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Endogenous prolactin-releasing peptide regulates food intake in rodents

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Food intake is regulated by a network of signals that emanate from the gut and the brainstem. The peripheral satiety signal cholecystokinin is released from the gut following food intake and acts on fibers of the vagus nerve, which project to the brainstem and activate neurons that modulate both gastrointestinal function and appetite. In this study, we found that neurons in the nucleus tractus solitarii of the brainstem that express prolactin-releasing peptide (PrRP) are activated rapidly by food ingestion. To further examine the role of this peptide in the control of food intake and energy metabolism, we generated PrRP-deficient mice and found that they displayed late-onset obesity and adiposity, phenotypes that reflected an increase in meal size, hyperphagia, and attenuated responses to the anorexigenic signals cholecystokinin and leptin. Hypothalamic expression of 6 other appetite-regulating peptides remained unchanged in the PrRP-deficient mice. Blockade of endogenous PrRP signaling in WT rats by central injection of PrRP-specific mAb resulted in an increase in food intake, as reflected by an increase in meal size. These data suggest that PrRP relays satiety signals within the brain and that selective disturbance of this system can result in obesity and associated metabolic disorders.

Introduction
Classically, feeding is regulated by an alternation between hunger and satiety signals, which include both circulating factors and neurally mediated signals from the gastrointestinal tract (1). These signals act on the peripheral organs and on the CNS, including the hypothalamus and brainstem, to initiate or terminate food intake. One important satiety signal is the brain-gut peptide cholecystokinin (CCK). CCK, released from the gut in response to a meal, has an important regulatory role in gastrointestinal function, inhibiting gastric motility and emptying via a neural reflex within the caudal brainstem or via a reflex loop that ascends to the hypothalamus or brainstem, to initiate or terminate food intake. Some of these noradrenergic neurons express prolactin-releasing peptide (PrRP; encoded by the Prlh gene) (2). PrRP was discovered as an endogenous ligand for the GPCR GPR10 (encoded by the Prlh gene) (3), and PrRP-expressing neurons are localized in the NTS and ventrolateral medulla oblongata and in the dorsomedial hypothalamus (4). In the medulla oblongata, PrRP is exclusively colocalized in noradrenergic neurons (5). PrRP has been suggested to be involved in energy metabolism (10–15), stress responses (16–19), and analgesia (20).

Peripheral administration of CCK activates neurons expressing PrRP (11). There have also been several other indications that PrRP might be involved in the regulation of feeding and energy balance. In particular, central administration of PrRP reduces food intake in rats (10), and PrRP mRNA expression decreases during fasting and is low during lactation, a physiological state of negative energy balance (10). Mice that lack the PrRP receptor GPR10 show adult-onset obesity (15, 21) and, most interestingly, do not reduce their feeding in response to CCK (22).

Here, we examined the role of endogenous PrRP in the control of food intake and energy metabolism by studies in Tg mice deficient in PrRP and by neutralizing the actions of endogenous PrRP in mice and rats using mAb specific for PrRP. We also investigated whether food intake activates PrRP neurons in the caudal brainstem. In this study, we demonstrate that in rodents, PrRP relays satiety signals within the brain and that perturbation of this system can predispose to obesity and associated metabolic disorders.

Results
Generation of PrRP-deficient mice. To generate mice deficient in PrRP, we designed a targeting vector to disrupt exons 1 and 2 including full coding regions of the prepro-PrRP sequence (Figure 1A). Male
The heterozygous mice were apparently normal and were intercrossed to obtain homozygous offspring; these mice were viable (Figure 1B). PrRP transcripts and proteins were not detectable in PrRP-deficient mice, confirming the disruption of the Prlh gene (Figure 1, C and D).

