60 YEARS OF POMC

From POMC and α-MSH to PAM, molecular oxygen, copper, and vitamin C

Dhivya Kumar1, Richard E Mains2 and Betty A Eipper1,2

1Departments of Molecular Biology and Biophysics, University of Connecticut Health Center, Farmington, Connecticut, USA
2Department of Neuroscience, University of Connecticut Health Center, Farmington, Connecticut, USA

Abstract

A critical role for peptide C-terminal amidation was apparent when the first bioactive peptides were identified. The conversion of POMC into adrenocorticotropic hormone and then into α-melanocyte-stimulating hormone, an amidated peptide, provided a model system for identifying the amidating enzyme. Peptidylglycine α-amidating monooxygenase (PAM), the only enzyme that catalyzes this modification, is essential; mice lacking PAM survive only until mid-gestation. Purification and cloning led to the discovery that the amidation of peptidylglycine substrates proceeds in two steps: peptidylglycine α-hydroxylating monooxygenase catalyzes the copper- and ascorbate-dependent α-hydroxylation of the peptidylglycine substrate; peptidyl-α-hydroxyglycine α-amidating lyase cleaves the N–C bond, producing amidated product and glyoxylate. Both enzymes are contained in the luminal domain of PAM, a type 1 integral membrane protein. The structures of both catalytic cores have been determined, revealing how they interact with metals, molecular oxygen, and substrate to catalyze both reactions. Although not essential for activity, the intrinsically disordered cytosolic domain is essential for PAM trafficking. A phylogenetic survey led to the identification of bifunctional membrane PAM in Chlamydomonas, a unicellular eukaryote. Accumulating evidence points to a role for PAM in copper homeostasis and in retrograde signaling from the lumen of the secretory pathway to the nucleus. The discovery of PAM in cilia, cellular antennae that sense and respond to environmental stimuli, suggests that much remains to be learned about this ancient protein.

POMC and PAM: where it all began

Over the last three decades, we have amassed a great deal of information on the function, trafficking, and biochemical properties of the only known peptide-amidating enzyme, peptidylglycine α-amidating monooxygenase (PAM). Until its discovery in 1982, even the existence of such an enzyme was questioned (Fig. 1). Based on the first biologically active peptides identified (vasopressin, oxytocin, and α-melanocyte-stimulating hormone (α-MSH)), it was clear that a C-terminal amide group was essential; however, there was no reason to suspect that a mechanism other than transamination (such as in glutamine synthesis) might be in place. The discovery of
glycine-extended precursors for amidated peptides such as α-MSH, adipokinetin hormone, and melittin raised the possibility that an enzyme recognizing the terminal glycine was involved in generating the mature amidated peptide (Harris & Lerner 1957, Stone et al. 1976, Suchanek & Kreil 1977).

Using a synthetic radiolabeled peptidylglycine substrate (based on the last three amino acid residues of the α-MSH precursor), Bradbury and coworkers demonstrated the presence of an activity catalyzing the amidation reaction in secretory granules of bovine pituitaries (Bradbury et al. 1982). In this landmark study, the amide group nitrogen was shown to be derived from the glycine residue, ruling out the possibility of a transaminase reaction; the formation of glyoxylate during the reaction pointed to a hydroxylation step in the reaction mechanism (Bradbury et al. 1982).

Around this time, our laboratory was focused on understanding the tissue-specific differential processing of POMC. The proteases that produced the longer peptides (such as pro-γ-MSH, adrenocorticotropic hormone (ACTH), joining peptide (JP), and β-lipotropin (LPH) in corticotropes) or the shorter peptides (such as α-MSH, γ-MSH, and β-endorphin in melanotropes and hypothalamic pro-opiomelanocortin (POMC) neurons) were of special interest. Establishing primary rat intermediate pituitary cultures seemed to be a convenient way to characterize the production of α-MSH from what was then known as pro-ACTH. In order to study secretion, it was important to culture cells in a serum-free medium. However, it soon became obvious that serum contained a factor that was essential for the conversion of α-MSH-Gly into amidated α-MSH. Antibody specific for amidated α-MSH was key in realizing that otherwise healthy pituitary cells maintained in a serum-free medium performed all of the processing steps required for generating active α-MSH, including proteolytic cleavage and acetylation, except for amidation (Glembotski et al. 1983, Eipper et al. 1983a). In order to identify the serum factor(s) required for amidation, we turned to the newly developed enzyme assay to take a closer look at the amidating enzyme.

