γ-MSH, sodium metabolism, and salt-sensitive hypertension

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Humphreys, Michael H. γ-MSH, sodium metabolism, and salt-sensitive hypertension. Am J Physiol Regul Integr Comp Physiol 286: R417–R430, 2004; 10.1152/ajpregu.00365.2003.—α-, β-, and γ-melanocyte stimulating hormones (MSHs) are melanotropin peptides that are derived from the ACTH/β-endorphin prohormone proopiomelanocortin (POMC). They have been highly conserved through evolutionary development, although their functions in mammals have remained obscure. The identification in the last decade of a family of five membrane-spanning melanocortin receptors (MC-Rs), for which the melanotropins are the natural ligands, has permitted the characterization of a number of important actions of these peptides, although the physiological function(s) of γ-MSH have remained elusive. Much evidence indicates that γ-MSH stimulates sympathetic outflow and raises blood pressure through a central mechanism. However, this review focuses on newer cardiovascular and renal actions of the peptide, acting in most cases through the MC3-R. In rodents, a high-sodium diet (HSD) increases the pituitary abundance of POMC mRNA and of γ-MSH content and results in a doubling of plasma γ-MSH concentration. The peptide is natriuretic and acts through renal MC3-Rs, which are also upregulated by the HSD. Thus the system appears designed to participate in the integrated response to dietary sodium excess. Genetic or pharmacologic induction of γ-MSH deficiency results in marked salt-sensitive hypertension that is corrected by the administration of the peptide, probably through a central site of action. Deletion of the MC3-R also produces salt-sensitive hypertension, which, however, is not corrected by infusion of the hormone. These observations in aggregate suggest the operation of a hormonal system important in blood pressure control and in the regulation of sodium excretion. The relationship of these two actions to each other and the significance of this system in humans are important questions for future research.

peptide hormone; pituitary; proopiomelanocortin; melanotropin; central nervous system; neurointermediate lobe

IN 1989, GRUBER AND CALLAHAN (44) published in this journal a detailed review of the cardiovascular actions of a group of peptides derived from the ACTH/β-endorphin precursor proopiomelanocortin (POMC). This group includes the melanocortins, or more properly the melanotropins, melanocyte stimulating hormones (MSHs) of α-, β-, and γ-primary structure. Since then, a wealth of new information has emerged on the functions of these peptides and the receptors with which they interact. In particular, the role of these peptides in mediating satiety has opened up a new vista on the molecular basis of obesity (reviewed in Refs. 99, 124, 132); it cleaves POMC into the larger peptides ACTH, melanotropin, and the large NH2-terminal fragment. PC2 is more prominent in melanotrophs of the intermediate lobe but is also expressed at low levels in anterior lobe corticotrophs; its action gives rise to the smaller peptides β-endorphin and α-, β-, and γ-MSH (132). Other enzymes are involved in COOH-terminal amidation and NH2-terminal acetylation of some of these peptides to complete processing.

POMC METABOLISM AND PROCESSING

POMC is best known as the prohormone of ACTH and β-endorphin. It is heavily expressed in corticotrophs of the anterior lobe of the pituitary and in melanotrophs of the intermediate lobe. However, it is also expressed in other parts of the central nervous system (CNS), notably the arcuate nucleus of the hypothalamus and the nucleus of the solitary tract and in extracranial tissues, including the skin, testis, thyroid, placenta, pancreas, gastrointestinal tract, kidney, and liver (21, 111). It is the product of a single gene composed of three exons separated by two introns, a structure similar among all mammalian species. Current understanding holds that circulating POMC-derived peptides are secreted from the pituitary, whereas peptides in extrapituitary tissues function in an autocrine or paracrine manner.

Processing of POMC into its component peptides is driven by two prohormone convertases, PC1 and PC2. These are subtilisin-like endoproteases that cleave polypeptides at sites of dibasic amino acid pairs (Lys-Lys, Lys-Arg, Arg-Arg, Arg-Lys), and all the POMC-derived peptides are flanked by such pairs. PC1 is expressed predominately in anterior lobe corticotrophs and to only a low extent in intermediate lobe (20, 132); it cleaves POMC into the larger peptides ACTH, β-lipotropin, and the large NH2-terminal fragment. PC2 is more prominent in melanotrophs of the intermediate lobe but is also expressed at low levels in anterior lobe corticotrophs; its action gives rise to the smaller peptides β-endorphin and α-, β-, and γ-MSH (132). Other enzymes are involved in COOH-terminal amidation and NH2-terminal acetylation of some of these peptides to complete processing.
Regulation of POMC synthesis and processing occurs through markedly different mechanisms in anterior and intermediate lobes. In anterior lobe corticotrophs, the major stimulus for POMC synthesis is CRF from the hypothalamus (4, 111). This peptide induces a rapid increase in POMC gene transcription and its mRNA. Glucocorticoids exert a negative feedback control on POMC gene expression by inhibiting POMC gene expression directly and also reduce the expression of PC1 and PC2 (20). In the intact animal, synthesis of POMC by corticotrophs is the resultant of CRF-mediated stimulation balanced by glucocorticoid inhibition. A number of other regulatory factors including vasopressin, catecholamines, serotonin, and angiotensin II have also been shown to regulate POMC expression (4, 111).

