve the signal-to-noise ratio of our assay, we engineered two trafficking-competent β4-subunits to allow characterization of the role of palmitoylation in β4-subunit trafficking. Firstly, we mutated the central Lys-206 and Arg-207 amino
acids of the KKXX ER retention motif to alanine (KAAX construct), leading to a significantly enhanced cell surface expression of the KAAX mutant when compared with WT (Fig. 1E). Secondly, we found that similar enhancement of cell surface expression of the β4-subunit was manifest in constructs in which a Myc tag (Mycc) was engineered at the very C terminus of the β4-subunit and the alanine mutant C193A. A, acyl-RAC of murine cerebellum with Western blot probed with anti-b4. D, representative single confocal images of the β4 and C193A mutant expressed in HEK293 cells and co-labeled for the ER. Scale bars are 2 μm. E and F, bar graphs of membrane expression (expressed as a percentage of wild-type β4) (E) and co-localization with the ER (expressed as Pearson’s correlation coefficient, R) (F) of the wild-type β4 and C193A mutant. Data are means ± S.E. N > 5, n > 200. **, p < 0.01 when compared with wild-type β4 group, ANOVA with post hoc Dunnett’s test.

**β4-Subunits Palmitoylation Controls BK Channel Trafficking.**

Previous studies have reported that β4-subunits may either down-regulate BK channel surface expression (15) or conversely enhance surface expression of the related pH-sensitive Kcnu1 (Slo3) pore-forming subunits (17). β4-Subunits assemble with the BK channel pore-forming α-subunits in the ER (16), and as depalmitoylated β4-subunits are retarded in the ER, we hypothesized that β4-subunits control the surface expression of α-subunits by restricting their exit from the ER. In initial studies, we used the ZERO variant of murine BK channels that encodes from the initiator methionine MDAL...and terminates in the C-terminal variant...REVEDEC (here also referred to as MDA-DEC, see Fig. 4A). We exploited a co-expression strategy in HEK293 cells and used quantitative immunofluorescence to determine the subcellular localization and trafficking of the ZERO variant in the presence and absence of the WT and C193A mutant β4-subunit. Expression of the ZERO variant alone leads to robust expression with a proportion of the channel localizing with the ER (Fig. 2, A–C). Co-expression with WT β4-subunits resulted in a significant reduction of the ZERO channel variant co-localizing with the ER and subsequent increased expression at the cell surface (Fig. 2, A–C). This suggests that the WT β4-subunit facilitated ER export and trafficking of the ZERO variant to the cell surface. In contrast, expression of the C193A mutant of the β4-subunit had no significant effect on ER localization of the ZERO variant and did not result in an increased expression of the α-subunit at the cell surface (Fig. 2, A–C). Thus, the
...beta4-subunits can override the inhibitory effects of ZERO alpha-subunit depalmitoylation on cell surface expression, suggesting that in cells that express beta4-subunits, this mechanism may predominate.

Beta4-Subunits are predominantly, albeit not exclusively, expressed in many neurons and endocrine cells (6). We thus asked whether beta4-subunit-mediated enhancement of alpha-subunit cell surface expression was recapitulated in neurons. To test this, we expressed the WT ZERO alpha-subunit alone or co-expressed with either WT beta4-subunits or the C193A palmitoylation-deficient beta4-subunits in murine N2A neurons. In agreement with the data in HEK293 cells, co-expression of the WT beta4-subunits significantly enhanced surface expression of the ZERO variant, whereas the C193A beta-subunit mutant had no effect (Fig. 2E). This was again recapitulated with untagged beta4-subunits as WT and palmitoylation-deficient C193A mutant beta4-subunits increased ZERO surface expression to 219.7 ± 12.4 and 116.2 ± 4.3%, respectively, when compared with ZERO alone (100%) in N2a cells.