As a first step, secretory granules were purified from rat and bovine anterior, intermediate, and neural pituitary; β-endorphin immunoreactivity served as a convenient marker for granule fractions (Bradbury et al. 1982). In this landmark study, the amide group nitrogen was shown to be derived from the glycine residue, ruling out the possibility of a transaminase reaction; the formation of glyoxylate during the reaction pointed to a hydroxylation step in the reaction mechanism (Bradbury et al. 1982).

Figure 1
Timeline highlighting key developments leading from POMC processing studies to PAM. The landmark study of Bradbury and coworkers provided a means of assaying peptide amidating activity in tissue lysates (Bradbury et al. 1982). Purification, cloning, and structural/mechanistic studies focused on PAM and then expanded to include cell biological studies on secretory granule biogenesis, retrograde signaling from the granule lumen to the nucleus, and the delivery of essential cofactors (ascorbate and copper) to the secretory pathway. Key unanswered questions are marked by red arrows.
sulfonic acid buffers. Subsequent experiments confirmed an essential role for copper (Eipper et al. 1983b). Similar to other copper-dependent enzymes involved in redox reactions requiring molecular oxygen, the amidation reaction was dependent on oxygen availability. The remarkable similarity of the amidation reaction to that of dopamine β-monooxygenase (DBM), which converts dopamine to norepinephrine in a copper-, molecular oxygen-, and ascorbate (vitamin C)-dependent manner, suggested that ascorbate might provide the reducing equivalents essential for peptide amidation. As predicted, ascorbate was a potent stimulator of peptide amidation catalyzed by PAM (Eipper et al. 1983b). Knowing the cofactors required for its catalytic activity, we were not surprised that simply adding ascorbate to our serum-free medium allowed melanotropes to produce amidated α-MSH. PAM (EC 1.14.17.3) and DBM (EC 1.14.17.1) were thought to form a family of related copper-dependent monoxygenases; this meant that the detailed structural and mechanistic studies carried out on DBM (Stewart & Klinman 1988) could guide studies of PAM.

What have we learned about PAM since its identification?

Structure of the PAM gene

The flurry of activity that ensued centered on cloning the gene-encoding PAM (Fig. 1). The protein was purified from bovine pituitaries and used to generate antibodies (Murthy et al. 1986, Eipper et al. 1987). Having antibodies allowed identification of a cDNA-encoding PAM using a phage expression library generated from bovine intermediate pituitary RNA (Eipper et al. 1987). At the same time, a cDNA-encoding PAM was cloned from Xenopus laevis skin (Mizuno et al. 1987, Ohsuye et al. 1988). Analysis of the protein encoded by the PAM cDNA delivered a few surprises. As expected, a cleaved signal peptide was found, allowing the entry of PAM into the secretory pathway lumen. The cDNA encoded a protein more than twice the size expected. Although the enzyme purified from the pituitary was soluble, the cDNA encoded what was predicted to be a type 1 integral membrane protein; its single membrane-spanning domain was followed by a short stretch of hydrophilic residues predicted to reside in the cytoplasm. Several pairs of basic amino acids (recognition sites for prohormone convertase-like endoproteases) were also present in the intraluminal part of the PAM protein. Several questions arose: Why would an enzyme catalyzing amidation of bioactive peptides include a transmembrane domain? Why did it include endoproteolytic cleavage sites and how did they affect its processing and activity? Efforts spanning over two decades have unraveled the answers to some of these puzzling questions.

