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Glutamate receptor antagonist suppresses the activation of nesfatin-1 neurons following refeeding or glucose administration

S. Serter Kocoglu et al., Nesfatin-1 neurons following refeeding or glucose administration

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ABSTRACT

Background: Nesfatin-1 is a newly identified satiety peptide that has regulatory effects on food intake and glucose metabolism, and is located in the hypothalamic nuclei, including the supraoptic nucleus (SON). In this study, we have investigated the hypothesis that nesfatin-1 neurons are activated by refeeding and intraperitoneal (ip) glucose injection and that the glutamatergic system has regulatory influences on nesfatin-1 neurons in the SON.
Materials and methods: The first set of experiments analyzed activation of nesfatin-1 neurons after refeeding as a physiological stimulus and the effectiveness of the glutamatergic system on this physiological stimulation. The subjects were randomly divided into three groups: fasting group, refeeding group and antagonist (CNQX+refeeding) group. The second set of experiments analyzed activation of nesfatin-1 neurons by glucose injection as a metabolic stimulus and the effectiveness of the glutamatergic system on this metabolic stimulation. The subjects were randomly divided into three groups: saline group, glucose group and antagonist (CNQX+glucose) group.
Results: Refeeding significantly increased the number of activated nesfatin-1 neurons by

approximately 66%, and intraperitoneal glucose injection activated these neurons by about 55%, compared to the fasting and saline controls. The injections of glutamate antagonist (CNQX) greatly decreased the number of activated nesfatin-1 neurons.

Conclusions: This study suggested that nesfatin-1 neurons were activated by peripheral and/or metabolic signals and that this effect was mediated through the glutamatergic system.

Key words: CNQX, glucose, glutamate, nesfatin-1, refeeding

INTRODUCTION

Nesfatin-1 is an 82 amino acid peptide that has modulating effects in regulating food intake, body weight and gluconeogenesis (11, 41). NUCB2/Nesfatin-1 is widely expressed in peripheral tissues and the central nervous system (51). Nesfatin-1 is expressed in the hypothalamic nuclei which are involved with the regulation of food intake including the paraventricular nucleus (PVN), arcuate nucleus (ARC), supraoptic nucleus (SON), lateral hypothalamic area (LHA), zona incerta, and the solitary tract (11, 23, 41, 43, 44). NUCB2/Nesfatin-1 has also shown to be expressed in the periphery such as the gastric mucosa, adipose tissue, ovaries, testes, uterus, epididymis, cardiomyocytes and pancreatic beta cells (41). Surprisingly, NUCB2/Nesfatin-1 immunoreactivity was found to be 10 times higher in the gastric mucosa than in the brain (15). The inhibitory effects on food intake of nesfatin-1 have been studied and it has also been shown to influence the regulation of cardiac functions, lipid metabolism, glucose homeostasis and reproductive functions (5). It has been shown that intracerebroventricular injection of nesfatin-1 into the 3rd and 4th ventricles reduces food intake in mice and rats (29, 35, 44, 49).

Immunohistochemically, the expression of transcription factors such as c-Fos, phosphorylated CREB or phosphorylated STATs (phosphorylated signal transducers and transcription activators) are used as markers for determining neuronal activity changes (1, 4, 20, 52). Nesfatin-1 injection to the third ventricle has been shown to cause c-Fos expression, especially in the PVN and NTS (11, 29). The expression of c-Fos in these nuclei shows the anorectic signaling mechanism of nesfatin-1 (11).

Glucose sensitive neurons include glucose homeostasis and glucoprivic feeding. Recently, these neurons have received more attention due to their regulatory effects on appetite (51). Nesfatin-1 inhibits food intake by increasing the number of the glucose sensitive neurons in the hypothalamus (dorsal vagal complex) (51). Nesfatin-1 participates in blood glucose regulation. Subcutaneous injection of nesfatin-1 reduces the glucose levels in the blood during the oral glucose tolerance test (OGTT). However, intracerebroventricular injection of nesfatin-1 does not reduce glucose levels in the blood (28). This finding suggests that the glycemic effect of nesfatin-1 may be peripheral. Co-injection of insulin and nesfatin-1 increased the phosphorylation of AKT kinase in liver, skeletal muscle and adipose tissue. As a result, GluT4 expression increased to increase glucose uptake (15).