**Adult-onset obesity in PrRP-deficient mice.** When WT, PrRP-heterozygous, and PrRP-deficient mice from heterozygous intercrosses were fed a high-fat diet ad libitum from the age of 5 weeks, PrRP-deficient mice became significantly heavier than either WT mice or PrRP-heterozygous mice by the age of 7 weeks (Figure 2A). When maintained on standard laboratory chow, PrRP-deficient mice weighed significantly more than WT mice at 18 weeks of age (Figure 2B), and this was accompanied by reduced glucose tolerance and increased insulin resistance (Figure 2C). PrRP-deficient mice had substantially more body fat than WT mice (Figure 2D), and this was accompanied by reduced glucose tolerance and increased insulin resistance (Figure 2E). Both WAT mass, in either subcutaneous pads or intraabdominal pads (perirenal, mesenteric, epididymal), and brown adipose tissue (BAT) mass were greater in PrRP-deficient mice than in WT mice (Figure 2G), and epididymal adipocytes of PrRP-deficient mice were larger than those in WT mice (Figure 2H). The hepatic tissue of PrRP-deficient mice contained many large fatty vesicles, indicating fatty liver (Figure 2H). Plasma concentrations of insulin, leptin, and triglyceride were higher in PrRP-deficient than in WT mice (insulin: WT, 850 ± 191 pg/ml, PrRP-deficient, 3,001 ± 672 pg/ml; leptin: WT, 11.5 ± 5.9 ng/ml, PrRP-deficient, 40.3 ± 12.9 ng/ml; triglyceride: WT, 71.2 ± 3.5 ng/dl, PrRP-deficient, 95.5 ± 5.7 ng/dl). Hepatic triglyceride concentrations were also higher in PrRP-deficient mice than in WT mice (1.23 ± 0.25 vs. 0.27 ± 0.04 mg/mg protein). The greater BW gain of PrRP-deficient mice was more prominent when they were fed a high-fat diet (Figure 3A), and this was associated with a significantly greater food intake (Figure 3B).

**Energy expenditure in PrRP-deficient mice.** To examine the pathogenesis of obesity in PrRP-deficient mice, amounts of food supplied were restricted to the mean food intake of age-matched WT mice. Under these conditions, the BWs of pair-fed PrRP-deficient mice did not differ significantly from those of WT mice (Figure 3C). Glucose tolerance and insulin resistance were also not significantly different in WT and pair-fed PrRP-deficient mice (Figure 3D and E).

We found no significant differences between WT and PrRP-deficient mice in locomotor activity in their home cages (Figure 4A).
and no significant differences in oxygen consumption (VO₂) during 12-hour dark, 12-hour light, and 24-hour periods for mice at the ages of 9, 16, and 51 weeks (Figure 4B). The mean respiratory exchange ratios were also not significantly different in WT and PrRP-deficient mice at the age of 9 (WT, 0.92 ± 0.01, PrRP-deficient, 0.92 ± 0.01), 16 (WT, 0.91 ± 0.01, PrRP-deficient, 0.88 ± 0.01), or 51 weeks (WT, 0.81 ± 0.02, PrRP-deficient, 0.84 ± 0.01). In paired PrRP-deficient mice at the age of 52–54 weeks, neither the total VO₂ nor the mean respiratory exchange ratios were significantly different from those in WT mice (Table 1).

We then examined VO₂ in animals whose endogenous PrRP functions were acutely blocked by neutralizing PrRP mAb. We found no significant differences between control animals and animals pretreated with anti-PrRP mAb (Figure 4C).

Uncoupling proteins are involved in the regulation of thermogenesis and energy expenditure through the sympathetic
nervous system. Therefore, we examined body temperature and uncoupling protein 1 (UCP1) mRNA expression in the BAT after exposure to cold. There was no significant difference in core body temperature between WT and PrRP-deficient mice either before (37.5 ± 0.1°C and 37.5 ± 0.1°C, respectively) or after (37.3 ± 0.1 and 37.2°C ± 0.2°C, respectively) exposure to cold. Expression of UCP1 mRNA in the BAT was increased after exposure to cold, but with no significant difference between WT and PrRP-deficient mice (Figure 4D).

Collectively, these data indicate that the obesity in PrRP-deficient mice mainly reflects hyperphagia rather than lower energy consumption.