A PAL for PAM

It was soon discovered that the peptidyl-α-hydroxyglycine α-amidating lyase (PAM) cDNA encoded two enzymatic domains, both of which were necessary to yield an amidated peptide (Fig. 2). Formation of an α-hydroxyglycine intermediate by the stereo-specific hydroxylation of the glycine-extended peptide precursor was proposed as the first step in the reaction mediated by PAM (Young & Tamburini 1989). Although the second step of this reaction, cleavage of the N–C bond to yield amidated product is spontaneous in alkaline pH, it is impeded in the acidic environment of secretory granules. The stability of synthetic peptides terminating with a COOH-terminal α-hydroxyglycine residue was shown to decline at pH values above 6, with half-lives of 8 h at pH 7.4 (Bundgaard & Kahns 1991). An enzyme catalyzing N–C bond cleavage was identified in bovine neurointermediate pituitaries; it was found that the bovine PAM precursor also contained this enzymatic activity. Thus, the PAM gene encodes two enzymatic domains that function sequentially to generate amidated peptides: peptidylglycine α-hydroxylating monoxygenase (PHM; EC 1.14.17.3) and peptidyl-α-hydroxyglycine α-amidating lyase (PAL; 4.3.2.5) (Katopodis et al. 1990, Perkins et al. 1990). Studies with purified PAL protein revealed its pH optimum to be in the acidic range and its dependence on zinc (Eipper et al. 1991).

Apart from endoproteolytic processing, functionally different forms of PAM can also be generated by alternative splicing. The longest isoform (PAM-1) (Fig. 3A) contains the two enzymatic domains, a transmembrane domain and a cytosolic domain, with an endoprotease-sensitive linker region between PHM and PAL. This endoprotease-sensitive region is not included in the PAM-2 isoform; as a result, PHM and PAL are rarely separated by cleavage. A third major isoform (PAM-3) lacks both the endoproteolytic cleavage site and the transmembrane domain, allowing soluble, bifunctional PAM to be secreted. PAM expression is not limited to neuroendocrine tissues; PAM is expressed at widely varying levels in almost all mammalian cell types, with significant expression in airway epithelium, ependymal cells in the brain, endothelial cells, and adult atrium as well as the brain and pituitary (Eipper et al. 1988, Oldham et al. 1992, Schafer et al. 1992). PAM expression is
developmentally regulated; isoform-specific regulation is especially apparent in heart and neural tissues, suggesting that different isoforms have distinct functions (Braas et al. 1989, Stoffers et al. 1989, 1991, Eipper et al. 1992). Both in neurons and in endocrine cells, soluble PHM and PAL are secreted along with neuropeptides and peptide hormones upon stimulation; PHM and PAL can be detected in serum and cerebrospinal fluid (Mains et al. 1985, Wand et al. 1985).

**Cellular requirements for PAM activity**

PAM activity requires the delivery of copper and ascorbate to the lumen of the secretory pathway. Cells devote considerable energy to compartmentalizing and tightly regulating the flow of copper, a transition metal that can participate in free radical formation. Copper transporters deliver copper to intracellular copper chaperones such as COX17 and Atox1, which deliver copper to specific acceptor proteins. For the secretory pathway, two P-type ATPases, ATP7A and ATP7B, receive copper from Atox1 and transport it into the lumen (Prohaska 2008). No copper chaperones have been identified in the secretory pathway lumen, and it has been suggested that PHM is metallated directly by the P-type ATPases (El Meskini et al. 2001, Otoikhian et al. 2012). Although most organisms, including rodents, synthesize ascorbate from glucose, humans lack this ability and must acquire it from their diet. Two Na+-dependent ascorbate transporters (SVCT1 and SVCT2) expressed in intestinal epithelial cells and neuroendocrine cells, respectively, import ascorbate into cells (Burzle & Hediger 2012); neuroendocrine cells lack gulonolactone oxidase and must use SVCT2 to obtain ascorbate from the circulation. It is not known how ascorbate enters the secretory pathway lumen, but it is maintained in the reduced state by the action of cytochrome b$_{561}$, which shuttles electrons across the secretory pathway membrane (Asada et al. 2005, Iliadi et al. 2008).

Another important factor necessary for amidation is the low pH of the secretory pathway lumen. Both PHM and PAL exhibit optimal activity under acidic conditions. Intraluminal pH is maintained by the proton-pumping activity of the multisubunit vacuolar or V-ATPase. In addition to its role in acidification, the V-ATPase plays a role in secretory granule biogenesis through its role in sorting of vesicular cargo (Sobota et al. 2009). This...
proton pump also relays information about amino acid levels in the interior of lysosomes to mammalian target of rapamycin (mTOR), a cytosolic Ser/Thr kinase that serves as a master energy regulator (Jewell et al. 2013).