Glutamate is the major excitatory amino acid neurotransmitter in the mammalian central nervous system (7, 8). Glutamate plays an important role in the regulation of the neuroendocrine systems and the hypothalamus-pituitary-endocrine system axis by acting on many neuroendocrine and peptidergic neurons localized in the hypothalamus (7, 8, 40). Glutamate-mediated neurotransmission occurs via metabotropic and ionotropic glutamate receptors (22). Ionotropic glutamate receptors are classified according to their agonists: N-methyl-D-aspartate (NMDA), α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid (AMPA) and 2-carboxy-3-carboxymethyl-4-isopropenylpyrrolidine (kainate) receptors (22, 27, 45). NMDA receptors are composed of subunits named GluN1, GluN2A-D and GluN3A-B (9, 24). These receptors have a critical function in excitatory synaptic transmission, plasticity and neurotoxicity (10, 30, 36-38).

Despite the many publications describing the mechanisms of action of nesfatin-1, there are no data about the peripheral and central control systems which play a role in the regulation of nesfatin-1 neuron activation. In this study, we analyzed the effects of glutamatergic receptor antagonist (CNQX) on the activation of Nesfatin-1 neurons following refeeding or glucose administration.

MATERIALS AND METHODS

Animals

All animal experiments were carried out in accordance with the National Institute of Health Guide for the Care and Use of Laboratory Animals and approved by the Experimental Ethics Committee of Bursa Uludag University (Date: 01.03.2016, No: HDP(T)-2016/25). 60-day-old male Sprague-Dawley rats (200-250 g) (n=30), obtained from the Bursa Uludag University Laboratory Animal Breeding, Usage and Research Center, were used in this study. Animals were kept in a light- and temperature-controlled facility (12:12 h light-dark cycle with lights off at 7:00 am and at 21°C) with water freely available.

Experimental groups

Experiment 1: Suppressive effect of glutamate receptor antagonist (CNQX) on nesfatin-1 neuronal activation induced by refeeding

The animals were divided into three groups (n= 5 per group). After a 48-hour fasting period, the refeeding group was allowed to eat ad libitum for 2 hours, while the fasting group was unfed and the antagonist group was injected intraperitoneally with non-NMDA glutamate antagonist (CNQX) (2 mg/kg CNQX in 300 µl distilled water, DW) 15 minutes before the 2-h refeeding period. After the 48-hour fasting, refeeding was started at 9:00 am at the beginning of the dark period of the dark-light cycle and the animals were allowed to feed for 2 hours. Also, the CNQX injections were performed at 9:00 am.

Experiment 2: Suppressive effect of glutamate receptor antagonist (CNQX) on nesfatin-1 neuronal activation induced by glucose injection

The animals were divided into three groups (n=5 per group). After a 48-hour fasting period, the control group received saline (400 µl saline, intraperitoneally [ip]), the glucose group was injected with glucose (2 g/kg glucose in 400 µl saline, ip) and the antagonist group was injected with non-NMDA glutamate antagonist (2 mg/kg CNQX in 400 µl saline, ip) 15 minutes before the glucose injection. The dosage of glucose injection was determined by referring the previous reports in the literature (21, 46-47).

Tissue preparation

All injections were performed between 9:00 and 11:00 am and 90 minutes after injection, the animals were deeply anesthetized with ether and fixed by trans-cardiac perfusion with 4% paraformaldehyde (PFA) in 0.13 M Sorenson's phosphate buffer, pH

7.4 (300 ml/animal). Brains and brainstems were carefully removed and post-fixed overnight in the same fixative at +4°C. Five series of brain sections with a thickness of 40 μm were taken along the rostral-caudal axis of the hypothalamus with a vibratome and collected into Tris-HCl buffer (0.05 M, pH 7.6). The brain sections were washed 3 times with Tris-HCl buffer (0.05 M, pH 7.6) and then stored at -20°C in cryoprotectant until use.