Importantly, these data reveal that in both HEK293 cells and N2a neurons, the ability of beta4-subunits to enhance alpha-subunit surface expression is not dependent upon the ability of the beta4-subunits per se to be able to traffic to the cell surface. Rather, the increased trafficking of ZERO is dependent upon the palmitoylation of the beta4-subunit. In further support of this, although the ER retention-deficient beta4-subunit mutant KAAK itself alone can traffic to the plasma membrane, in contrast to WT beta4-subunits (Fig. 1), only beta4-KAAK subunits that are palmitoylated enhance alpha-subunit surface expression. The ER retention-deficient beta4-subunit mutant KAAK increased ZERO variant cell surface expression by 155.7 ± 7.6%, comparable with that observed with the WT beta4-subunit, and this effect was abolished by the C193A mutation in the beta4-KAAK mutant (surface expression was 101.6 ± 7.6% when compared with ZERO (100%) alone).

To investigate whether palmitoylation of the beta4-subunit modified functional coupling of the beta4-subunit with alpha-subunits at the cell surface, we undertook patch clamp electrophysiological analysis of co-expressed WT and C193A mutant beta4-subunits with ZERO variants in HEK293 cells. Co-expression of WT beta4-subunits resulted in a significant (p < 0.01, ANOVA) left shift (by 12.5 ± 2.9 mV) of the V_{0.5,max} determined from the conductance/voltage (G/V) relationship of tail currents recorded in 10 μM intracellular free calcium (Fig. 3, A and B). The C193A mutant displayed a similar left shift in V_{0.5,max} of 15.6 ± 3.6 mV (Fig. 3, A and B). The WT beta4-subunit confers a significant slowing of both activation (Fig. 3C) and deactivation (Fig. 3D) kinetics of the ZERO variant. The C193A mutant displayed a similar slowing of activation kinetics (Fig. 3C). However, although deactivation kinetics were also significantly slowed when compared with ZERO alone, the deactivation time constant for the palmitoylation-deficient C193A mutant was significantly smaller than that observed with the WT beta4-subunit (Fig. 3D). Taken together, although beta4-subunit palmitoylation subtly modifies channel deactivation, these data support a predominant role for palmitoylation in controlling surface trafficking rather than the biophysical properties of the channel at the plasma membrane.