It is intriguing to consider a role for PAM in signaling nutritional status information from distal parts of the secretory pathway (glycine levels, for example) to mTOR through the V-ATPase.

### Crystal structures and insights into the mechanism of peptide amidation

As mentioned previously, the cofactor requirements for the PHM domain of PAM are strikingly similar to those of DBM. The similarity extends to their amino acid sequences, with about 30% identity in the catalytic cores of the two molecules (Prigge et al. 1997). Another member of this small family of copper-dependent monoxygenases is the endoplasmic reticulum-localized monoxygenase X, predicted to hydroxylate an unidentified hydrophobic substrate (Xin et al. 2004). Of these three monoxygenases, PHM is the only one with a solved crystal structure (Fig. 3B and C), providing key insights into reaction mechanism (Prigge et al. 1997, 1999, 2004). Only small structural differences were observed when the protein was crystallized in the reduced, oxidized, or substrate-bound form. The catalytic core of PHM has two domains, each composed primarily of eight antiparallel β-strands (Fig. 3B). Resembling a jelly roll motif, each domain has a hydrophobic interior held together by disulfide linkages; the two domains are linked by a single polypeptide chain. Each domain has one copper binding site: the three His residues of the CuH site are in the N-terminal domain; the two His and one Met of the CuM site are in the C-terminal domain. An 11 Å solvent-exposed hydrophilic cleft separates CuH from CuM in two single-electron steps, both sites are reduced. Molecular oxygen binds to the CuM site, with the peptidylglycine substrate bound close by;
glycine and d-alanine are the only amino acids that can be accommodated, and there is no indication that the distance between CuII and CuIII varies during the reaction. The active site of PHM can accommodate large substrates (e.g., ubiquitin and selected immunoglobulin heavy chains) as well as fatty acyl glycines and other nonpeptide substrates (Wilcox et al. 1999, Chew et al. 2005, Skulj et al. 2014).

The crystal structure of the catalytic core of PAL was solved about 10 years later (Fig. 3C): it is a six-bladed β-propeller, with long loops extending from the propeller surface (Chufan et al. 2009). The central cavity houses a calcium ion required for structural integrity and a zinc ion required for catalytic activity. The peptidyl-α-hydroxyglycine substrate binds close to the zinc, which is coordinated by three His residues. Well-conserved tyrosine (Tyr854) and arginine (Arg706) residues play a critical role in catalysis (De et al. 2006, Chufan et al. 2009). As in the catalytic core of PHM (PHMcc), disulfide linkages play an essential role in the structural integrity of PAL. The N- and C-termini of PAL are positioned close to each other, and its C-terminus is tethered to the membrane; the unique geometry of the β-propeller structure positions PHM close to the membrane to receive copper and ascorbate from transmembrane P-type ATPases and cytochrome b561.

With the ability to produce active PHMcc and site-directed mutants in mammalian cells, the unique properties of the two essential copper-binding sites and the effects of pH on PHM were determined (Siebert et al. 2005, Evans et al. 2006, Jaron et al. 2002, Kline et al. 2013). The detailed mechanistic studies carried out previously on purified dopamine β-monoxygenase guided similar studies on PHMcc (Stewart & Klinman 1988). The initial focus was on the 11 Å solvent-filled gap separating the two essential copper-binding sites: CuII, which has the properties expected of an electron transfer site, and CuIII, which binds O2 and is adjacent to the peptidylglycine substrate, are both essential. Current evidence indicates that the two copper domains are directly coupled through a solvent bridge that facilitates redox and catalysis, a remarkable level of precision for a solvent-accessible active site (Francisco et al. 2002, Jaron et al. 2002, Bauman et al. 2006). The effects of temperature on intrinsic isotope effects and modeling studies have led to the consensus that PHM-dependent C=O–H bond activation is dominated by quantum mechanical tunneling and tightly coupled with oxygen activation (Francisco et al. 2002, 2004, Klinman 2006, McIntyre et al. 2010). Efforts to develop inhibitors of PHM and PAL continue (Merkler et al. 2008, Langella et al. 2010). Disulfiram, a copper chelator, reduces levels of amidated peptides in rat pituitary and cerebral cortex, presumably by inhibiting PHM activity (Mueller et al. 1993). A mechanism-based suicide inhibitor, 4-phenyl-3-butenoic acid, has been shown to inhibit PHM activity in vivo (Mueller et al. 1999). Other potent inhibitors include hippurate analogs and N-substituted homocysteine analogs (Erion et al. 1994, Merkler et al. 2008).

