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Review

Regulation of hypothalamic NPY by diet and smoking

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ABSTRACT

Appetite is regulated by a number of hypothalamic neuropeptides including neuropeptide Y (NPY), a powerful feeding stimulator that responds to feeding status, and drugs such as nicotine and cannabis. There is debate regarding the extent of the influence of obesity on hypothalamic NPY. We measured hypothalamic NPY in male Sprague–Dawley rats after short or long term exposure to cafeteria-style high fat diet (32% energy as fat) or laboratory chow (12% fat). Caloric intake and body weight were increased in the high fat diet group, and brown fat and white fat masses were significantly increased after 2 weeks. Hypothalamic NPY concentration was only significantly decreased after long term consumption of the high fat diet. Nicotine decreases food intake and body weight, with conflicting effects on hypothalamic NPY reported. Body weight, plasma hormones and brain NPY were investigated in male Balb/c mice exposed to cigarette smoke for 4 days, 4 and 12 weeks. Food intake was significantly decreased by smoke exposure (2.32 ± 0.03 g/24 h versus 2.71 ± 0.04 g/24 h in control mice (non-smoke exposed) at 12 weeks). Relative to control mice, smoke exposure led to greater weight loss, while pair-feeding the equivalent amount of chow caused an intermediate weight loss. Chronic smoke exposure, but not pair-feeding, was associated with decreased hypothalamic NPY concentration, suggesting an inhibitory effect of cigarette smoking on brain NPY levels. Thus, consumption of a high fat diet and smoke exposure reprogram hypothalamic NPY. Reduced NPY may contribute to the anorexic effect of smoke exposure.

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1. Appetite regulation and neuropeptide Y (NPY)

Appetite is regulated by a well designed homeostatic network comprising central and peripheral components that maintain the balance between energy intake and energy expenditure [48,65]. The brain plays a critical role in the regulation of energy homeostasis. Circuits in the central nervous system (CNS) assess and integrate peripheral metabolic, endocrine and neuronal signals that reflect current energy status, influencing orexigenic and anorexigenic signals to allow adequate energy balance [49]. Therefore, despite considerable daily variation in both energy intake and expenditure, most animals including humans maintain a steady body weight for long periods. The hypothalamus is considered the main integrator and processor of peripheral metabolic information, and this region contains many neurotransmitters that stimulate and inhibit appetite.

NPY, a 36 amino acid peptide first isolated in 1982 from porcine brain, is a member of the pancreatic polypeptide family, abundant throughout the CNS [5,52]. Centrally, NPY is a powerful neurochemical stimulator of feeding in many species [27,43,56]. NPY levels reflect the nutritional status of the body, contributing to the long term regulation of energy homeostasis. The arcuate nucleus (Arc) is a major hypothalamic site of NPY expression [40]. NPY neurons in the Arc project to the paraventricular nucleus (PVN) to release NPY thus stimulating feeding. Repeated administration of NPY into the hypothalamus induces hyperphagia even under conditions of satiation, decreases energy expenditure and increases fat deposition promoting weight gain and obesity [10,20,43].

NPY may function as an orexigenic signal regulating periodic eating behavior. Hypothalamic NPY concentrations are elevated before the introduction of food, and decreased significantly during the course of eating [34]. Expression of NPY mRNA is increased in response to fasting or chronic food restriction, and decreased within 6–24 h of ad libitum refeeding [6,12,51]. The feeding effects of NPY are mediated by a combination of receptors, with the orexigenic effect being primarily mediated through Y_1 and Y_5 receptors [13,33,66]. Circulating hormones, such as leptin and insulin, can inhibit the anabolic NPY system [1,2,50], while ghrelin, released from the stomach, can stimulate the activity of hypothalamic neurons expressing NPY [60].

2. States of overnourishment and undernourishment

The outcome of an extended period of positive energy balance is overnutrition, characterized by excess accumulation of fat. Throughout the world the prevalence of overweight or obesity is increasing, and this disorder has been called a modern ''epidemic,'' with 1 billion adults overweight, and at least 300 million of them obese [62]. Obesity rates have risen three-fold or more since 1980 not only in western countries, but in eastern Europe, the Middle East, Pacific islands and China [62]. Childhood obesity is also rising at an alarming rate worldwide. In the USA, the number of overweight children has doubled and the number of overweight adolescents has tripled since 1980 [62]. Overweight and obesity are predisposing factors for diet-related chronic diseases, such as type 2 diabetes, hypertension and coronary heart disease.