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**FIGURE 2.** Beta4-subunit palmitoylation controls surface expression and ER retention of the pore-forming alpha-subunit ZERO variant of BK channels. A, representative single confocal images of the ZERO variant of the pore-forming alpha-subunit of BK channels expressed in HEK293 cells in the absence and presence of the wild-type beta4-subunit and the palmitoylation-deficient C193A subunit. Total alpha-subunit expression and co-labeling for the ER with merged images are shown. Scale bars are 2 μm. B and C, quantification of the effect of beta4, or its C193A mutant, on ER co-localization (ER colo.) (B) and cell surface expression of the ZERO alpha-subunit (C). D, beta4, but not C193A, also increases cell surface expression of the ZERO alpha-subunit palmitoylation-deficient mutant C53:54:56A. E, recapitulation of cell surface enhancement of ZERO variant expression by beta4 in the neuronal cell line N2A for cell surface expression of the ZERO alpha-subunit channel, protein was probed under nonpermeabilized (surface) and permeabilized (total) conditions, and the surface/total ratio was expressed as a percentage of the alpha-subunit in the absence of regulatory subunit as indicated. Data are means ± S.E., N > 7, **p < 0.01 when compared with respective alpha-subunit expressed alone, ANOVA with post hoc Dunnett’s test.
β4-Enhancement of α-Subunit Surface Expression Is Splice Variant-dependent—A recent study (15) reported that β4-subunits suppressed cell surface expression of BK channels in contrast to the data above. In contrast, β4-subunits have been reported to enhance surface expression of the related pH-sensitive pore-forming subunit encoded by Kcnu1 (17). In the former studies (15), BK channel α-subunit variants were used that differ in both the N termini and the C termini sequences when compared with the ZERO variant (MDA-DEC) used here. Taken together, these data suggested that β4-subunit-dependent trafficking may also be dependent upon the characteristics of the co-assembled α-subunit variant. To address this and to further understand the mechanism(s) by which β4-subunits promote ER exit and cell surface expression of the ZERO channels, we asked whether this effect was also mediated with other α-subunit splice variants. The very C terminus of the intracellular domain of BK channel α-subunits is subjected to alternative pre-mRNA splicing that has been reported to differentially control cell surface expression of the channel (20–23). In particular, α-subunits that contained the longest C-terminal splice variant that terminates in the heptapeptide sequence ... REVEDEC sequence, as in our ZERO construct, display reduced cell surface expression when compared with α-subunit splice variants with shorter C termini that terminate in alternative sequences such as ... QEREL and ... VEMYR (20–23). Indeed, these studies demonstrated that swapping of the ... VEDEC sequence to channels with the shorter C termini generated channel α-subunits that displayed a dominant negative motif for cell surface expression. Furthermore, transfection of cells with peptides encoding the ... VEDEC sequence (20) or overexpression of a GFP fusion of the alternative spliced insert encoding the ... VEDEC sequence (21) significantly increased cell surface expression of ... VEDEC-expressing α-subunits. These data suggest that the ... VEDEC peptide interacts with endogenous proteins to retard forward trafficking, although the mechanism and subcellular localization of trapped ... VEDEC-containing α-subunits have not been defined (20). We thus hypothesized that the palmitoylated β4-subunit may mask interaction of ... VEDEC with its endogenous target and thus promote α-subunit exit from the ER and enhance surface expression. We first verified whether swapping just the very C terminus of our ZERO α-subunits (which start with MDA ... and terminate in ... DEC, also referred to as MDA-DEC) with a shorter alternatively spliced C terminus increased surface expression of the α-subunit alone as reported previously (20, 21). To do this, we engineered in the C-terminal variant that terminates in the sequence ... QEREL (Fig. 4A). This variant (MDA-ERL) when expressed alone showed a significantly increased cell surface expression when compared with the WT ZERO variant (i.e. MDA-DEC), as determined by quantitative immunofluorescence (Fig. 4, B and C). Co-expression of WT β4-subunits now had no effect on cell surface expression of the MDA-ERL variant (Fig. 4D). Similarly, co-expression with the C193A β4-subunit had no effect (Fig. 4D). These data thus suggest that the very C terminus of the pore-forming α-subunit is critical in determining the β4-mediated enhancement of cell surface expression. However, as surface expression of the MDA-ERL α-subunits alone was already significantly elevated when compared with WT ZERO, and in fact comparable with that observed upon co-expression of ZERO with WT β4-subunits, an alternative explanation could be that the surface expression of the MDA-ERL α-subunit is already maximal. To test this possibility, we took advantage of another splice variant of the BK channel. This variant (MAN-ERL) has the same C terminus as for the MDA-ERL construct and only differs by having an extended extracellular N terminus, upstream of the MDAL... start site, with starting sequence MAN... . In our assays, this variant expresses at the cell surface with comparable levels when compared with the ZERO variant (i.e. MDA-DEC) α-subunits alone as reported previously (20, 21). Co-expression with either WT or C193A mutant β4-subunits had no statistically significant effect on cell surface expression of the MAN-ERL α-subunits in HEK293 cells (Fig. 4E). However, in N2a neurons, the depalmitoylated (C193A) β4-subunits significantly reduced surface expression of the MAN-ERL α-subunit (Fig. 5B). Although the mechanism of this suppression remains to be resolved, this suggests that previous observations of β4-subunit-mediated down-regulation of CA3 hippocampal BK channels may represent conditions under which depalmitoylated β4-subunits assemble with distinct α-subunit splice variants (15). Taken together, these data suggest that the most C-terminal domain of ZERO is critical for the β4-mediated enhancement of cell surface expression of the ZERO (MDA-DEC) splice variant.