Immunohistochemistry

Tris-HCl buffer was used for all washing steps. Primary and secondary antibodies were diluted in blocking buffer (10% normal horse serum, 0.2% Triton X-100, and 0.1% sodium azide in Tris-HCl buffer) for 2 h in order to prevent non-specific binding. Following 2-h incubation in blocking buffer, sections were transferred into rabbit anti-c-Fos antibody solution at a dilution of 1/20 000 (Chemican, Billerica, MA, USA). The sections were incubated in donkey anti-rabbit IgG (1/300 dilution, Jackson ImmunoResearch Laboratories, West Grove, PA, USA) for 2 h, processed with avidin-biotin complex according to the manufacturer's instructions (ABC Elite Standard Kit, Vector Laboratories, Burlingame, CA, USA) for 1 h and stained with diaminobenzidine (DAB) solution (25 mg DAB, 2 g nickel ammonium sulfate, 2,5 μl hydrogen peroxide in 100 ml Tris-HCl buffer). After washing, the sections were secondarily blocked with 10% normal horse serum, and incubated in rabbit anti-nesfatin-1 antibody (1/20 000 dilution, H-060-50, Phoenix Pharmaceuticals, Inc., USA) overnight at room temperature. This step was followed by secondary antibody incubation using biotin conjugated donkey anti-rabbit IgG (1/400 dilution, Jackson ImmunoResearch Labs, West Grove, PA, USA) for 2 h. DAB (25 mg DAB, 2.5 μl hydrogen peroxide in 50 ml Tris-HCl buffer) was used for visualization of the immunochemical complex.). Double-stained sections were then transferred into Tris-HCl buffer, washed, mounted on glass slides, dried and coverslipped with DPX.

c-Fos antibody used in this study have been used in many reports in the literature as well as in our previous studies (17, 42). Nesfatin-1 antibody specifity was shown in previous studies in the literature (6).

Cell counting

Sections were analyzed and photographed with Olympus BX-50 photomicroscope attached to a CCD camera (Olympus DP71, CCD color camera, 1.5 million pixels, Olympus Corporation, Japan). Sections between the coordinates determined according to the rat brain atlas (bregma -0.48 mm and -1,44 mm SON) were used for double immunohistochemical labeling (39). Cross sections taken at 5 different levels at the same coordinate and at equal distance for each animal in the rostrocaudal plane were used for cell counting. All nesfatin-1-positive cells, with and without c-Fos-positive nuclei neurons in the SON were counted bilaterally and blindedly in every fourth section between the stereotaxic coordinates of bregma -0.48 mm- bregma -1.44 mm. Then the percentage of c-Fos-positive nesfatin-1 neurons to all nesfatin neurons was calculated within each animal in dual indirect immunoperoxidase-labeled sections.

Statistical analysis

The percentage of the c-Fos positivity in nesfatin-1 positive cells is expressed as mean ± standard deviation. The significance of differences between the groups was assessed with ANOVA test. The level of statistical significance was set at $P < 0.05$. Statistical data analysis was performed with IBM SPSS, 23.0.

RESULTS

The agonist and antagonist injections did not cause adverse reactions or mortality during the experiments.

Nesfatin-1 positivity was visualized by brown reaction product with chromogen in the cytoplasm and c-Fos positivity by blue/black reaction product in the nuclei (Fig. 1). After the 48-h fasting, refeeding and ip glucose injection significantly increased the number of c-Fos-expressing nesfatin-1 neurons, compared with the fasting and saline controls. These effects were also blocked by antagonist injection (CNQX).

Refeeding induced c-Fos expression in nesfatin-1 neurons and CNQX reduced the number of active nesfatin-1 neurons

After refeeding for 2 h following 48 h fasting, c-Fos-immunoreactive neurons were observed abundantly in the SON, PVN.

The 2-h refeeding after 48-h fasting caused a significant increase in the number of c-Fos-positive nesfatin-1 neurons compared with the fasting group. These effects were also blocked by antagonist (CNQX). In the refeeding group, about 66% of nesfatin-1 neurons localized in the SON were c-Fos-positive, whereas this ratio was 1% in the fasting group (P=0.000). The ratio of the activated nesfatin-1 neurons was reduced to 25% after CNQX injection (P=0.009). The number of nesfatin-1 neurons expressing c-Fos immunoreactivity was significantly (66 times) greater under refeeding, compared with fasting conditions (Table 1, Fig. 2, and Fig. 4A).