Regulation in the neurointermediate lobe (NIL) is mediated primarily by the neurotransmitter dopamine acting through the dopamine D2 receptor. In NIL, this receptor is negatively coupled to adenylate cyclase; activation of the receptor inhibits POMC gene expression and secretion of derived peptides, whereas antagonism of the receptor upregulates POMC expression (4, 111). Abundance of PC1 and PC2 mRNA and protein are involved in a wide variety of important actions. This work was facilitated by the cloning of a family of five receptors with which the peptides interact (Table 1). These receptors are members of the superfAMILY of seven-transmembrane-spanning receptors and share considerable amino acid homology among themselves. They are positively coupled to adenylate cyclase, and their activation results in an increase in cellular cAMP (80, 107). However, other signaling pathways have been identified, including activation of inositol trisphosphate with mobilization of intracellular calcium (59, 79), an influx of extracellular calcium (58), and the MAP kinase pathway (33). The MC1-R is the receptor mediating the classical effects of α-MSH on melanin dispersion; it is expressed by cutaneous melanocytes but is also found on monocytes and other immunomodulatory cells and has been proposed to mediate the anti-inflammatory actions of α-MSH (41, 107). Loss-of-function mutations of MC1-R in humans are relatively common and are associated with red hair color (110). The MC2-R is expressed in the zona

Fig. 1. A: overview of the proopiomelanocortin (POMC) molecule showing the dibasic amino acid sites of processing into the hormones derived from it. B: amino acid sequences of melanocyte stimulating hormone (MSH) peptides. α-, β-, and γ-MSH share a core heptapeptide sequence. Three species of γ-MSH have been recognized as described in the text. [Borrowed with permission of the American Heart Association (54a).]
Table 1. Characteristics of the melanocortin receptors

<table>
<thead>
<tr>
<th>Receptor</th>
<th>Ligands</th>
<th>Tissue Distribution</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC1-R</td>
<td>α-MSH &gt; β-MSH &gt; γ-MSH &gt; ACTH</td>
<td>Melanocytes, macrophages</td>
<td>Skin pigmentation; immune modulation</td>
</tr>
<tr>
<td>MC2-R</td>
<td>ACTH</td>
<td>Adrenal cortex</td>
<td>Steroidogenesis</td>
</tr>
<tr>
<td>MC3-R</td>
<td>γ1-MSH = γ2-MSH = α-MSH = β-MSH &gt; γγ-MSH</td>
<td>Hypothalamus, thalamus, other brain regions; kidney, gut, placenta, heart</td>
<td>Sodium metabolism, blood pressure regulation, energy homeostasis</td>
</tr>
<tr>
<td>MC4-R</td>
<td>α-MSH = β-MSH &gt; ACTH &gt; γ-MSH</td>
<td>Brain, spinal cord</td>
<td>Energy metabolism, food intake</td>
</tr>
<tr>
<td>MC5-R</td>
<td>α-MSH = ACTH &gt; β-MSH &gt; γ-MSH</td>
<td>Adrenal cortex, brain, lung, spleen, exocrine glands</td>
<td>Sebaceous gland function</td>
</tr>
</tbody>
</table>

MSH, melanocortin stimulating hormone; -R, receptor.