Palmitoylated β4-Subunits Mask a C-terminal Trafficking Motif in the Pore-forming ZERO α-Subunit Variant to Promote Cell Surface Expression—β4-Subunits only enhanced surface expression of α-subunit splice variants that included the
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**FIGURE 4.** β4-mediated enhancement of channel surface expression is α-subunit splice variant-dependent. A, schematic of three distinct α-subunit splice variants that differ only in their very N or C termini, analyzed with the first and last 3 amino acids shown. The ZERO variant used in Fig. 2 is MDA-DEC with the variant with the same start methionine but shorter C terminus (MDA-ERL) and variant with upstream methionine with truncated C terminus (MAN-ERL) indicated. B, representative single confocal images of the surface (nonpermeabilized), total (permeabilized), and merged images of the three α-subunit splice variants. Scale bars are 2 μm. C, quantification of the surface expression of the three variants expressed as a percentage of ZERO (MDA-DEC) variant BK channels in HEK293. Data are means ± S.E., N > 5, n > 200. **p < 0.01 when compared with respective α-subunit alone, ANOVA with post hoc Dunnett’s test.

extended C-terminal tail that terminates in . . . DEC. This strongly suggested that the mechanism of β4-mediated enhancement of cell surface expression is dependent upon motifs within this C-terminal splice insert. The final heptapeptide ( . . . REVEDEC) has been reported to reduce cell surface expression (20–23), and our data demonstrate that palmitoylated β4-subunits promote cell surface expression and facilitate ER export of α-subunits containing the . . . REVEDEC C terminus. We thus hypothesized that the . . . REVEDEC motif may act as a trafficking signal that may be masked upon expression with β4-subunits. If this was the case, we would predict that engineering the . . . REVEDEC sequence onto β4-subunit-inhibitive α-subunits would result in depressed cell surface expression that could be rescued by WT, but not C193A mutant, β4-subunits. To determine whether the . . . REVEDEC sequence in fact behaved as a trafficking signal, we engineered the final 7 amino acids onto the C terminus of the MAN . . . E R L α-subunit variant to generate the chimera MAN-(REVEDEC).

**FIGURE 5.** The heptapeptide . . . REVEDEC is sufficient to confer β4-mediated enhancement of BK channel cell surface expression. A, representative confocal images of the MAN-ERL α-subunit variant and the chimera in which the last 7 amino acids of MAN-ERL have been replaced by the heptapeptide REVEDEC (MAN-(R . . . DEC)) expressed in N2a cells with or without the WT β4-subunit B and C, quantification of surface expression of MAN-ERL (B) and MAN-(R . . . DEC) (C) in N2a cells expressed in the absence and presence of WT β4-subunit or the C193A mutant. Data are expressed as a percentage of MAN-ERL surface expression. D, cell surface expression of MAN-(R . . . DEC) in the presence or absence of WT β4-subunit or the C193A mutant expressed in HEK293 cells. Data are means ± S.E., N > 4, n > 96/group. *, p < 0.05, **, p < 0.01 when compared with MAN-ERL in panels B and C or MAN-(R . . . DEC) in panel D variant surface expression, ANOVA with post hoc Dunnett’s test.
port a model in which the palmitoylated \( \beta_4 \)-subunit masks the C-terminal . . . REVEDEC trafficking motif to promote surface expression of \( \alpha \)-subunit splice variants that include this sequence.