Glucose induced c-Fos expression in nesfatin-1 neurons and CNQX reduced the number of active nesfatin-1 neurons

After glucose injection following 48 h fasting, c-Fos-immunoreactive neurons were observed abundantly in the SON, PVN.

The glucose injection after 48-h fasting significantly increased the number of c-Fos-positive nesfatin-1 neurons compared with the control group. These effects were also blocked by antagonist (CNQX). The glucose injection activated about 55% of c-Fos-positive neurons (55%, significantly more than in the control group: 1%, P=0.01). The ratio of the activated nesfatin-1 clearly decreased after antagonist injection (CNQX) (6%, P=0.01).

The number of c-Fos-expressing nesfatin-1 neurons was significantly increased following glucose injections when compared with saline conditions. The number of glucose-activated nesfatin-1 neurons was significantly reduced if CNQX was pre-injected (Table 1, Fig. 3, and Fig. 4B).

DISCUSSION

Nesfatin-1 is a newly identified peptide that has regulatory effects on food and water intake, energy consumption, cardiovascular and gastrointestinal functions, anxiety and depression and reproductive functions (41). Although there is some literature on the

effects of nesfatin-1 neurons in the target cells and organs, no experimental studies have been found on central neurotransmitter systems. In the present study, we investigated the hypothesis that nesfatin-1 neurons are activated by refeeding and glucose injection as peripheral and metabolic factors and that the glutamatergic system has regulatory influences on nesfatin-1 neurons in the SON.

The regulatory effects related to neurogenesis, apoptosis, neurite development and synapse formation of glutamate, the main excitatory neurotransmitter of the central nervous system, on the hypothalamic neuroendocrine systems, is intensively investigated (12-14, 32). Glutamate is the dominant excitatory transmitter in neuroendocrine regulation in the hypothalamus. There were large amounts of glutamate in boutons making synaptic contact with neuroendocrine neurons in the arcuate, paraventricular, and supraoptic nuclei. The immunohistochemical studies showed that high level glutamate-immunoreactive terminals were present in the SON. Glutamate is also one of the major excitatory neurotransmitters in the SON (31). In our laboratories we showed that kainic acid activates oxytocinergic neurons through non-NMDA glutamate receptors in the SON and PVN (34). Our immunohistochemical studies showed that systemic administration of ionotropic non-NMDA and NMDA glutamate receptor agonists directly or indirectly activate neuronostatin neurons at different rates (42). Also, we detected increased number of c-Fos positive nesfatin-1 neurons in kainic acid, AMPA and NMDA injected subjects in the SON (18). In addition, expression of the ionotropic glutamate receptors has been demonstrated with fluorescence microscopy on nesfatin-1 neurons in the SON (18). In the present study, after refeeding and glucose injection, c-Fos-immunoreactive neurons were observed abundantly in the SON. We anayzed the SON for the effects of the glutamatergic system on nesfatin-1 neurons induced by refeeding and glucose injection.

The anorexigenic effect after injection into brain ventricles of nesfatin-1 has been studied in various animal groups such as rats (25, 44, 50), mice (3, 16), pigs (26) and goldfish (19), and it has been found to have a strong anorexigenic effect. Inhibition of dark phase food intake after third ventricle injection of nesfatin-1 has been described (35). Low dose injection into the 4th ventricle of nesfatin-1 has been shown to reduce food intake in the first 4 hours and suppress cumulative food intake in the 5th hour (43). Intracerebroventricular (ICV) injection of nesfatin-1 has been shown to reduce water intake as well as food intake (48). In the SON, refeeding has been shown to activate the

number of nesfatin-1-immunoreactive neurons and mRNA expression of NUCB2 (23). Refeeding after fasting also increased the number of c-Fos-positive nesfatin-1 neurons in the SON (23). Our results not only confirmed this previous report by showing that activation of the nesfatin-1 neurons was caused by refeeding after fasting, but also that this activation was significantly suppressed by the administration of the AMPA/kainate receptor antagonist CNQX. This result suggests that the regulatory effect of glutamate on nesfatin-1 neurons is unique. In our previous study, we showed that 2-h refeeding after 48-h fasting induced pSTAT5 expression in the neuronostatin neurons in the anterior hypothalamic periventricular nucleus and this expression was significantly suppressed by glutamate receptor antagonist (CNQX) (42). This information supports that a peripheral factor, such as refeeding, was effective in regulating the functions of nesfatin-1 neurons and that this effect was mediated through the glutamatergic system.