More than just an enzyme: a multitasking protein

Evolutionary distribution of PAM

Amidated peptides are widespread, with roles in organisms with simple nervous systems, such as Hydra and Aplysia (Fujisawa et al. 1999, Grunder & Assmann 2015). Furthermore, PAM has been characterized in sea anemone, fly, and flatworm (Kolhekar et al. 1997, Williamson et al. 2000, Han et al. 2004, Mair et al. 2004). Although it was assumed that PAM co-evolved with the nervous system, recent studies suggest otherwise. A phylogenetic study identified PAM-like sequences in non-neural organisms such as Amphimedon queenslandica, a sponge, and Trichoplax adhaerens, a placozoan. Neuropeptide-like sequences have been found in the Trichoplax genome, and immunoreactivity to amidated peptides has been demonstrated in cells of Trichoplax (Jekely 2013, Smith et al. 2014). Perhaps more surprising was finding PAM-like sequences in several green algal genomes; the presence of PAM in Chlamydomonas reinhardtii, Volvox carteri, and Ostreococcus tauri raised the possibility that PAM evolved before the divergence of plants and animals (Attenborough et al. 2012). Active PAM enzyme has been demonstrated in the unicellular green alga, C. reinhardtii, raising the question of ancestral function (Kumar et al. 2015). Although amidated peptides have not been identified in green algae, the evolutionary conservation of components essential for PAM activity (copper homeostatic machinery, ascorbate synthesis, the V-ATPase) in eukaryotes certainly supports the possibility of amidation reactions occurring in these nonneural organisms. It is also possible that PAM amidates nonpeptide substrates in these organisms or has a completely novel role distinct from those discovered in mammals.

The cytosolic domain of PAM

Although a cytosolic domain is not essential for PHM or PAL activity, the PAM gene in C. reinhardtii encodes a protein of identical topology (Kumar et al. 2015). Unlike soluble granule content proteins, granule membrane
proteins are not secreted; after exocytosis and insertion into the plasma membrane, membrane PAM can be retrieved, traveling through the endocytic pathway in a regulated manner. In Drosophila, gene duplication is thought to have produced separate genes encoding soluble PHM, soluble PAL, and membrane PAL.

Unlike the catalytic domains of PAM, its cytosolic domain is protease sensitive; the specific activity of PHM is increased following removal of the cytosolic domain. The cytosolic domain of PAM plays an essential role in its trafficking in mammalian cells; although soluble PHM and soluble PAL accumulate in secretory granules, PAM lacking its cytosolic domain accumulates on the plasma membrane (Tausk et al. 1992, Milgram et al. 1993). Furthermore, an epitope-tagged protein consisting of the transmembrane and cytosolic domains of PAM localizes to the trans-Golgi network and secretory granules, indicating that it contains key trafficking information (El Meskini et al. 2001).

The cytosolic domain (86 residues in mammalian PAM) is unstructured and contains no characteristic motifs. It is sensitive to proteolytic degradation, a feature characteristic of intrinsically disordered proteins involved in signaling, where the signal must be turned off just as rapidly as it is turned on (Rajagopal et al. 2009). Unstructured domains are often hubs of protein/protein interactions, and multiple PAM cytosolic domain interactors have been identified. Kalirin and Trio, members of the Rho GDP/GTP exchange factor (Rho-GEF) family, play roles in cytoskeletal control and additional to its enzymatic role, these studies indicate that PAM relays signals from the lumen of the secretory/endocytic pathway to the nucleus, in a manner similar to other type 1 integral membrane proteins in the endoplasmic reticulum such as sterol regulatory element binding protein (SREBP) and activating transcription factor 6 (ATF6) (Rajagopal et al. 2012).