Activation of PrRP neurons by food intake. We examined the expression of phosphorylated cAMP response element–binding protein (p-CREB) and Fos protein in PrRP neurons after food intake as a marker of neuronal activation. Refeeding following a 24-hour fast increased the percentage of p-CREB–positive PrRP neurons in the NTS (Figure 5A). The number of Fos-positive PrRP neurons in the NTS also significantly increased after refeeding (Figure 5B). By contrast, there were no significant increases in the percentages of p-CREB–positive PrRP neurons either in the ventrolateral medulla oblongata (89.6% ± 3.6% [control] and 90.1% ± 2.1% [refeeding]) or in the dorsomedial hypothalamus following refeeding (3.0% ± 1.5% [control] and 2.4% ± 1.1% [refeeding]). The number of Fos-positive PrRP neurons was increased slightly in the ventrolateral medulla oblongata (0 ± 0 cells/rat [control] and 2.8 ± 1.2 cells/rat [refeeding]; P < 0.05) but not in the dorsomedial hypothalamus following refeeding (1.0 ± 1.0 cells/rat [control] and 5.0 ± 2.0 cells/rat [refeeding]).

Food intake after impairment of PrRP signaling. Up to the age of 14 weeks, the daily food intake of PrRP-deficient mice was not significant (Figure 3C). In contrast, PrRP-deficient mice showed significantly greater gain in BW compared with WT mice (Figure 3A, B). Thus, PrRP-deficient mice ate significantly more after they were heavier than WT mice (n = 4). (C) BWs of WT and pair-fed PrRP-deficient mice from 6 to 57 weeks of age. Half of the mice were fed standard laboratory chow or high-fat diet from the age of 12 weeks. The BWs of pair-fed PrRP-deficient mice were not significantly different from those of WT mice (n = 6 or 7). (D) At the age of 39–40 weeks, pair-fed PrRP-deficient mice on standard laboratory chow had glucose tolerance similar to that of WT mice (n = 6 or 7). (E) At the age of 40–41 weeks, pair-fed PrRP-deficient mice on standard laboratory chow showed insulin resistance similar to that of WT mice. (Blood glucose concentrations before insulin administration were set as 100%; n = 6 or 7.) Error bars indicate SEM. *P < 0.01, †P < 0.001 versus WT mice; **P < 0.05, ***P < 0.01, ****P < 0.001 versus mice fed standard chow.

### Table 1

<table>
<thead>
<tr>
<th>VO_{2} and respiratory exchange ratios in pair-fed PrRP-deficient and WT mice</th>
<th>VO_{2} (ml/kg^{0.75} per hour)</th>
<th>Respiratory exchange ratio</th>
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<tbody>
<tr>
<td></td>
<td>WT</td>
<td>PrRP-deficient</td>
</tr>
<tr>
<td>Standard chow (n = 6 or 7)</td>
<td>1,466 ± 73</td>
<td>1,331 ± 82</td>
</tr>
<tr>
<td>High-fat diet (n = 4)</td>
<td>1,485 ± 118</td>
<td>1,535 ± 58</td>
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Data are expressed as mean ± SEM.
nificantly different from that of WT mice. However, even at this young age when no obesity was evident, PrRP-deficient mice are significantly more after a 24-hour fast than WT mice (Figure 5C), suggesting that PrRP is involved in food intake when food intake is facilitated by fasting. At the age of 24 weeks, PrRP-deficient mice ate more food than WT mice (Figure 5D).

We then examined food intake in rats whose endogenous PrRP functions were acutely blocked by neutralizing PrRP mAb. Rats pretreated with anti-PrRP mAb ate more during the dark period than control rats, whether anti-PrRP mAb was injected immediately before the dark period or during the light period (Figure 5, E and F). Rats injected intracerebroventricularly (i.c.v.) with anti-PrRP mAb are more after a 24-hour fast as measured either during the dark or the light period (Figure 5, G and H). Thus, immunoneutralization of central PrRP facilitates food intake whether meal initiation is triggered by the onset of the dark period or by fasting. Total daily food intake can be considered as the product of meal size and meal frequency. We investigated meal pattern in PrRP-deficient mice (Figure 5I) and in rats injected with anti-PrRP mAb (Figure 5J). The meal size, but not the meal frequency, was higher in PrRP-deficient mice than in WT mice and in rats was increased after i.c.v. injection of anti-PrRP mAb.