CARDIOVASCULAR ACTIONS OF γ-MSH

α-MSH and ACTH-(1–24) have been shown to exert resuscitative effects in models of hemorrhagic and septic shock (reviewed in Refs. 41, 107, 127). Some of these actions occur through a central site of action, whereas others appear to result from inhibition of production of cytokines like TNF-α. These anti-inflammatory actions inhibit acute renal and hepatic injury in rodent models (16, 17, 18); γ-MSH and structurally related peptides are not effective (127). On the other hand, γ-MSH-like peptides have been recognized to possess a variety of cardiovascular actions not shared by α- and β-MSH. Injections of γ-MSH intravenously or into a carotid artery result in a transient pressor and cardioaccelerator response that is due to central activation of sympathetic outflow. This may involve a vasopressinergic pathway, because it is blunted in Brattleboro rats lacking vasopressin (45), although not all observations are consistent with this (119). It likely also involves a neural circuit in the anteroventral region of the third ventricle, because lesions of this region reduced the pressor response to intravenous γ-MSH (11). This part of the hypothalamus lies outside the blood-brain barrier and so can respond to intravenously delivered peptide. γ-MSH administered directly into the cerebroventricular system (icv) also raises blood pressure but over a different time course of 10–15 min as opposed to a few seconds (115). In general, α-MSH has no effect on blood pressure or heart rate when given intravenously (23, 101, 121). However, it elevates blood pressure and heart rate when given intracerebroventricularly (29, 47, 72). This effect results from stimulation of sympathetic outflow and is mediated via MC4-Rs (74, 75). In contrast, microinjection of α-MSH into the dorsoventral complex of the medulla or the nucleus of the solitary tract lowers blood pressure and heart rate (65, 95), also likely mediated via MC4-R (65, 95). This action may help to explain the observation that acute intracerebroventricular administration of α-MSH raises blood pressure, whereas chronic administration lowers it (47). γ-MSH itself produced bradycardia and lowered blood pressure when injected directly into the nucleus of the solitary tract in contrast to its effects when given intravenously or intracerebroventricularly (24, 65). These observations indicate that the circuitry mediating the various cardiovascular actions of these peptides is complex; whereas the usual effect of γ-MSH peptides is to elevate blood pressure and heart rate, a vasodepressor effect can be manifest when they are injected directly into specific brain regions or when sympathetic outflow is depressed as under certain conditions of anesthesia (23, 44).
Structure-function studies have identified some features of MSH peptides that account for their cardiovascular activities. The sequence Arg-Phe at positions 10 and 11 of γ1- and γ2-MSH is necessary for the hypertensive effect of these peptides when administered intravenously, because analogs like α-MSH that lack them have no activity (Fig. 1). They must be at or near the COOH terminus, because γ2-MSH possesses this sequence but also has a long COOH-terminal extension and is inactive relative to the shorter forms when injected intravenously; however, it was equipotent to γ2-MSH in raising mean arterial pressure (MAP) when given into the cerebral ventricle (101), raising the possibility that its greater size in some way restricts its access to active sites in the central nervous system. Asp at position 9 confers selectivity for MC3-R relative to MC4-R (91). NH2-terminal shortening produces peptides that maintain cardiovascular activity, with γ-MSH-(6–12) being if anything more potent than γ2-MSH (89, 120, 121, 122). These observations, and others, raise important questions about the melanocortin receptor(s) mediating these activities. As discussed above, the cardiovascular actions of α-MSH appear to be mediated by MC4-R. γ-MSH has affinity in the concentration range at which it circulates only for MC3-R, and it would be reasonable to consider this receptor to mediate the pressor and tachycardic actions of this group of peptides. However, Li and colleagues (65) found that the hypertensive effect of intravenous γ2-MSH was not blocked by intracarotid injection of the MC3-R and MC4-R antagonist SHU9005, and others observed that the ability of peptide fragments to bind to and activate the various receptors correlated very poorly with their effects on blood pressure and heart rate; indeed, γ-MSH-(6–12) failed to activate in vitro the MC3-R, MC4-R, or MC5-R yet possessed potent activity in vivo (120, 121, 122). Such observations as these have led to the suspicion that the cardiovascular actions of γ-MSH and related peptides are mediated by an as yet undetected melanocortin receptor and/or a different class of receptor (65, 89, 123). Speculation has centered on the FMRFamide-gated sodium channel as a candidate receptor. FMRFamide (Phe-Met-Arg-Pro-Gln-Arg-Phe-NH2) was originally isolated from ganglia of the clam Macrocystis nimbosa (98), and a related peptide, neuropeptide FF (Phe-Leu-Phe-Gln-Pro-Gln-Arg-Phe-NH2), later identified in bovine brain (Ref. 57; reviewed in Ref. 105). These and related peptides are pressor and cardioaccelerator when injected systemically through central activation of the sympathetic nervous system, with a time course identical to that of γ1-MSH (81, 115). Thiémermann and associates (115) studied a number of related peptides and observed that the dipetidope Arg-Phe was the most potent pressor. Arg-Phe-NH2 is the NH2-terminal sequence of γ1-MSH; as discussed earlier, these two amino acids are necessary for the pressor actions of γ1-MSH and γ2-MSH. In 1995, Linguaglia and colleagues (71) reported the cloning of an amiloride-sensitive FMRFamide peptide-gated sodium channel from snail nervous tissue, for which FMRFamide and possibly related sympathoexcitatory peptides like γ1- and γ2-MSH could be the natural ligands. Subsequent work has suggested that activation of this system may be involved in the development of salt-sensitive hypertension (51, 90). These observations are relevant to the finding of salt-sensitive hypertension in γ-MSH-deficient rodents presented below. Although much more work needs to be done, the possibility exists that this amiloride-sensitive sodium channel could be the receptor activated by γ-MSH and related peptides to increase sympathetic outflow, raising blood pressure and heart rate. The availability of MC3-R-deficient mice (10) should allow definitive conclusions about the role of this receptor in the cardiovascular actions of MSH peptides; in a preliminary study, we observed that the cardiovascular responses to injections of γ-MSH are the same in wild-type and MC3-R knockout mice (86), a finding that argues against any role of MC3-R in these responses.