Lessons learned from knockout and heterozygous mice

Mice lacking both copies of Pam show no detectable peptide amidation activity and do not survive past mid-gestation, dying at e14.5–e15.5 (Czyzyk et al. 2005). The Pam null embryos display severe edema, cardiac malformations, and poor vasculature compared with wild-type littermates. However, the heterozygous animals have half the wild-type level of PAM activity and are viable. They showed only minor changes in the levels of the amidated peptides tested, suggesting that the reduced levels of PAM in PAM−/− mice were sufficient to catalyze the amidation reaction (Czyzyk et al. 2005).

As they age, PAM−/− mice display increased adiposity compared to age-matched wild-type littermates. Glucose metabolism, which is regulated in part by amidated peptides, is impaired in older PAM heterozygous mice compared to wild-type controls (Czyzyk et al. 2005). The PAM−/− animals demonstrate other behavioral deficits: they are unable to regulate body temperature, show increased anxiety-like behavior, and are more susceptible
to seizures compared with wild-type mice. Moreover, wild-type mice maintained on a copper restricted diet mimic many of the behavioral deficits observed in PAM+/− mice, and supplemental dietary copper reverses some of the behavioral defects observed in PAM+/− animals (Bousquet-Moore et al. 2009, 2010). These data suggest that altered copper homeostasis contributes to the behavioral defects observed in PAM heterozygous mice. A role for PAM in copper homeostasis had not previously been suspected.

Sensory roles of PAM

Comparative genomic analyses suggest that cuproproteins evolved following oxygenation of the earth; thus, PAM belongs to a small set of cuproenzymes with primitive roles predating multicellularity. As one of the few proteins dependent on a steady supply of copper and molecular oxygen for activity, PAM is well positioned to function as a sensor for these critical factors. As mentioned previously, studies with mice lacking one copy of Pam and signaling mediated by PAM sf-CD suggest an involvement in copper sensing. Additional support for this hypothesis comes from studies using corticotrope cell lines. Depleting or overloading these cells with copper alters the trafficking of PAM through the secretory and endocytic pathways but does not lead to its degradation, as in the case of other cuproproteins (De et al. 2007).

The absolute dependence of the amidation reaction on molecular oxygen has been known for a long time; however, whether physiologically relevant changes in oxygen levels affected PHM activity was not known. A recent study shows that the ability of PAM to produce amidated products is as sensitive to changes in oxygen level as the prolyl hydroxylases that control the stability of hypoxia-inducible factor (HIF), a key oxygen-signaling protein. The speed and sensitivity with which PAM activity responds to hypoxia suggest a novel, paracrine signaling mechanism that could operate during oxygen homeostasis in vivo (Simpson et al. 2015).

The pH gradient in the lumen of the secretory pathway plays an essential role in the biosynthesis and processing of proteins. Enzymes like PAM, which operate late in the secretory pathway, display acidic pH optima; the pH gradient in the luminal compartment often dictates which biosynthetic enzymes are active and which processing steps can occur. The protease-sensitive linker region that connects the catalytic core of PHM to the catalytic core of PAL contains a cluster of histidine residues (His–Gly–His–His) that confer pH sensitivity (Vishwanatha et al. 2014). PAM lacking these histidine residues (Ala–Gly–Ala–Ala) is handled differently in corticotrope cell lines; instead of being recycled, endocytosed PAM lacking this His cluster is rapidly degraded. The γ-secretase-mediated production of PAM sf-CD is largely eliminated, and the morphological changes associated with PAM expression no longer occur.

What the future holds for PAM biology

The involvement of PAM in sensing environmental signals and generating factors involved in transcriptional regulation led us to expand our studies beyond the role of PAM as an amidating enzyme. Thus, there has been a paradigm shift in our understanding of this multitasking protein. We see understanding the role of PAM in non-neural tissues and organs as key to uncovering all of the functions of this ancient, evolutionarily conserved protein. For instance, it will be interesting to determine the significance of abundant levels of PAM in the atrium, where it comprises about 1% of the total proteome (O’Donnell et al. 2003).