CNQX application to the fasting group was considered while designing the presented study. But in preliminary experiments, c-fos positivity was only 1% in nesfatin neurons in the fasting group. We did not use this group because we predicted that CNQX administration before fasting will not significantly change the activation of nesfatin neurons.

The hypothalamus plays an important role in regulating food intake and glucose homeostasis (33). Glucose is the primary fuel for the brain and enters the CNS with the high affinity glucose transporter (GLUT) type 1 (2). Glucosensitive and glucoresponsive neurons are found in the hypothalamic nuclei and participate in glucose homeostasis (33). Glucose sensitive neurons are glucose-activated or glucose-inhibited neurons. Glucose sensitive neurons are found in the hypothalamic nuclei such as ARC, PVN, SON, VMH, and lateral hypothalamus, and respond to blood glucose changes (33). Neuronal activation of the hypothalamic nuclei after glucose infusion has been demonstrated using the c-Fos as the neuronal activation marker. The number of c-Fos-positive neurons peaks in 90 minutes after stimulus as a response to acute physiological stimuli. After intracarotid glucose injection, c-Fos, immunoreactive neurons are detected in PVN and VMH. The number of c-Fos-positive neurons in ARC and PVN was significantly higher than in the saline group (33). We not only found that glucose injection after fasting dramatically increased the number of c-Fos immunoreactive-nesfatin-1 neurons in the SON but also determined that the number of active nesfatin-1 neurons was significantly reduced after glutamate receptor

antagonist (CNQX) injections. This information suggests that nesfatin-1 neurons are glucose sensitive neurons and glutamatergic system regulates this mechanism.

In the present study, the increase in the number of activated nesfatin-1 neurons was observed to be about 66-fold with refeeding and 55-fold with glucose injection after fasting. These results suggest that refeeding and/or glucose injection after fasting led to activation of nesfatin-1 neurons and this activation was mediated by the intracellular pathway with c-Fos. This data also supports the possibility of an intracellular pathway using c-Fos as the trancription factor, has a role in the regulation of the physiological activities of nesfatin-1 neurons. Furthermore, the number of activated nesfatin-1 neurons was significantly suppressed by glutamate receptor antagonist (CNQX) application. To our knowledge, this is the first report that has shown the regulatory effect of glutamatergic system on nesfatin-1 neurons. Our previous studies supports that glutamate receptor antagonist (CNQX) can reach the central nervous system and affect the neuronal activation (13, 18, 34, 42). Also, our data showed that nesfatin-1 neurons express glutamate receptor subunits (18). Taken together, we can suggest that glutamatergic signals may reach the nesfatin-1 neurons directly. Another possibility of course is that, an indirect mechanism involving glutamate-receptive interneurons may play a role in the regulation of nesfatinergic system.

It is important to implicate that the immunohistochemistry is limited to the detectable levels of the proteins that are analyzed in this study. Our results only include the nesfatin-1 neurons that can be identified by immunohistochemistry, and the numbers provided in this study only represents these neurons.

CONCLUSIONS

In conclusion, this study demonstrated that refeeding and glucose intake highly selectively activates nesfatin-1 neurons in the SON. This activation suggests that nesfatin-1 neurons in the SON may play a role in the regulation of feeding behavior and glucose metabolism. The results also demonstrated that glutamate antagonist CNQX can specifically block this activation, suggesting that this effect was mediated through the glutamatergic system.