**DISCUSSION**

Regulatory \( \beta_4 \)-subunits promote significant functional diversity in BK channels through modification of channel pharmacology, kinetics, surface trafficking, and complex effects on calcium/voltage sensitivity (6, 15, 16, 24, 25). Here we demonstrate that \( \beta_4 \)-subunits are regulated by the only reversible lipid post-translational modification of proteins, \( S \)-acylation (palmitoylation), in native tissues and heterologous expression systems. Importantly, \( S \)-acylation of \( \beta_4 \) controls cell surface expression of the pore-forming \( \alpha \)-subunit, an effect that is dependent upon alternative splicing of a trafficking signal ( . . . REVEDEC) in the very C terminus of the \( \alpha \)-subunit. Using a chimera approach, we demonstrate that palmitoylated \( \beta_4 \)-subunits can specifically promote cell surface expression of \( \alpha \)-subunits containing this motif. The data support a model in which \( \beta_4 \)-mediated enhancement of surface expression is mediated by \( \beta_4 \)-subunits masking the . . . REVEDEC trafficking signal as co-expression of \( \beta_4 \)-subunits enhanced \( \alpha \)-subunit surface expression to a similar extent as removal of the . . . REVEDEC trafficking sequence. In such a model, why is \( \beta_4 \)-subunit palmitoylation a critical determinant? A plausible explanation is that palmitoylation may be important for the correct structural orientation of the \( \beta_4 \)-subunit with respect to the \( \alpha \)-subunit to functionally mask the . . . REVEDEC signal. In this regard, the palmitoylated cysteine (Cys-193) is juxtaposed to the intracellular aspect of the second transmembrane domain of the \( \beta_4 \)-subunit. In other systems, juxta-transmembrane palmitoylation allows tilting of transmembrane domains, effectively shortening the transmembrane domain to both reduce hydrophobic mismatch (26), in particular at the thinner ER membrane (27), as well as induce conformational restraints on the peptide. Thus, the TM2 of depalmitoylated \( \beta_4 \)-subunits may display hydrophobic mismatch at the ER, reducing ER exit, and may have a conformation that is unfavorable for interaction with \( \alpha \)-subunits. In this regard, disulfide cross-linking experiments (28) suggest that the extracellular aspect of TM2 of the \( \beta_4 \)-subunit is in close proximity to the S0 transmembrane domain of the \( \alpha \)-subunit. Whether such a mechanism is important for control of trafficking that is dependent upon a motif ( . . . REVEDEC) at the very C terminus of the \( \alpha \)-subunit remains to be determined.

\( S \)-Acylation of \( \beta_4 \)-subunits adds to the repertoire of post-translational mechanisms that can control BK channel function through the \( \beta_4 \)-subunit. For example, glycosylation of extracellular residues is important for determining the reduced efficacy of extracellular blockade by iberiotoxin (16), and phosphorylation of multiple intracellular residues is implicated in the control of functional interaction with \( \alpha \)-subunits (29). Importantly, \( S \)-acylation provides a mechanism to control surface trafficking, and intriguingly, this effect is dependent upon the assembled \( \alpha \)-subunit splice variant. A recent study (15) revealed that \( \beta_4 \)-subunits down-regulated surface expression of BK channel \( \alpha \)-subunit variants with different C termini ( . . . KEMVYR), and other studies have shown that \( \beta_4 \)-subunits can enhance surface expression of Kcnqu subunits (17). Together with our observation that surface expression of the MAN-ERL variant is suppressed only by depalmitoylated \( \beta_4 \)-subunits, this suggests that \( S \)-acylation of \( \beta_4 \) may provide a specific regulatory signal to specifically control cell surface expression of BK channels assembled from different \( \alpha \)-subunit splice variants containing the . . . REVEDEC sequence. Although the physiological consequence of such a mechanism remains to be determined, \( \beta_4 \)-subunits are important in a wide variety of physiological control systems ranging from dampening of excitability in the hippocampus (6) to regulation of potassium excretion from the kidney (5) and sensitivity of cells to alcohol (30) and neurosteroids (31). Furthermore, as \( S \)-acylation can be dynamically regulated, including by cell stress and diet (32), and \( \beta_4 \) and \( \alpha \)-subunit splice variant expression is spatially and temporally controlled (6, 8), this may provide a mechanism to allow fine tuning of specific physiological responses.

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