**Figure 4**

Energy consumption of PrRP-deficient mice. (A) At the age of 16 weeks, locomotor activity was not significantly different in WT and PrRP-deficient mice (*n* = 7). (B) VO₂ was not significantly different in WT and PrRP-deficient mice at the age of 9 (*n* = 9 or 11; right), 16 (*n* = 9 or 11; left, middle, and right), and 51 weeks (*n* = 5 or 6; right). (C) VO₂ was not significantly different in 10- to 11-week-old mice (left) and 12-week-old rats (right) that received an i.c.v. injection of anti-PrRP mAb (mice, *n* = 8; rats, *n* = 4). (D) Exposure to a cold environment increased UCP1 mRNA expression in the BAT similarly in WT and PrRP-deficient mice at the age of 24 weeks (*n* = 4). Error bars indicate SEM. NS, *P* > 0.05 versus WT mice.
PrRP neurons are activated after systemic injections of the peripheral satiety signal CCK (11). We therefore measured the effects of systemic administration of CCK on food intake in mice that had been fasted for 24 hours. CCK had less effect on food intake in PrRP-deficient mice than in WT mice (Figure 5K), suggesting that PrRP mediates a satiety signaling of CCK.

To investigate whether PrRP-deficient mice have enhanced fat preference, mice were tested on 2-choice macronutrient diet; they were given free access to both high-fat and high-carbohydrate diets or to both tallow and standard diet. There was no significant difference between WT and PrRP-deficient mice in the intake ratio of high-fat food (Figure 5L) or tallow (Figure 5M), suggesting that PrRP-deficient mice had no enhanced preference for fat meals.

Food intake–related peptides in the hypothalamus. We examined the expression of appetite-regulating peptides in the hypothalamus using in situ hybridization histochemistry. In obese PrRP-deficient mice fed a high-fat diet, the expression of mRNA for the anorexigenic peptide corticotrophin-releasing hormone (CRH) in the hypothalamic paraventricular nucleus was not different as compared with that in WT mice (Table 2). In nonobese PrRP-defi-
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Leptin effects on BW and food intake in PrRP-deficient mice

Table 2

<table>
<thead>
<tr>
<th>Peptide</th>
<th>STD WT</th>
<th>STD KO</th>
<th>HF WT</th>
<th>HF KO</th>
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<tr>
<td>AgRP</td>
<td>100 ± 14</td>
<td>98 ± 9</td>
<td>93 ± 29</td>
<td>89 ± 9</td>
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<tr>
<td>NPY</td>
<td>100 ± 16</td>
<td>109 ± 9</td>
<td>108 ± 11</td>
<td>108 ± 11</td>
</tr>
<tr>
<td>Orexin</td>
<td>100 ± 2</td>
<td>105 ± 7</td>
<td>89 ± 9</td>
<td>78 ± 7</td>
</tr>
<tr>
<td>CART</td>
<td>100 ± 12</td>
<td>126 ± 8</td>
<td>136 ± 14</td>
<td>82 ± 5</td>
</tr>
<tr>
<td>CRH</td>
<td>100 ± 8</td>
<td>70 ± 2</td>
<td>87 ± 9</td>
<td>94 ± 5</td>
</tr>
<tr>
<td>POMC</td>
<td>100 ± 7</td>
<td>95 ± 5</td>
<td>78 ± 7</td>
<td>94 ± 5</td>
</tr>
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</table>

Values are expressed as the mean percentage of probe binding as compared with that in WT mice fed standard chow. Mean levels of mRNAs (±SEM) for AgRP, NPY, CART, and POMC in the arcuate; orexin in the lateral hypothalamus; and CRH in the paraventricular nucleus in mice at the age of 16 weeks given free access to standard chow or high-fat diet for 4 weeks. There were no significant differences between WT mice and PrRP-deficient (KO) mice (n = 4).

STD, standard chow; HF, high-fat diet.

Discussion

PrRP is expressed in subpopulations of neurons in the NTS, the ventrolateral medulla, and the dorsomedial hypothalamus and has been implicated in several physiological processes (24, 25), including satiety signaling (10–13, 22), stress-induced release of ACTH and oxytocin (16, 19, 26, 27), and nociception (20). In the present study, blocking PrRP signaling in rats by administration of anti-PrRP mAb facilitated food intake only when food intake was initiated by the onset of the dark period or by fasting, suggesting that blocking PrRP actions does not itself initiate feeding but instead that feeding continues for longer once initiated. This suggests that PrRP might be involved in satiety signaling—a conclusion supported by the observation that CCK-induced reduction in food intake was impaired in PrRP-deficient mice. These findings are consistent with reports that GPR10-deficient mice have impaired responses to CCK (22). As peripheral administration of CCK activates most of the PrRP neurons in the medulla oblongata (11), these data suggest that PrRP/GPR10 systems mediate the satiety-inducing effects of peripheral CCK. We also found that PrRP-deficient mice showed an increase in meal size rather than meal frequency, similar to observations in CCKA receptor–deficient mice (23), indicating that CCK/PrRP signaling is important for determining meal size.