While obesity is an emerging problem, cigarette smoking is a long-standing health issue worldwide. Globally about one third of male adults and one in five teenagers smoke. Smoking-related diseases threaten the life of one in ten adults. If the current trend continues, this is predicted to increase to one in six by 2030 [61]. Smokers weigh less than non-smokers of the same age and gender [4,36]. Anorexia often occurs with cigarette smoking [42], and this has also been demonstrated in animals [57]. Suppression of appetite is one of the major motives for smoking, especially among the young and in women [3,4,36,42].

3. Modeling dietary obesity

The reasons for the worldwide increase in obesity are hotly debated. Genetically obese animals, such as the obese *ob/ob* mouse and diabetic *db/db* mouse, have been thoroughly studied to investigate the link between NPY and the etiology of obesity [31,47,64,67]. However, genetic mutations only account for a small portion of human obesity. Consumption of sugar-sweetened soft drinks and fast-food intake predicts a weight gain of about 0.4 kg per year independent of energy intake, physical activity and television viewing [8]. Diet-induced obesity is a model that may be a better representation of the physiological changes in response to diet-related obesity in humans than the genetically obese animal models [39]. In order to investigate the link between brain NPY levels and dietary obesity, our laboratory has developed a palatable high fat diet for rodents that can be applied in young adulthood, allowing us to examine brain NPY peptide level and physiological changes during the development of obesity [26,27,41].

Young adult (5–60-week-old) weight-matched (200 g) groups of male Sprague–Dawley rats received standard chow (12% calories as fat) or a highly palatable cafeteria-style diet (consisting of supplemented chow, meat pies, pasta and cakes, 32% calories as fat) [26]. Animals can be followed for various periods of dietary intervention, from 2 to 20 weeks [26,27]. The caloric intake of the animals on the high fat diet was maintained at 160–196% that of the chow fed control animals [27]. Body weight, fat mass and plasma leptin concentration increase soon after exposure to the high fat diet [26]. At 2 weeks, when a body weight change was not obvious, both white and brown fat masses had nearly doubled in the animals on a high fat diet [27]. As a result, the level of the adipose-derived hormone leptin was doubled in plasma, and this was maintained after 17 weeks [27] and 20 weeks [26] of diet. At 17 weeks, the body weight of the high-fat diet fed rats was 26% greater than chow fed control animals [27]. However, hypothalamic NPY peptide concentration measured by radio-immunoassay only decreased with chronic high-fat feeding, including the preoptic and anterior hypothalamus, Arc and PVN (Table 1) [27]. These changes may be a physiological response to elevated plasma leptin levels or an adaptive response to prolonged enhanced caloric intake. We observed a significant negative correlation between total hypothalamic

Table 1 – Effects of diet-induced obesity on body weight, adiposity and hypothalamic NPY concentration in the rat

	9 weeks		17 weeks	
	Control, $n = 9$	High-fat diet, $n = 8$	Control, $n = 16$	High fat-diet, $n = 17$
Body weight (g)	568 ± 45	$699 \pm 29^{*}$	637 ± 12	$801 \pm 14^{*}$
RpWAT (g)	8.2 ± 1.5	$19.1 \pm 3.3^{*}$	9.0 ± 0.5	$19.5 \pm 1.1^{*}$
Arc NPY (ng/mg tissue)	5.2 ± 0.4	4.7 ± 0.3	5.6 ± 0.5	$4.4 \pm 0.3^{*}$
PVN NPY (ng/mg tissue)	2.2 ± 0.4	1.8 ± 0.2	2.2 ± 0.1	$1.7 \pm 0.2^{*}$

Data shown as mean ± S.E.M. Data were analyzed by Student's unpaired *t* test. Arc, arcuate nucleus; PVN, paraventricular nucleus; RpWAT, retroperitoneal white adipose tissue.
* $p < 0.05$, compared to chow fed animals at the same time point (adapted from ref. [25]).