**γ-MSH AND NATRIURESIS**

Early studies by Orias and McCann (92), and subsequently by Hradek and Horky (49), demonstrated that α- and β-MSH were natriuretic when injected intraperitoneally into the rat and hamster. In 1984, Lymangrover and associates (73) showed that γ2-MSH also is natriuretic when injected as a bolus intravenously in doses from 0.64 to 64 pmol; doses higher than 64 pmol lost natriuretic activity. These groups of investigators concluded that the natriuretic effect of MSH peptides was likely a direct one on the kidney, although the systemic route of administration of the peptides did not allow a firm conclusion on this point. In 1987, Lin and colleagues (67) reported that γ2-MSH was natriuretic when infused directly into the renal artery at a rate that caused no change in sodium excretion from the contralateral kidney. This clearly indicated an intrarenal mechanism for the natriuresis; because no change in glomerular filtration rate occurred, the data were interpreted to indicate that the natriuresis resulted from inhibition of tubular sodium reabsorption (14, 67).

The mechanism of γ-MSH natriuresis has not been fully elucidated. Both mRNA and protein for MC3-R, MC4-R, and MC5-R have been identified in rat renal cortex and medulla (85), although their exact cellular localization has not been determined. Studies showed that the MC3-R and MC4-R antagonists SHU9005 and SHU9119 (50) infused intravenously blocked the natriuresis induced by γ-MSH, supporting a receptor-mediated mechanism of action (14). Excretion rates of both cGMP (U<sub>GMP</sub>V) and cAMP (U<sub>CAMP</sub>V) increased in proportion to the increase in sodium excretion after intravenous infusion of γ-MSH, and U<sub>GMP</sub>V also rose after intrarenal γ-MSH infusion (14). Excretion rates of cyclic nucleotides are often used as indexes of hormonal action in the kidneys; as discussed earlier, melanocortin receptors are positively coupled to adenylate cyclase, and the increase in U<sub>GMP</sub>V was therefore surprising. An increase in plasma atrial natriuretic peptide (ANP) concentration was observed after intravenous infusion of γ-MSH, so the possibility of an indirect effect of the peptide, acting through ANP to cause natriuresis, was raised (14). However, neutralization of secreted ANP by treatment with an anti-ANP antiserum did not alter the natriuresis caused by intravenous infusion of γ-MSH, and the authors concluded that the increase in plasma ANP resulting from γ-MSH infusion was not involved in the renal actions of this peptide (14). This same study also indicated that the renal nerves may be involved in the natriuretic effect of γ-MSH. Acute renal denervation blocked the natriuresis caused by intrarenal infusion of the peptide, whereas denervation did not alter the natriuresis resulting from intrarenal ANP infusion (14). The nature of this interaction between the renal nerves and γ-MSH-mediated natriuresis remains to be defined.
Interest in the possible role of γ-MSH as a physiological regulator of sodium metabolism arose from studies of the natriuresis that occurs after acute unilateral nephrectomy (AUN). The postnephrectomy natriuresis was first clearly described by Peters (97) and has been confirmed in numerous subsequent reports. The natriuresis from the remaining kidney occurs within minutes of AUN (26, 27, 100) and takes place without an increase in glomerular filtration rate (GFR), indicating that it results from a decrease in tubular sodium reabsorption (69, 70, 97, 103). Although a transient increase in MAP is observed after AUN (5, 26, 87; see below), there is no overall increase in blood pressure that could account for the natriuresis. Because there is no discernible change in the volume or composition of the blood after AUN, a neurohumoral mechanism was suggested to mediate the postnephrectomy natriuresis. Such a mechanism could be considered to represent the efferent limb of a reflex arc activated by AUN, the other components of which include afferent inputs and central integrative pathways.