PrRP is localized in the A2 noradrenergic neurons of the NTS, in the A1 noradrenergic neurons of the ventrolateral medulla, and in neurons in the dorsomedial hypothalamus (6, 8, 9). Meal consumption activates neurons in the NTS (28, 29), including in particular noradrenergic neurons (30). In part, this reflects activation of satiety pathways arising from the gastric vagus, which are responsive to CCK. Thus, peripheral administration of CCK activates noradrenergic neurons in the NTS (5), and these neurons are critical for CCK signaling (31, 32). Here we show that food intake rapidly activates PrRP neurons in the NTS. The data suggest that PrRP neurons in the NTS mediate satiety signaling and support the view that satiety circuits are activated coincidentally with food intake (30). At present, the precise mechanisms by which PrRP reduces food intake remain to be clarified. PrRP may convey satiety signals to the hypothalamus (22), but microinjection of PrRP into the dorsal motor nucleus of the vagus also modulates gastric motor function (33). It is thus also possible that PrRP may inhibit food intake via an action on gastric emptying.

Mice deficient in CCKA receptors do not show obesity (23), so the defects in CCKA receptor signaling in PrRP-deficient or GPR10-deficient mice might not fully explain the obesity observed in PrRP-deficient mice. Leptin administration induces nuclear translocation of STAT3 in the dorsomedial hypothalamus (34) and p-STAT3 expression in the NTS (35), where PrRP neurons are localized. PrRP neurons express leptin receptors (25), and leptin administration increases PrRP mRNA (36), suggesting that the activity of PrRP neurons is under the control of leptin. Here we showed that leptin induces p-STAT3 expression in PrRP neurons, especially in the dorsomedial hypothalamus, and that the leptin-induced reduction in food intake and BW is impaired in PrRP-deficient mice. These data suggest that PrRP neurons, especially those in the dorsomedial hypothalamus, might be an important target for regulating food intake.
of leptin’s actions to restrain food intake or that leptin modulates the effects of PrRP by its actions on the neuronal targets of PrRP.

GPR10-deficient mice show reduced energy expenditure (15), and as acute administration of PrRP increases VO$_2$ (13), these data suggest that PrRP plays a role in energy expenditure. However, in the present study, VO$_2$ was not different in WT and PrRP-deficient mice, and acute blockade of PrRP signaling by anti-PrRP mAb did not increase VO$_2$. Furthermore, the obesity observed in PrRP-deficient mice could be fully reversed by pair feeding. These data suggest that endogenous PrRP does not play an important role in energy expenditure in basal conditions. The apparent discrepancies concerning energy expenditure between GPR10-deficient and PrRP-deficient mice remain to be clarified.

Energy homeostasis is regulated by various orexigenic and anorexigenic peptides in the hypothalamus. Administration of PrRP activates CRH neurons in the hypothalamus (37), and PrRP-induced anorexia is attenuated by a CRH receptor antagonist (13). However, in the present study, there was no significant decrease in CRH mRNA expression in the paraventricular nucleus, suggesting that changes in CRH neuronal activity may not be the main cause of obesity in PrRP-deficient mice. We also found that the expression levels of mRNAs encoding appetite-regulating peptides, AgRP, NPY, orexin, CART, and POMC, were normal in PrRP-deficient mice, indicating that the hyperphagia observed in PrRP-deficient mice is unlikely to be the result of a grossly perturbed functioning of these hypothalamic neuronal populations.