NPY and plasma leptin concentration [27]. We have observed similar reductions in hypothalamic NPY levels using this dietary model in the mouse, with more pronounced changes in the Arc (35% reduction) and a similar level of reduction in the PVN as in the rat after 10 weeks of diet, with an eight-fold increase in plasma leptin concentrations [17]. Subsequent studies in our dietary obese rats also revealed hypersensitivity to exogenous NPY injection compared with chow fed control animals [27].

The reduced hypothalamic NPY peptide in the animals on a high fat diet contrasts with the observations in genetically obese animals, such as the *ob*/*ob* and agouti mouse, where increased hypothalamic NPY is a major driver of hyperphagia and obesity [47,53,64]. Thus, the changes in hypothalamic NPY content in response to dietary intervention are different from genetically obese animals, which highlights the importance of using dietary obese models.

4. Modeling cigarette smoking

This body weight and appetite reducing action of smoking appears to be nicotine mediated as indicated by Hajek et al. [25]. The effects of nicotine on body weight and caloric intake have been well studied in both humans and animals [7,11,24,25,57]. Cigarette smoke contains at least 4000 components that may directly or indirectly affect caloric intake and energy expenditure. Furthermore, smoking exerts an inflammatory stimulus on macrophages which brings about the production of inflammatory cytokines, such as tumor necrosis factor α and interleukin 6, which might be an important early event in the development of disease states associated with smoking [22]. These cytokines have been shown to affect appetite regulation and lipid metabolism [14,32,37,54,55]. Therefore, direct study of the effects of cigarette smoke gives a better insight into smoking-related anorexia and weight loss.

In a short term study, young adult Balb/c mice (8 weeks of age) were exposed to the smoke produced from three cigarettes, three times a day, for 4 consecutive days or sham-exposed (non-smoke exposure, control group) [18]. Food intake dropped significantly after the first day of cigarette smoke exposure, and over 4 days, it was reduced by 34% (2.4 g/mouse/day versus 3.6 g/mouse/day in the smoke and sham-exposed control animals, respectively, $p < 0.05$). Weight loss became evident within 2 days of smoke exposure, and by the end of the experiment (day 5), body weight of the mice exposed to cigarette smoke was 10% less than the control animals. This was accompanied by significantly reduced brown fat and retroperitoneal white fat masses, and a 34% reduction in plasma leptin concentration [18]. However, the reduced food intake did not lead to any changes in hypothalamic NPY concentrations over this short time frame.

Uncoupling proteins (UCPs) are mitochondrial carrier proteins, which are able to dissipate the proton gradient of the inner mitochondrial membrane to increase energy expenditure and thermogenesis [19]. This process is closely related to energy metabolism. UCP3 is implicated in the regulation of mitochondrial fatty acid transport and influences basal metabolic rate [44,46,58]. UCP3 mRNA expression was increased in the brown fat of the smoke exposed animals, suggesting increased energy expenditure despite their reduced caloric intake, which may contribute to the rapid fat loss in these animals.

The question that arises is whether the lower caloric intake in animals during short term smoke exposure is the main contributor to the reduced body weight in those animals. To answer this question, a pair-fed group was added in another longer term experiment [15]. In the long term study, animals were exposed to a lower dose of cigarette smoke that was generated from one cigarette, three times a day, 5 days a week for 4 weeks. A group of sham-exposed mice was given the same amount of chow consumed by smoke exposed animals in the previous 24 h (pair-fed), and a control group had ad libitum chow feeding and were sham-exposed. Food intake of the animals exposed to smoke was decreased by 31% after the first day of smoke exposure, and during the 4 week experimental period it was significantly reduced by 19%. The weight gain of animals exposed to cigarette smoke was slower than control sham-exposed animals, resulting in a nearly 10% lower body weight after 4 weeks of smoke exposure compared with control animals. Equivalent food restriction in the pair-fed group resulted in a 7% reduction in body weight. As observed in the short term experiment, mice exposed to cigarette smoke had lower fat mass and plasma leptin concentrations, but this was not observed in the pair-fed group. Interestingly, a significant reduction in PVN NPY concentration was observed only in the animals exposed to cigarette smoke, not in the animals on equivalent food restriction (pair-feeding) [15]. Physiologically, low plasma leptin levels due to fat loss and/or low caloric intake could be expected to stimulate hypothalamic NPY production and release to stimulate feeding [1,21,50]. This may represent a direct inhibitory effect of cigarette smoke exposure on the brain NPY pathway, which may in turn contribute to the spontaneously reduced food

intake upon smoke exposure. When the smoke exposure period was extended to 12 weeks, an increase in hypothalamic NPY was observed in the pair-fed animals, which was significantly suppressed by smoke exposure [16]. Relative to sham-exposed control animals, UCP1 and UCP3 mRNA expression was reduced in animals on food restriction, but was preserved in the smoke exposed animals after 4 weeks of smoke exposure [15], suggesting cigarette smoke exposure encourages energy expenditure despite reduced caloric intake.