Several components involved in this reflex natriuresis after AUN have been identified and are summarized in Fig. 2. The reflex is initiated by the abrupt rise in arterial pressure that occurs immediately after clamping of the renal artery (5, 26, 87; Fig. 2, #1). This in turn is the result of the hydrodynamic consequence of the removal of one organ vascular resistance circuit (the kidney) in parallel with the multiple other regional vascular resistance networks (the other kidney, brain, heart, skeletal muscle, splanchnic circulation, etc.) that contribute to total peripheral resistance. In a parallel circuit, removal of one component must inevitably lead to an increase in overall resistance. Because cardiac output initially is unchanged and maintains constant flow, the result of the increased resistance is an increase in arterial pressure sensed by high-pressure baroreceptors in the carotid sinus. This rise in blood pressure proved to be the signal initiating the reflex: prevention of this hemodynamic consequence of AUN by opening a peripheral arteriovenous (AV) fistula at the time of AUN also prevented the postnephrectomy natriuresis (53), and both the hemodynamic changes and the excretory response resemble those seen on closure of a chronic AV fistula (52). Subsequent reflex effects reduce cardiac output and restore blood pressure back to control (52, 53, 54). Additional experiments established the importance of the carotid sinus baroreceptors (Fig. 2, #2): maneuvers that interfered with normal carotid sinus function or that prevented transmission of the increased pressure signal to the baroreceptors also prevented the postnephrectomy natriuresis (5). CNS involvement was more clearly established in the natriuretic response to AUN by experiments demonstrating that ventriculocisternal perfusion with pharmacologic agents blocked the natriuresis at doses that had no effect when given systemically (68; Fig. 2, #3). A role of the pituitary emerged from the finding that the postnephrectomy natriuresis did not occur in hypophysectomized animals (70; Fig. 2, #4). Finally, pituitary POMC became implicated when the plasma concentration of immunoreactive material from the midregion of the NH₂-terminal fragment of POMC, termed NTF 32–49, was observed to increase after AUN in a manner that was closely correlated with the increase in U₅₆₀V (70). Further evidence of a pituitary source for the secretion of this immunoreactivity came from studies in which a lesion of the arcuate nucleus of the hypothalamus was produced by neonatal administration of monosodium glutamate (69). The arcuate nucleus is an important neuroendocrine control station regulating pituitary function; rats treated in this manner exhibit a number of endocrine, metabolic, and behavioral disturbances attributed to altered pituitary function (84). Rats with this lesion failed to increase either U₅₆₀V or plasma NTF 32–49 concentration after AUN. This lack of response was associated with a reduction in NTF-like material in the pituitary of these rats (69).

We speculated that γ-MSH could be the component of the NH₂-terminal region of POMC that was associated with the postnephrectomy natriuresis, and we obtained evidence consistent with this possibility (67). AUN led to natriuresis that was accompanied by an increase in plasma γ-MSH immuno-

Fig. 2. Schematic model to depict the reflex activated by acute unilateral nephrectomy that results in natriuresis by the remaining kidney. See γ-MSH AND THE POSTNEPHRECTOMY NATRIURESIS for details. [Modified from Ref. 52, with permission of the publisher.]
reactivity. This increase correlated with the increase in NTF22.40 (100) and with the increase in UNaV (67); as discussed above, the peptide itself was natriuretic when infused either intravenously or directly into one renal artery. Pretreatment with rabbit anti-γ-MSH antiserum blocked the natriuretic response to AUN (63). These observations therefore suggested that γ-MSH acted as a classic circulating hormone after AUN (Fig. 2, #5): its concentration in plasma (presumably reflecting increased secretion) rose after AUN but not after sham nephrectomy; it possessed natriuretic potency when infused intravenously or directly in one renal artery; and the presence of an antiserum, which likely bound and rendered inactive any freshly released peptide, prevented the postnephrectomy natriuresis. The characteristics of the antiserum used in these studies led to the conclusion that γ2-MSH, as opposed to γ1- or γ3-MSH, mediates the natriuretic response (55, 67, 100). Of note, no change in the plasma concentration of another POMC-derived peptide, ACTH, occurred after AUN, suggesting a selective effect of this maneuver on secretion of γ1-MSH. Moreover, no change in plasma ANP concentration was observed, indicating that activation of this potent natriuretic pathway was not responsible for the postnephrectomy natriuresis (100). Further support for mediation of the natriuresis after AUN by γ-MSH came from experiments in which the melanocortin receptor antagonists SHU9119 and SHU9005 were infused into the renal artery of the remaining kidney before carrying out AUN. These compounds have high potency and selectivity for the MC3-R and MC4-R while retaining full agonist activity at MC1-R and MC5-R (50). Intrarenal infusion of either compound prevented the postnephrectomy natriuresis despite equivalent elevations of plasma γ-MSH concentration (87), providing additional evidence for a receptor-mediated mechanism as being responsible for the natriuresis.

Mention was made earlier that renal denervation prevented the natriuretic response to infusion of γ-MSH. Similarly, renal denervation also prevented the postnephrectomy natriuresis (55, 103) but in a complex manner. Renal innervation appeared necessary for the nephrectomy to stimulate γ-MSH release into the circulation, a requirement that was attributed toafferent renal nerves (103; Fig. 2, #6).

γ-MSH AND SODIUM METABOLISM

The identification of a role of γ-MSH in the reflex natriuresis initiated by AUN suggested the possibility that this humoral system could be involved in a more general way in sodium metabolism. Indeed, the components of this reflex arc (baroreceptor inputs, hypothalamic integration, hypothalamic-pituitary axis) mediate other circumstances of body fluid homeostasis and circulatory control. Duchen (28) demonstrated an increase in the number of secretory granules in NIL but not anterior lobe (AL) of rats drinking hypertonic saline, and Howe and Thody (48) extended this observation by measuring an increase in NIL MSH content by bioassay in rats drinking 2% saline for 10–15 days. Elkabes and Loh (32) measured plasma α-MSH concentration and pituitary POMC mRNA and synthetic rate in mice drinking either tap water or 2% saline for 15 days. Elkabes and Loh (32) that they re

