New Insights into G-Protein-Coupled Receptor Signaling from the Melanocortin Receptor System

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For decades, geneticists, as well as breeders of “fancy” pets, have been interested in the interaction of the melanocortin 1 receptor locus (Mc1r; also known as melanocyte-stimulating hormone receptor, Ms circulating hormone; AGRP, agouti-related protein. MCR, melanocortin receptor; GPCR, G protein-coupled receptor; ACTHR, corticotropin receptor; MSH, melanocyte-stimu- lating hormone receptor, receptor locus (also known as melanocyte-stimulating hormone receptor) with the Agouti locus because of the array of coat colors that alterations at these loci generate. In the simplest case, a mouse with two wild-type Mc1r alleles and two recessive Agouti alleles (Fig. 1b, Mc1r<sup>-/-</sup>/Mc1r<sup>-/-</sup>, a/a) is expectedly darker than the wild-type mouse (Fig. 1a, Mc1r<sup>+/+</sup>/Mc1r<sup>+/+</sup>, A<sup>+/+</sup>) of “agouti” coloring, and a mouse with a pair of recessive alleles at both the Mc1r and Agouti loci is yellow (Fig. 1c, Mc1r<sup>-/-</sup>/Mc1r<sup>-/-</sup>, a/a). Geneticists have taken advantage of this unique system in model organisms to serve as readily visible markers for such experiments as gene targeting (Simpson et al., 1997). However, it is a century-old enigmatic observation that a mouse with wild-type Mc1r alleles and one of several dominant Agouti alleles (Fig. 1d, Mc1r<sup>-/-</sup>/Mc1r<sup>-/-</sup>, A<sup>+/</sup>a) is not only yellow, but obese. Furthermore, a pair of recessive alleles at yet another locus, mahogany (also known as Attractin, Attrn), abolates the affects of the dominant Agouti allele (Fig. 1e). These observations have led more recently to a series of investigations identifying new receptors and mediators of the melanocortin receptor (MCR) pathway making this signal transduction pathway an important model in the study of G-protein coupled receptor (GPCR) pathways in complex disease and for pharmacological insights as well.

The MCR pathway includes five known differentially expressed GPCRs: MC1R, corticotropin receptor (ACTHR), MC3R, MC4R, and MC5R (Mountjoy et al., 1992). Although all five receptors are known to be Gs-coupled, MC3R has also been shown to function through phospholipase C-mediated hydrolysis of phosphoinositides (Konda et al., 1994). MC1R is predominantly expressed in melanocytes, where it is known for its classic role in skin and hair pigmentation in many species. MC1R is also expressed in other tissues and cells, such as the pituitary and leukocytes (Chhajlani 1996), indicating putative physiological roles yet to be unveiled. MC3R and MC4R are found in the central nervous system but are notably absent from the melanocytes (Gantz et al., 1993); both are highly expressed in the hypothalamus, where they are involved in energy homeostasis. ACTHR is expressed in the adrenal cortex and MC5R in peripheral cells such as adipocytes. Melanocortins are the endogenous agonists to which the MCRs have differential affinities. These are small peptides derived from proopiomelanocortin: ACTH, α-MSH, β-MSH, and γ-MSH. α-MSH is the predominant melanocortin of action in the hypothalamus and skin and potently activates all MCRs except ACTHR. The effects of α-MSH in vivo are modulated by two endogenous paracrine peptides, agouti (or agouti signaling protein) and agouti-related protein (AGRP). Specifically, AGRP potently antagonizes MC3R, MC4R, and MC5R, whereas agouti potently antagonizes MC1R, ACTHR, and MC4R (Yang et al., 1997). Agouti and AGRP are normally expressed in the skin and brain, respectively.

In mice, agouti is a 131-amino acid peptide synthesized in the skin that causes the mouse melanocytes to produce yellow pigment instead of the brown/black pigment by competitively inhibiting the action of α-MSH on MC1R (Lu et al., 1994). The “agouti” coloring of wild-type animals is produced by a brown/black pigmented hair with a subapical yellow pigmented band resulting from transient expression of Agouti during hair development (Fig. 1a). Dominant mutations of Mc1r in which the receptor is constitutively active or has enhanced affinity for α-MSH result in dark, nonagouti mice, even in the presence of agouti, implicating agouti’s role upstream of the receptor; recessive mutations of murine Mc1r rendering a nonfunctional MC1R produces yellow mice (Robbins et al., 1993). The role of agouti in human pigmentation or other physiological roles is not understood; however, agouti is found in human tissue and has been shown to antag-

**ABBREVIATIONS:** MCR, melanocortin receptor; GPCR, G protein-coupled receptor; ACTHR, corticotropin receptor; MSH, melanocyte-stimulating hormone; AGRP, agouti-related protein.
onize human MCRs in vitro (Yang et al., 1997). Unlike agouti’s elusive role in human physiology, AGRP is thought to regulate energy homeostasis. The exact mechanism of action on the MCRs by agouti and AGRP is still not well understood. Several potential explanations for AGRP action exist, including competitive antagonism, inverse agonism, or action on an effector other than adenyl cyclase (Siegrist et al., 1997). As summarized above, mice that are wild-type for the Mc1r haplotype (Agouti allele). However, some dominant Mc1r alleles (Mc1r<sup>[a]</sup>/Mc1r<sup>[a]</sup>) produc- ing hair without subapical yellow band; (c) mouse with a pair of recessive alleles at both the Mc1r and agouti loci (Mc1r<sup>[a]</sup>/Mc1r<sup>[a]</sup>, a/a) is yellow; (d) mouse with genotype consisting of two wild-type Mc1r alleles and one dominant Agouti allele (Mc1r<sup>[A]</sup>/Mc1r<sup>[A]</sup>, A<sup>a</sup>) is yellow and obese; (e) mouse with two recessive mahogany alleles on a dominant Agouti background is similar to wild-type mouse in pigmentation and body mass.