Both PrRP-deficient mice and GPR10-deficient mice show adult-onset obesity (15, 21), but there are several differences. Hyperphagia is not obvious in GPR10-deficient mice (22) but is clear in PrRP-deficient mice, and a high-fat diet can induce obesity in PrRP-deficient but not in GPR10-deficient mice (21). It is possible that PrRP acts on not only GPR10 but also other receptors, including neuropeptide FF receptor 2 (38). Administration of PrRP reduces food intake in rats with a naturally occurring polymorphism of the Prlhr gene that abolishes its ability to bind PrRP (39), suggesting that receptors other than GPR10 also play a role in the action of PrRP on feeding behavior. It is also possible that ligands other than PrRP might exist for GPR10. In conclusion, this study indicates that PrRP is a potent satiety peptide in the rodent CNS that contributes to the determination of meal size and that perturbation of PrRP signaling can predispose to obesity, mainly due to hyperphagia.

**Methods**

*Generation of PrRP-deficient mice.* To construct the targeting vector, a Prlhr genomic clone was isolated from a 129/SvJ-derived RW-4 ES cell genomic library. The Prlhr gene targeting vector was designed to replace a 2.0-kb BamHI-HpaI fragment including exons 1 and 2 constituting the entire coding region, with a neomycin phosphotransferase resistance cassette (neo). A 2.1-kb Vpl-BamHI fragment was used as the S’ homology region and a 5.0-kb HpaI-EcoRI fragment was used as the 3’ homology region. We linearized the targeting vector and electroporated it into RW-4 ES cells (Genome Systems Inc.). We selected G418-resistant clones and screened them by Southern blot analysis. Heterozygous ES cell clones were injected into blastocysts of C57BL/6N mice (Charles River Laboratories) and transplanted into pseudo-pregnant females.
ferred into uteri of pseudopregnant females. Chimeric males were mated to C57BL/6N females, and the resulting heterozygous mice were intercrossed. Their offspring were screened by Southern blot analysis. PrRP-deficient mice backcrossed into C57BL/6N background for 8 generations were used in this study. Permission of Takeda Chemical Industries Ltd. is necessary for the distribution of PrRP-deficient mice.

**Animals.** Animals were housed in a temperature- (22 ± 2°C) and humidity-controlled (40%-70%) room with a 12-hour light/12-hour dark cycle (light on 7:30–19:30). Food and water were available ad libitum. All animal procedures were approved by the Judging Committee of Experimental Animal Ethics of Jichi Medical University and were in accordance with Japanese legislation concerning animal experiments.

**Intraperitoneal glucose tolerance test and insulin tolerance test.** For the glucose tolerance test, male WT and PrRP-deficient mice (39–40 weeks old) were fasted for 14 hours (23:00–13:00) and injected i.p. with glucose (2 g/kg BW). For the insulin tolerance test, male mice (40–41 weeks old) were fasted for 4 hours (9:00–13:00) and then injected i.p. with insulin (1 U/kg BW; Novolin; Novo Nordisk). For both tests, blood samples were taken from the tail vein at 0, 15, 30, 60, and 120 minutes after loading. Blood glucose concentrations were determined by an enzymatic method using a GLUCOCARD DIA meter (ARKRAY).

**High-fat diet.** Male WT mice or PrRP-deficient mice were given either standard laboratory chow (CE-2; CLEA Japan) or a high-fat diet (Quick Fat; CLEA Japan) from the age of 5 weeks or for 4 weeks from the age of 12 weeks. The standard laboratory chow contains 12% fat, 29% protein, and 59% carbohydrates, with a caloric density of 3.45 kcal/g. The high-fat diet has 31% fat, 24% protein, and 45% carbohydrates, with a caloric density of 4.11 kcal/g.

**Pair feeding.** Male WT and PrRP-deficient mice were housed individually from 6 weeks of age, provided with food ad libitum, and weighed weekly. Pair feeding of standard laboratory chow or high-fat diet was started at the age of 12 weeks.

**Surgery and i.c.v. injection of an anti-PrRP mAb.** Male animals were anesthetized with Avertin (200 mg/kg BW, i.p.; tribromoethanol; Sigma-Aldrich) and placed in a stereotaxic frame. Stainless steel guide cannulae (25-gauge [mice] or 30-gauge [rats]). Permission of Takeda Chemical Industries Ltd. is necessary for the distribution of anti-PrRP mAB (P2L-1C).