Mutations in the luminal copper-transporting P-type ATPase, ATP7A, cause Menkes disease, a copper metabolism disorder characterized by neurodegeneration, mental retardation, connective tissue abnormalities, and early childhood lethality. Several cuproenzymes, including PAM, are affected by the loss of functional ATP7A. Using the mottled-brindled mouse, an animal model for Menkes disease, normal levels of PAM expression but reduced levels of amidated peptides such as joining peptide, α-MSH, and cholecystokinin were shown, suggesting that alterations in PAM activity might contribute to some of the phenotypes observed in these patients (Steveson et al. 2003). Altered PAM levels and activity have also been reported in the cerebrospinal fluid of multiple sclerosis and post-polio syndrome patients (Tsukamoto et al. 1995, Gonzalez et al. 2009). The ability to assay PAM activity in serum makes it an attractive biomarker candidate (Gaier et al. 2014).

During its endocytic trafficking, PAM enters the intraluminal vesicles that characterize multivesicular bodies (Fig. 4); the fusion of multivesicular bodies with the plasma membrane results in release of these intraluminal vesicles, which are then known as exosomes (Rajagopal et al. 2010). As they can be isolated from a variety of sources such as saliva, serum, and urine, exosomes are being explored as a diagnostic tool (Simpson et al. 2009). PAM was identified in exosomes derived from human saliva and prostate cancer cells (Gonzalez-Begne et al. 2009).
et al. 2009, Minciacchi et al. 2015). It will be interesting to determine if PAM-containing exosome release is differentially regulated, especially during genetic or metabolic alterations.

PAM, cilia, and POMC in obesity

A close look at the phylogenetic distribution of PAM suggested a strong correlation with the presence of cilia, leading us to explore the presence of PAM in this signaling organelle (Kumar et al. 2015). PAM localizes to primary and motile cilia in mammalian cells and to the motile cilium of C. reinhardtii, a unicellular eukaryote, suggesting an important, evolutionarily conserved role for PAM in this organelle (Fig. 5). Cilia are tiny hairlike, microtubule-based organelles that extend from the cell surface of almost all mammalian cells. Primary cilia are critical sensory and signaling structures, important for sensing and responding to environmental stimuli. Multiple motile cilia in unicellular eukaryotes and tracheal and ependymal cells play additional roles in cell motility and fluid propulsion. Acting as tiny reaction chambers, cilia compartmentalize signaling pathways and proteins. Ciliary protein entry and exit is tightly regulated by specialized trafficking pathways. Only proteins destined for the cilium are recognized by the intraflagellar trafficking machinery. Ciliary dysfunction affects a number of different tissues, including the kidney, heart, and eyes, resulting in disorders collectively known as ciliopathies (Fliegauf et al. 2007).

The significance of POMC in energy homeostasis is clear: loss of POMC or melanocortin receptors, MC3R and MC4R, causes an obesity phenotype in mice, and mutations in POMC result in obesity in humans (Hinney et al. 1998, Yaswen et al. 1999, Challis et al. 2004). The leptin/melanocortin system plays a central role in regulating feeding behavior and obesity. Leptin, a satiety hormone, is secreted by adipocytes in proportion to body fat and acts on POMC and neuropeptide Y (NPY) neurons in the hypothalamus to reduce food intake and promote thermogenesis. Increased POMC production as a result of leptin signaling leads to a rise in α-MSH and β-MSH levels; their binding to melanocortin receptors regulates energy balance (Sen Gupta et al. 2009).
A number of recent studies have shown that cilia play an important role in energy homeostasis. Several G protein coupled receptors (GPCRs), including melanin-concentrating hormone receptor 1 (MCHR1), localize to cilia (Fig. 5), suggesting that G-protein signaling might occur in cilia (Berbari et al. 2008a). Furthermore, this localization is perturbed in mice lacking components of the BBSome (Berbari et al. 2008b). The BBSome, a multiprotein complex composed of seven Bardet–Biedl syndrome proteins, is implicated in membrane protein trafficking and ciliary biogenesis (Jin & Nachury 2009). Mutations in these BBS genes result in a ciliopathy (BBS) characterized by mental retardation, retinopathy, and renal defects. Obesity is also observed in these patients and mouse models of the disease, further strengthening the link between energy homeostasis and cilia (Sen Gupta et al. 2009).