REFERENCES

1. Altarejos JY, Montminy M. CREB and the CRTC co-activators: sensors for hormonal and metabolic signals. Nature Reviews Molecular Cell Biology. 2011; 12(3): 141–151.
2. Alvarsson A, Stanley SA. Remote control of glucose-sensing neurons to analyze glucose metabolism. American Journal of Physiology - Endocrinology and Metabolism. 2018; 315(3): E327–E339.
3. Atsuchi K, Asakawa A, Ushikai M, et al. Centrally administered nesfatin-1 inhibits feeding behaviour and gastroduodenal motility in mice. Neuroreport. 2010;21 (15): 1008–11.
4. Balazs R. Trophic Effect of Glutamate. Current Topics in Medicinal Chemistry. 2006; 6(10): 961–968.
5. Blanco AM, Velasco C, Bertucci JI, et al. Nesfatin-1 regulates feeding, glucosensing and lipid metabolism in rainbow trout. Frontiers in Endocrinology. 2018; 9: 1–12.
6. Brailoiu GC, Dun SL, Brailoiu E, et al. Nesfatin-1: distribution and interaction with a G protein-coupled receptor in the rat brain. Endocrinology. 2007; 148(10): 5088-5094.
7. Brann DW. Glutamate: A Major Excitatory Transmitter in Neuroendocrine Regulation. Neuroendocrinology. 1995; 61(3): 213–225.
8. Brann DW, Mahesh VB. Excitatory Amino Acids: Function and Significance in Reproduction and Neuroendocrine Regulation. Frontiers in Neuroendocrinology. 1994; 15(1): 3–49.
9. Collingridge GL, Olsen RW, Peters J, et al. A nomenclature for ligand-gated ion channels. Neuropharmacology. 2009; 56(1): 2–5.
10. Cull-Candy S, Brickley S, Farrant M. NMDA receptor subunits: Diversity, development and disease. Current Opinion in Neurobiology. 2001; 11(3): 327–335.
11. Dong J, Guan HZ, Jiang ZY, et al. Nesfatin-1 influences the excitability of glucosensing neurons in the dorsal vagal complex and inhibits food intake. PLoS ONE. 2014; 9(6): 2–10.
12. Eyigor O, Centers A, Jennes L. Distribution of ionotropic glutamate receptor subunit mRNAs in the rat hypothalamus. The Journal of comparative neurology. 2001; 434(1): 101–24.
13. Eyigor O, Minbay Z, Cavusoglu I. Activation of orexin neurons through non-NMDA glutamate receptors evidenced by c-Fos immunohistochemistry. Endocrine. 2010; 37(1): 167–172.
14. Eyigor O, Minbay Z, Cavusoglu I, et al. Localization of kainate receptor subunit GluR5-immunoreactive cells in the rat hypothalamus. Molecular Brain Research. 2005; 136(1–2): 38–44.
15. Fan XT, Tian Z, Li SZ, et al. Ghrelin receptor is required for the effect of nesfatin-1 on glucose metabolism. Frontiers in Endocrinology. 2018; 9: 1–13.
16. Goebel M, Stengel A, Wang L, et al. Central nesfatin-1 reduces the nocturnal food intake in mice by reducing meal size and increasing inter-meal intervals. Peptides. 2011; 32(1): 36–43.
17. Gok-Yurtseven D, Kafa IM, Minbay Z, et al. Glutamatergic activation of A1 and A2 noradrenergic neurons in the rat brain stem. Croatian Medical Journal. 2019; 60: 352-360.
18. Gok-Yurtseven D, Serter-Kocoglu S, Minbay Z, et al. Immunohistochemical evidence for glutamatergic regulation of nesfatin-1 neurons in the rat hypothalamus. Brain Sciences. 2020; 10(9): 1–18.
19. Gonzalez R, Kerbel B, Chun A, et al. Molecular, cellular and physiological evidences for the anorexigenic actions of nesfatin-1 in goldfish. PloS one. 2010; 5(12): e15201.
20. Hoffman GE, Lyo D. Anatomical markers of activity in neuroendocrine systems: are we all "fos-ed out"? Journal of neuroendocrinology. 2002; 14(4): 259–68.
21. Huo L, Gamber K, Greeley S, et al. Leptin-dependent control of glucose balance and locomotor activity by POMC neurons. Cell Metabolism. 2009; 9: 537–547.
22. Kew JNC, Kemp JA. Ionotropic and metabotropic glutamate receptor structure and pharmacology. Psychopharmacology. 2005; 179(1): 4–29.
23. Kohno D, Nakata M, Maejima Y, et al. Nesfatin-1 neurons in paraventricular and supraoptic nuclei of the rat hypothalamus coexpress oxytocin and vasopressin and are activated by refeeding. Endocrinology. 2008; 149(3): 1295–1301.
24. Köles L, Wirkner K, Illes P. Modulation of ionotropic glutamate receptor channels. Neurochemical Research. 2001; 26(8–9): 925–932.
25. Könczöl K, Pintér O, Ferenczi S, et al. Nesfatin-1 exerts long-term effect on food intake and body temperature. International journal of obesity. 2012; 36(12): 1514–21.
26. Lents CA, Barb CR, Hausman GJ, et al. Effects of nesfatin-1 on food intake and LH secretion in prepubertal gilts and genomic association of the porcine NUCB2 gene with growth traits. Domestic animal endocrinology. 2013; 45(2): 89–97.
27. Lerma J, Paternain A V., Rodríguez-Moreno A, et al. Molecular physiology of kainate receptors. Physiological Reviews. 2001; 81(3): 971–998.