**Locomotor activity and VO2.** Spontaneous motor activity was recorded in the home cage by the activity sensor unit (O’hara and Co.) (40). VO2 and carbon dioxide production (VCO2) were measured simultaneously for 4 animals using an indirect calorimeter (Oxymax Equa Flow System; Columbus Instruments) with an airflow of 0.8 l/min (mouse) or 2 l/min (rats). Animals were placed in individual calorimeter chambers. After a 2-hour acclimation period, VO2 (ml/kg BW × 75) per hour) was measured every 5 minutes for 24 hours. In the experiments with WT and PrRP-deficient mice, the measurements were conducted in male mice with free access to food (9, 16, and 51 weeks old) or under pair-fed conditions (52–54 weeks old). In the experiments with an i.c.v. injection, anti-PrRP mAb or mouse IgG was injected i.c.v. into male mice (10–11 weeks old; C57BL/6N; Charles River Laboratories) or male rats (12 weeks old, std: Wistar; SLC Japan) after a 1-hour baseline measurement of VO2, and the measurements were conducted in animals with no access to food. The VO2 values from 12 consecutive readings, encompassing a 1-hour period, were averaged for analysis. The respiratory exchange ratio was calculated as VCO2/VO2.

**Exposure to a cold environment.** Male WT or PrRP-deficient mice (24 weeks old) were placed in an incubator at 2°C for 6 hours. Body temperature was measured with a rectal temperature probe (model BDT-100; BRC). For measurements of Ucp1 mRNA, mice were deeply anesthetized i.p. with pentobarbital (50 mg/kg BW; Nembutal; Dainippon Pharmaceutical) 24 hours after the cold exposure, and the BAT was obtained. The total RNA of the BAT was isolated using TRIzol (Invitrogen) and treated with RQI-DNase (Promega) to remove residual contamination with DNA. First-strand cDNA synthesis was completed using ReverTra Ace (Toyobo). Primers for quantitative RT-PCR were first examined by HotStarTaq DNA polymerase (94°C for 15 seconds, 60°C for 20 seconds, and 72°C for 20 seconds × 30 cycles; QIAGEN) and agarose gel electrophoresis for correct product size and absence of primer-dimer formation. Using a Quantitect SYBR Green PCR kit (QIAGEN), quantitative RT-PCRs (95°C for 15 seconds, 60°C for 20 seconds, and 72°C for 20 seconds × 40 cycles) were performed in an ABI-Priism 7500 sequence detector (Applied Biosystems). Product accumulation was measured in real time, and the mean Ct was determined for replicate samples on the same plate. Different cDNA samples were normalized using primer sets to Gapdh. Primers for Gapdh were 5′-GGCACAGTCAAGGCTGAGAATG-3′ and 5′-ATGGTGGT-GAAGAGCGGAGTA-3′; those for Ucp1 were 5′-CGACAACTTCCGAGG- GCAC-3′ and 5′-TGATCTGAGGCGGACTT-3′.