TABLE 1
Phenotypes associated with variants of the MCR system
Coding region single nucleotide polymorphisms (cSNPs) alter the protein coding sequence. Other types of variants (e.g., deletions, promoter polymorphisms) exist at these loci, and many contribute to altered phenotype as well. Not all cSNPs counted have been associated with an altered phenotype.

<table>
<thead>
<tr>
<th>Human Phenotypes</th>
<th>Mouse Phenotypes</th>
<th>Human cSNPs</th>
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<tbody>
<tr>
<td>MC1R</td>
<td>Skin and hair pigmentation (Flanagan et al., 2000)</td>
<td>Hair pigmentation (Robbins et al., 1993)</td>
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<td></td>
<td>Melanoma susceptibility (Palmer et al., 2000)</td>
<td>Pain modulation (Mogil et al., 2003)</td>
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<tr>
<td>ACTHR</td>
<td>Familial glucocorticoid deficiency (Clark et al. 1993; Tsigos et al., 1993)</td>
<td>Feed efficiency (Chen et al, 2000)</td>
</tr>
<tr>
<td>MC3R</td>
<td>Dominantly inherited obesity (Vaisse et al. 1998; Yeo et al., 1998)</td>
<td></td>
</tr>
<tr>
<td>MC4R</td>
<td></td>
<td>Hair pigmentation and obesity (Duhl et al. 1994)</td>
</tr>
<tr>
<td>Agouti/ASIP</td>
<td>Fatness and abdominal adiposity (Argyropoulos et al., 2002)</td>
<td></td>
</tr>
<tr>
<td>AGRP</td>
<td>Red hair, severe early-onset obesity, and adrenal insufficiency (Krude et al., 1998)</td>
<td></td>
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<tr>
<td>POMC</td>
<td></td>
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ASIP, agouti signaling protein; POMC, proopiomelanocortin.
mann et al., 1997). This indicated that AGRP lacks affinity for MC1R, as later confirmed by in vitro studies (Yang et al., 1999). In their article in this issue of Molecular Pharmacology, Yang et al. (2003) have used this AGRP binding selectivity for MC4R over MC1R in their chimeric receptors to begin to unravel the GPCR domains involved in differential binding properties of agonists and antagonists. For example, Yang et al. (2003) show that although the third and fourth transmembrane domains of human MC4R play a significant role in C-terminal AGRP binding in vitro, the fourth transmembrane domain does not affect agonist [(Nle^4,D-Phe^7)]-α-MSH, an analog of α-MSH] binding. These and further such pharmacological studies of the domains of MC1R, MC4R, agouti, and AGRP should help determine the differential agonist and antagonist binding properties of GPCRs.

Through these studies, a model is emerging on the action of AGRP and MC4R on feeding and obesity phenotype in mouse (Fig. 2). Neurons producing α-MSH and AGRP respond to energy balance changes to regulate food intake via the MC3 and MC4 receptors of downstream neurons. AGRP antagonist increases food intake by inhibiting the action of α-MSH on MC4R, as agouti antagonizes the effect of α-MSH on MC1R to regulate pigmentation (reviewed in Barsh and Schwartz, 2002).

The MCR pathway has also introduced new regulators of the G-protein-coupled receptor pathway. The pleiotropic effects of the dominant Agouti mutations described above were not seen in mice carrying two recessive alleles at the mahogany locus. The product of the murine mahogany locus was cloned and found to be expressed in many cells and tissues, including melanocytes and the hypothalamus (Gunn et al., 1999). It is orthologous to a transmembrane domain-coding splice variant of the human attractin molecule (Tang et al., 2000). The mechanism of action of this membrane-bound protein is also not fully understood; however, He et al. (2001) provided biochemical evidence of a mechanism in which the mahogany product, attractin, functions as a low-affinity receptor for agouti, but not for AGRP, that increases its local cell-surface concentration, enabling agouti to antagonize the action of α-MSH on MC1R and, when ectopically expressed, on MC4R (Fig. 2, b and d).

As described here, the plethora of naturally occurring polymorphisms and mutations of the MCR signal transduction pathway in human and mouse, coupled with their visibly altered phenotypes, provide for a unique model for understanding the mechanisms by which components of the GPCR signal transduction pathway interact and contribute to complex disease and traits. This system introduces new components that modify activation of the GPCR signal transduction pathway, provides numerous phenotype-associated human and mouse single nucleotide polymorphisms in GPCRs for “natural” site-directed mutagenesis studies into the roles of specific amino acid residues in GPCR structure-function, and provides naturally occurring animal variant models to study the action of endogenous antagonists on GPCRs and their modifiers. In addition to their traditional roles in pigmentation and adrenal function and the now established role in energy homeostasis, melanocortins have been observed to have numerous other actions such as on anti-inflammatory, analgesic, learning and memory, and sexual function (reviewed in Wikberg et al., 2000; Gantz and Fong, 2003). Further pharmacological studies on the interactions of these small peptides with their MCR pathway components have the potential to lead to new therapeutic approaches in disease involving GPCRs.

References


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