5. Why is a decreased hypothalamic NPY observed in these different dietary states?

In both dietary obesity and cigarette smoking models, hypothalamic NPY concentrations were reduced in the face of two opposite feeding behaviors, hyperphagia and hypophagia. The question raised here is why reductions in hypothalamic NPY happened in two contrasting nutritional states.

In the cigarette smoke exposure model, there appears to be direct inhibitory effects of nicotine or other elements in cigarette smoke on hypothalamic NPY peptide level. Although the decreased NPY peptide levels can potentially upregulate NPY receptor expression, hypothalamic NPY Y_1 receptor density has been observed to be reduced by chronic nicotine treatment [35]. Therefore, reduced peptide level as well as receptor density may directly contribute to the altered feeding behavior.

In the diet-induced obese animals, the reduced hypothalamic NPY concentration would be expected to reduce caloric intake. However, as observed in different experiments using the same diet in our laboratory, hyperphagia was maintained throughout the experimental period. One explanation is that lower endogenous agonist concentration may lead to a possible increase in receptor expression. This was suggested by experiments administering exogenous NPY to dietary obese animals [27]. In previous studies, an increase in receptor expression and binding in the hypothalamus was observed in diet-induced obese animals [30,63], although this was not measured in our studies. Therefore, although hypothalamic NPY content appears to be reduced in dietary obese animals, an altered receptor expression may still allow the orexigenic effects of NPY to maintain hyperphagia and promote fat accumulation. It also has been speculated that NPY may only initiate the hyperphagia and is not necessary to maintain the hyperphagic state [9].

Furthermore, NPY is not the only neuropeptide in the CNS that regulates appetite and energy balance. Neurons expressing orexigenic NPY and agouti-related protein (AgRP) cooperate with neurons expressing anorexigenic proopiomelanocortin (POMC) and cocaine- and amphetamine-regulated transcript. An interaction between NPY and α-melanocyte stimulating hormone, one of the peptide cleavage products of the POMC molecule, on feeding regulation has been shown in a previous study [28]. When hypothalamic NPY mRNA expression was reduced in response to high-fat diet feeding, AgRP and POMC mRNA were also downregulated [38,59]. This suggests the anorexigenic neurons containing POMC respond synchronously with orexigenic neurons to maintain the harmony between hyperphagic and anorexigenic neuropeptides.

Feeding is not only controlled by homeostatic mechanisms, which theoretically would allow an individual to maintain an ideal body weight. The brain reward system has been identified to reinforce the motives without homeostatic value [45]. Consumption of a palatable high-fat diet may be considered to be an addictive behavior, and NPY can directly enhance rewards [23,29]. Interactions between the lateral hypothalamus and the nucleus accumbens, and between the neurotransmitters dopamine, serotonin and the opioid system most likely play predominant roles [45].

6. Summary

The regulation of feeding and the response of hypothalamic NPY to altered feeding states is complex, and it is difficult to draw conclusions based solely on NPY mRNA expression or absolute NPY peptide levels. In dietary obesity, decreased hypothalamic NPY was a physiological response to excess caloric intake. However, the reduced peptide level may upregulate NPY receptor expression, which could compensate and maintain the orexigenic function of NPY even with reduced endogenous NPY. This may explain the sustained hyperphagic state in high-fat diet fed animals in the face of reduced hypothalamic NPY peptide. In contrast, the reduced NPY concentration in the hypothalamus of cigarette smoke exposed mice is likely due to the inhibitory effects of nicotine and other factors in cigarette smoke. Moreover, NPY receptor density in the hypothalamus has been shown to be reduced in response to nicotine injection, which in turn may limit the orexigenic effect of NPY, thus explaining the prolonged anorexia. Therefore, not only the production of NPY in the hypothalamus, but also its receptors and downstream signals, contribute to these altered feeding states.

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