**Detection of activated PrRP neurons after food intake.** To detect p-CREB in PrRP neurons, male rats (9 weeks old, std: Wistar; SLC Japan) were anesthetized with Avertin, and polyethylene catheters (PE50; BD) were inserted into the right jugular vein. Seven days later, the rats were fasted for 24 hours (19:30–19:30). One group of rats was refeed for 30 minutes after the fast, anesthetized with pentobarbital (60 mg/kg BW, i.v.), and perfused transcardially with heparinized saline (20 U/ml), followed by 3.75% acrolein and 2% PFA in 0.1 M phosphate buffer (pH 7.4). The brains were removed, postfixed in 3.75% acrolein and 2% PFA overnight, and transferred to 30% sucrose solution in 0.1 M phosphate buffer until tissue sank. The brains were frozen on dry ice and stored at −80°C. Coronal sections were cut at 30 μm with a freezing sledge microtome. Every fourth section of the hypothalamus and the medulla oblongata was collected and processed for immunohistochemistry. Sections were pretreated with 0.5% sodium metaperiodate for 20 minutes and with 1% sodium borohydride for 20 minutes. The sections were incubated for 15 minutes with 1.5% H2O2 solution to block endogenous peroxidase, with 10% normal goat serum for 1 hour, and then with a rabbit polyclonal Ab against p-CREB (diluted 1:200; Ser133; Cell Signaling Technology) for 48 hours at 4°C, followed by incubation with biotinylated goat anti-rabbit IgG (2 μg/ml BA-1000; Vector Laboratories) for 2 hours and then with avidin-biotinylated horseradish peroxidase complex (VECTASTAIN Elite ABC Kit; Vector Laboratories) for 30 minutes at room temperature. p-CREB immunoreactivity was visualized as a black nuclear precipitate using a glucose oxidase-based, nickel-intensified, 3.3′-diaminobenzidine procedure. p-CREB immunolabeled sections were treated with 1.5% H2O2 and 10% normal horse serum and then incubated with a mouse anti-PrRP mAb (5 μg/ml P2L-1T; Takeda Pharmaceutical Co.) for 48 hours at 4°C (6), followed by incubation with biotinylated horse anti-mouse IgG (1 μg/ml BA-2001; Vector Laboratories) and then with avidin-biotinylated horseradish peroxidase complex for 30 minutes at room temperature. PrRP immunoreactivity was visualized as a brown cytoplasmic precipitate using a 3.3′-diaminobenzidine procedure. For detection of Fos protein in PrRP neurons, male rats (9 weeks old, std: Wistar; SLC Japan) were fasted...
for 24 hours (10:00–10:00). One group of rats was refed for 2 hours after the fast, anesthetized i.p. with pentobarbital, and perfused with acrolein and PFA. Coronal brain sections were cut at 30 μm with a freezing sledge microtome. Every fourth section of the hypothalamus and the medulla oblongata was collected and processed for immunohistochemistry. Following treatments with sodium metaperiodate, sodium borohydride, and H2O2, the sections were incubated with 10% normal goat serum and incubated with a rabbit polyclonal Ab against Fox protein (diluted 1:10,000; Oncogene) for 48 hours at 4°C. The sections were incubated overnight with peroxidase-labeled goat anti-rabbit IgG (1 μg/ml PI-1000; Vector Laboratories) at 4°C. Fox immunoreactivity was visualized as a black nuclear precipitate using a glucose oxidase–based, nickel-intensified, 3,3′-diaminobenzidine procedure. Fos-immunolabeled sections were treated for detection of PrRP immunoreactivity, as described above. The number of PrRP-positive cells that were positive or negative for p-CREB or Fox protein was determined, and the percentage of PrRP-positive cells expressing p-CREB was calculated for each rat. Fourteen sections of the caudal brainstem (between −1,580 μm and 0 μm relative to the obex) were examined in each rat. For the dorsomedial hypothalamus, cells were counted in 3 sections per rat at a 120-μm interval to give a mean value for each rat; these values were averaged to determine a group mean. Permission of Takeda Chemical Industries, Ltd. is necessary for the distribution of anti-PrRP mAb (P2L-1T).

Measurements of food intake after i.c.v. injection of an anti-PrRP mAb. Seven days after cannula implantation, male rats (10 weeks old, std:Wistar; SLC Japan) were injected i.c.v. with anti-PrRP mAb or control IgG, and cumulative food intake was measured by an automatic food counter (O’hara and Co.). An i.c.v. injection was performed at the beginning of the dark period or 3 hours after the onset of the light period. Half of the rats were fasted for 24 hours until the i.c.v. administration.

Measurements of meal size and meal frequency. Food intake was recorded every minutes by an automatic food counter (O’hara and Co.). For male WT and PrRP-deficient mice (14 weeks old), meal initiation was defined as more than 50 mg pellets within 10 minutes. Once a meal was initiated, meal termination was defined as the onset of a 10-minute interval with no intake. For male rats (10 weeks old, std:Wistar; SLC Japan), meal initiation was defined as a minimum of 100 mg pellets within 10 minutes.

Administration of CCK. Male WT and PrRP-deficient mice (19–21 weeks old) were individually housed, deprived of food for 24 hours, and injected i.p. at 11:00 with saline or CCK-octapeptide22–33 (sulfated form) (20 μg/kg BW; Peptide Institute). Cumulative food intake was measured before and after injection.

Two-choice macronutrient diet test. Male WT and PrRP-deficient mice at the age of 34–37 weeks had free access to both high-fat diet (Quick Fat) and high-carbohydrate diet (63.7% of calories from carbohydrate and 9.6% of calories from fat, 360.7 kcal/100 g; KBT Ooriental Co.). Daily food intake was recorded with a comparison test or 2-tailed t test. A P value of less than 0.05 was considered statistically significant.

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