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protein abundance of MC3-R more than doubled in medulla but not cortex, whereas expression of the other receptors did not change (85). It thus seems that the HSD not only activates synthesis and secretion of γ-MSH from the NIL but also upregulates the expression of its receptors in the kidney, thereby amplifying the potency of its natriuretic action. This is in contrast to the ANP system, which is also activated by the HSD: plasma ANP concentration increases, but there is no change in the renal expression of the ANP receptor natriuretic peptide receptor (NPR)-A (37, 113). This dual action of the HSD to increase not only plasma γ-MSH concentration but also its receptor MC3-R in the kidney argues that this system is an important component of the integrated response to states of sodium surfeit.

**γ-MSH AND SALT-SENSITIVE HYPERTENSION**

The possibility of involvement of altered POMC metabolism in the pathogenesis of hypertension has been considered. Gaida and colleagues (40) found that β-endorphin immunoreactivity was increased in NIL of stroke-prone spontaneously hypertensive rats (SHR) and was not affected by antihypertensive treatment with clonidine, whereas Felder and Garland (35) observed that synthesis of POMC by hypertensive rat pituitary NIL was blunted compared with normotensive rats. Pharmacologic treatment of hypertensive rats with a variety of agents restored blood pressure to normal and also normalized POMC synthesis, leading the authors to conclude that the blunted synthesis while hypertensive was a consequence rather than a cause of the hypertension (35). These studies did not quantitate POMC mRNA, nor were the pituitary changes related to circulating concentrations of peptides derived from POMC. In contrast to these observations of altered POMC metabolism in NIL of hypertensive rats, Braas and associates (8) found reduced levels of POMC peptides and POMC mRNA in anterior lobes of hypertensive rats. In none of these studies was the temporal relationship of blood pressure changes to POMC metabolism examined or the consequence of alterations in sodium intake on these variables studied. Hao and Rabkin (46) reported still different results after measuring POMC mRNA in pituitaries of Dahl salt-resistant and salt-sensitive rats. They observed an increase in POMC mRNA abundance in resistant rats ingesting an HSD but not in salt-sensitive rats. They could not determine if this difference between salt resistant and salt sensitive was causally related to the hypertension of sensitive rats or a result of it, nor did they relate it to changes in circulating concentration of any POMC-derived peptides. Their study followed the earlier work of Rapp and Dahl (102), who showed decreased protein synthesis and α-MSH content in NIL in response to sodium loading in salt-sensitive compared with salt-resistant rats. We also observed in preliminary studies that Dahl salt-sensitive rats failed to increase pituitary POMC mRNA when ingesting the HSD and also did not increase plasma γ-MSH concentration (76). These last observations raise the possibility that impaired POMC metabolism may contribute to salt-sensitive hypertension.

The renal and cardiovascular effects of γ1- and γ2-MSH have also been studied in SHR and the normotensive control Wistar-Kyoto (WKY) rats (114). Both peptides caused dose-dependent increases in MAP and heart rate in conscious intact rats that were not observed in rats that had been pithed. These authors also presented data indicating that intravenous infusion of nonpressor doses of γ2-MSH led to equivalent natriuresis in both SHR and WKY, suggesting that the natriuretic component of the peptide’s actions was preserved in this form of genetically hypertensive rat. On the other hand, a preliminary study indicated that intrarenal infusion of γ2-MSH in untreated SHR did not exert a natriuretic action; treatment with the angiotensin-converting inhibitor captopril, added to the drinking water for 7–10 days, lowered MAP from 161 to 120 mmHg and restored natriuretic responsiveness to intrarenal infusion of γ2-MSH (131). The basis for these divergent observations on the renal action of γ-MSH in SHR has not been determined.