Leptin signaling has recently been linked to the cilium: hyperphagic BBS mutant mice have increased levels of circulating leptin and are resistant to exogenous leptin treatment, even when weight matched with control animals (Rahmouni et al. 2008, Seo et al. 2009). Although the leptin receptor has not been localized to cilia, it interacts with components of the BBSome and loss of BBS

Figure 5
Model of PAM function in cilia. PAM localizes to cilia, where it may play roles in peptide amidation and sensing of copper or oxygen. Ciliary PAM may also be subjected to cleavages leading to the release of sf-CD and changes in gene expression. It is not known if the BBSome is essential for PAM trafficking into the ciliary compartment. However, trafficking of the MCHR1 into the ciliary requires the BBSome, and leptin receptor localization is affected by loss of BBS components. The leptin/melanocortin system is critical for establishing energy homeostasis. Leptin binding to its receptor leads to upregulation of POMC and satiety responses. It is not known if PAM also plays a role in energy balance in POMC neurons.
components causes mislocalization of the leptin receptor in large vesicles (Seo et al. 2009). Further support for the importance of cilia in energy regulation comes from the conditional knockout of intraflagellar transport proteins, which leads to the loss of primary cilia in adult mice. Ablation of cilia only on POMC neurons causes mice to become hyperphagic and obese; a model proposing the disruption of a feedback mechanism between leptin and somatostatin signaling that regulates satiety responses has been proposed (Davenport et al. 2007, Satir 2007). These data are interesting, especially in light of the localization of PAM to cilia. It is currently not known if PAM localizes to cilia in POMC neurons, or if this localization is BBSome mediated (Fig. 5). It is also unclear if PAM performs a catalytic or signaling role in the cilium; however, there is certainly a link between PAM and energy metabolism, as seen in the increased adiposity phenotype in older PAM+/− mice. Two genome-wide association studies linked PAM to altered insulinogenic index and susceptibility to type 2 diabetes in Finnish and Icelandic populations, warranting a closer look at altered energy homeostasis in the context of PAM (Huyghe et al. 2013, Steinhorsdottir et al. 2014).

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of this review.

Funding
This work has been funded continuously by the National Institutes of Health (DK-32948 and DK-32949).

Acknowledgments
We thank the graduate students, postdoctoral fellows, and technicians with whom we have worked over the years for sharing their curiosity and passion for science. The expertise of our various collaborators has allowed us to expand our studies in ways we could not have imagined. Our special thanks go to M Amzel, N Blackburn, P Taghert, and N Back, without whom much of this work could not have been imagined, and to N McIntyre for sharing his knowledge of reaction mechanisms.

References


Czyzyk TA, Ning Y, Hsu MS, Peng B, Mains RE, Eipper BA & Pintar JE 2005 Deletion of peptide amidation enzymatic activity leads to


Jellis JL, Russell RC & Guan KL 2013 Amino acid signalling upstream of mTOR. *Nature Reviews Molecular Cell Biology* 14:133–139. (doi:10.1038/nrm3522)


Katopodis AG, Ping MV & May SW 1990 A novel enzyme from bovine intermediate pituitary catalyzes dealkylation of alpha-hydroxyglycine derivatives, thereby functioning sequentially with...
Milgram SL, Mains RE & Eipper BA 1993 COOH-terminal signals mediate the trafficking of a peptide processing enzyme in endocytic cells. Journal of Cell Biology 121 23–36. (doi:10.1083/jcb.121.1.23)
Stewart LC & Klinman JP 1988 Dopamine beta-hydroxylase of
Stoffers DA, Green CB & Eipper BA 1989 Alternative mRNA splicing
Stoffers DA, Green CB & Eipper BA 1989 Alternative mRNA splicing generates multiple forms of peptidyl-glycine alpha-amidating monoxygenase in rat atrium. PNAS 86 735–739. (doi:10.1073/pnas.86.2.735)
Stone JV, Mordue W, Batley KE & Morris HR 1976 Structure of locust adipokinetic hormone, a neurohormone that regulates lipid utilisation during flight. Nature 263 207–211. (doi:10.1038/263207a0)
Xin X, Mains RE & Eipper BA 2004 Monoxygenase X, a member of the copper-dependent monoxygenase family localized to the endoplasmic reticulum. Journal of Biological Chemistry 279 48159–48167. (doi:10.1074/jbc.m07.486200)
Received in final form 8 December 2015
Accepted 14 December 2015
Accepted Preprint published online 14 December 2015