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**Fig. 3.** A: in situ hybridization photomicrographs of pituitaries from rats fed a high-sodium diet (HSD; left) or a low-sodium diet (LSD; right) for 1 wk using a 32P-labeled POMC cRNA probe. Signal intensity is much greater on the high-sodium diet, and the signal is confined to the neurointermediate lobe. B: quantification of γ-MSH immunoreactivity in anterior and neurointermediate lobes of rat pituitaries after ingestion of HSD or LSD for 1 wk. Immunoreactivity was low in anterior lobe and was not affected by dietary sodium intake. Immunoreactivity was much higher in intermediate lobe and was doubled by ingestion of the HSD. [Modified from Ref. 71 with permission of the American Heart Association.]
More recent studies in rodents with γ-MSH deficiency or resistance identify the importance of the γ-MSH system in sodium metabolism. Mention was made earlier of the importance of PC2 in the processing of POMC into its secretory product γ-MSH. Mice with targeted deletion of the PC2 gene were first reported in 1997 by Steiner’s group (38); these mice exhibit a modest impairment in growth and have lower blood glucose concentration than their wild-type littermates but are otherwise phenotypically normal. They demonstrate defective processing of a number of peptide hormones in addition to POMC (3, 7, 39). PC2 knockout mice were compared with wild-type mice while ingesting either the LSD or the HSD for 1 wk; MAP was measured under ketamine-xylazine anesthesia, and plasma γ-MSH concentration was assayed. In wild-type mice fed the HSD, plasma peptide concentration was more than double the value observed in mice fed the LSD, whereas MAP was not significantly different (88) (Fig. 4); these results parallel those described above in normal rats. However, in PC2 knockout mice a different picture emerged. Plasma γ-MSH concentration on the LSD was only ~15% of the value seen in wild-type mice and was not any higher in knockout mice on the HSD. MAP in these mice on the LSD was marginally elevated compared with wild-type mice (104 vs. 83 mmHg) but was dramatically increased in knockout mice ingesting the HSD (158 mmHg; Fig. 4). Thus absence of functional PC2 led to γ-MSH deficiency and was accompanied by a marked degree of salt-sensitive hypertension (88). To test the role of the γ-MSH deficiency in the hypertension, we infused the peptide at a low rate and found that it rapidly lowered MAP to normal values, whereas α-MSH was without effect. This blood pressure-lowering effect of γ-MSH resulted from a central site of action, because a low dose of the peptide, which was without effect when administered intravenously, promptly reduced MAP in hypertensive knockout mice when given into the cerebroventricular system (88).

PC2 requires interaction with the neuroendocrine protein 7B2 for its maturation and development of full enzymatic activity. 7B2 is a small, acidic protein that is localized to neuroendocrine tissues and that binds to PC2 early in the secretory pathway (6). Although one might expect that reduction of PC2 activity by disruption of 7B2 would lead to a similar phenotype as observed in PC2 knockout mice (38), 7B2 null mice are markedly different (126). They show absence of PC2 enzymatic activity and impaired processing of proglucagon to glucagon but, in contrast to PC2 knockout mice, have markedly elevated plasma levels of ACTH and corticosterone and adrenal cortical expansion; they die before 9 wk of age of severe Cushing’s syndrome caused by excessive NIL secretion of ACTH (126). Adrenalectomy with steroid hormone replacement rescues the lethal phenotype of these mice, which also exhibit a defect in dopaminergic suppression of NIL ACTH secretion (62). Blood pressure was not reported in these studies, and it is not known if secretion of γ-MSH from the intermediate lobe was also impaired in 7B2 null mice. The basis for the phenotypic differences between PC2 knockout and 7B2 null mice is not clear, but these differences indicate that interruption of normal prohormone processing by PC2 can lead to pleiotropic effects.

The findings described above in PC2 knockout mice argue that γ-MSH deficiency results in salt-sensitive hypertension and document therefore the important role of this peptide in sodium metabolism. We sought to determine if γ-MSH resistance also resulted in a hypertensive phenotype by measuring MAP on the LSD vs. HSD in mice with targeted disruption of the MC3-R or MC4-R. Mc3r−/− mice exhibit a unique metabolic syndrome characterized by an increase in adipose tissue mass without obesity and with reduced energy expenditure (10), whereas Mc4r−/− mice are phenotypically obese with increased adipose tissue, hyperphagia, and insulin resistance (56). Mc3r−/− mice had a plasma γ-MSH concentration on the LSD that was more than double the value observed in wild-type controls, and the value increased even more in knockout mice ingesting the HSD. This suggested that these knockouts have a hormone-resistant state. MAP reflected the results in PC2−/− mice: it was somewhat higher in knockout mice on the LSD than in wild-type mice but became markedly hypertensive in Mc3r−/− mice that had been ingesting the HSD for 1 wk (88). In contrast to PC2−/− mice, infusion of γ-MSH had no effect on MAP in these Mc3r−/− mice, indicating that the restoration of MAP to normal by γ-MSH administration to hypertensive PC2−/− mice required integrity of this receptor. Mc4r−/− mice were normotensive on both the LSD and HSD (88).

In aggregate, these experiments paint a picture of a humoral system, the disruption of which, either by impairment of normal secretion or by blunting of its signaling through its...
receptor, results in salt-sensitive hypertension. Such a finding indicates the importance of this system in normal sodium metabolism. The mechanism(s) by which interruption of γ-MSH signaling causes hypertension is not yet clear. Plasma renin activity and plasma aldosterone concentration were equivalently suppressed during ingestion of the HSD in PC2−/− mice, arguing that these important determinants of MAP were not involved. Intravenously infused γ-MSH increased U_{Na}V in hypertensive PC2−/− mice as MAP was falling to normal levels, but the rapidity of the blood pressure-lowering effect of the peptide makes a reduction in plasma volume from the natriuresis seem unlikely. Moreover, cerebroventricular administration of the peptide led to even more rapid correction of MAP in doses that had no effect given intravenously, so that natriuresis could not be the mechanism by which MAP was lowered. However, the natriuretic property of the peptide could certainly interact with its blood pressure-lowering action to participate in the overall regulation of the circulation and body fluid volumes. The central site of action of the peptide given to γ-MSH-deficient mice suggests that it may possibly reduce central sympathetic outflow, an interesting hypothesis in view of the literature cited earlier in this review documenting the effect of γ-MSH, at much higher doses, to stimulate sympathetic outflow. Obviously, much further work will be required to characterize fully the mechanism(s) underlying salt-sensitive hypertension that occurs as a result of impaired γ-MSH signaling.

The pleiotropic consequences of PC2 deficiency, as described above, raise the concern that systems in addition to γ-MSH could contribute to the hypertension that these animals display. We consequently used a pharmacologic approach in an effort to interfere with NIL processing of POMC without perturbing other systems dependent on PC2. As discussed earlier, the major pathway regulating NIL function involves dopaminergic suppression. We treated male rats with the dopamine agonist bromocriptine (5 mg/kg ip by daily injection) or the dopamine receptor antagonist haloperidol (5 mg/kg ip each day) for 1 wk while they were ingesting either the LSD or the HSD and compared the results with those in vehicle-treated rats. Vehicle-treated rats on the HSD showed an elevation in plasma γ-MSH concentration and NIL γ-MSH content compared with rats ingesting the LSD (78) as we had seen earlier (77); MAP did not differ in the two groups. Haloperidol-treated rats had elevated plasma and NIL γ-MSH levels on the LSD, and these did not increase further on the HSD. MAP again was no different in the two groups. Bromocriptine treatment produced opposite results. Neither plasma γ-MSH concentration nor NIL γ-MSH content was elevated in bromocriptine-treated rats on the HSD compared with LSD values, and, interestingly, MAP was significantly higher in the HSD animals (132 ± 3 vs. 100 ± 3 mmHg in LSD rats, P < 0.001) (78). Thus dopaminergic stimulation with bromocriptine produced γ-MSH deficiency during ingestion of the HSD, and this was accompanied by the development of salt-sensitive hypertension. As was true with γ-MSH-deficient PC2−/− mice, infusion of the peptide at a physiologically relevant rate restored MAP to control values very quickly (78). These results indicate that pharmacologic treatment known to interfere with POMC processing results in γ-MSH deficiency and that this deficiency is associated with the occurrence of salt-sensitive hypertension. Because other pathways requiring PC2 for prohormone processing were not likely to be affected by bromocriptine treatment, this finding strengthens the contention that hypertension in PC2−/− mice is a reflection of impaired POMC processing into γ-MSH. These observations provide further support for an important role of γ-MSH in sodium metabolism; deficiency of this peptide results in the development of salt-sensitive hypertension.

The studies described above allow the development of a scheme depicting the major elements of the physiology and pathophysiology of the γ-MSH system in the regulation of sodium metabolism (Fig. 5). Ingestion of a diet high in sodium content generates a signal that ultimately reaches the pituitary. The nature of this signal is at present obscure. It could arise from sensory afferents in cardiopulmonary and arterial baroreceptor regions responding to the increase in blood volume, which results from sodium retention in the early period of exposure to the new dietary intake. An alteration in geometric relationships of structures surrounding the third cerebral ventricle has also been suggested to serve as a mediator of changes in sodium intake (63), as has an increase in sodium concentration in the cerebrospinal fluid (CSF) (82). This increase is then transmitted to the pituitary NIL via a series of intermediate steps. We showed that the opioid receptor antagonist naloxone blocked the postnephrectomy natriuresis when administered directly into the CSF (68); insofar as pathways regulating POMC processing and γ-MSH secretion in response to a high dietary sodium intake are the same as those mediating natriuresis after AUN, this observation indicates an opioidergic...
step in the neural pathway to the NIL. As discussed above, dopaminergic regulation of NIL function is established, and the data just presented indicate that manipulation of dopaminergic activity profoundly influences NIL γ-MSH content, plasma γ-MSH concentration, and MAP. Release of tonic dopaminergic suppression leads to increases in POMC and its processing enzymes PC1 and PC2 and an increase in NIL γ-MSH content.

The NIL is viewed as the source of circulating enzymes PC1 and PC2 and an increase in NIL γ-MSH content. The NIL is viewed as the source of circulating enzymes PC1 and PC2 and an increase in NIL γ-MSH content. The NIL is viewed as the source of circulating enzymes PC1 and PC2 and an increase in NIL γ-MSH content. The NIL is viewed as the source of circulating enzymes PC1 and PC2 and an increase in NIL γ-MSH content. The NIL is viewed as the source of circulating enzymes PC1 and PC2 and an increase in NIL γ-MSH content.
about this system, particularly γ-MSH, in cardiovascular homeostasis in humans. It is to be hoped that the data summarized in this review will stimulate interest in the study of this area.

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