28. Li Z, Gao L, Tang H, et al. Peripheral Effects of Nesfatin-1 on Glucose Homeostasis. PLoS ONE. 2013; 8(8).
29. Maejima Y, Sedbazar U, Suyama S, et al. Nesfatin-1-Regulated Oxytocinergic Signaling in the Paraventricular Nucleus Causes Anorexia through a Leptin-Independent Melanocortin Pathway. Cell Metabolism. 2009; 10(5): 355–365.
30. Mayer ML. Structural biology of glutamate receptor ion channel complexes. Current Opinion in Structural Biology. 2016; 41: 119–127.
31. Meeker RB, Greenwood RS, Hayward JN. Glutamate Is the Major Excitatory Transmitter in the Supraoptic Nuclei. Annals of the New York Academy of Sciences. 1993; 689(1): 636–639.
32. Meeker RB, McGinnis S, Greenwood RS, et al. Increased hypothalamic glutamate receptors induced by water deprivation. Neuroendocrinology. 1994; 60(5): 477–485.
33. Miñana-Solis MDC, Angeles-Castellanos M, Buijs RM, et al. Altered Fos immunoreactivity in the hypothalamus after glucose administration in pre-and post-weaning malnourished rats. Nutritional Neuroscience. 2010; 13(4): 152–160.
34. Minbay FZ, Eyigor O, Çavusoglu I. Kainic acid activates oxytocinergic neurons through non-NMDA glutamate receptors. International Journal of Neuroscience. 2006; 116(5): 587–600.
35. Oh-I S, Shimizu H, Satoh T, et al. Identification of nesfatin-1 as a satiety molecule in the hypothalamus. Nature. 2006; 443(7112): 709–12.
36. Ozawa S, Kamiya H, Tsuzuki K. Glutamate receptors in the mammalian central nervous system. Progress in Neurobiology. 1998; 54(5): 581–618.
37. Pachernegg S, Strutz-Seebohm N, Hollmann M. GluN3 subunit-containing NMDA receptors: Not just one-trick ponies. Trends in Neurosciences. 2012; 35(4): 240–249.
38. Paoletti P. Molecular basis of NMDA receptor functional diversity. European Journal of Neuroscience. 2011; 33(8): 1351–1365.
39. Paxinos G, Watson C. The rat brain in stereotaxic coordinates. London Acad Press. 2009.
40. Samson WK, Zhang J V, Avsian-Kretchmer O, et al. Neuronostatin encoded by the somatostatin gene regulates neuronal, cardiovascular, and metabolic functions. Journal of Biological Chemistry. 2008; 283(46): 31949–31959.
41. Schalla MA, Stengel A. Current Understanding of the Role of Nesfatin-1. Journal of the Endocrine Society. 2018; 2(10): 1188–1206.
42. Serter Kocoglu S, Gok Yurtseven D, Cakir C, et al. Glutamatergic Activation of Neuronostatin Neurons in the Periventricular Nucleus of the Hypothalamus. Brain Sciences. 2020; 10(4): 217.
43. Stengel A, Goebel M, Taché Y. Nesfatin-1: a novel inhibitory regulator of food intake and body weight. Obesity reviews : an official journal of the International Association for the Study of Obesity. 2011; 12(4): 261–71.
44. Stengel A, Goebel M, Wang L, et al. Central nesfatin-1 reduces dark-phase food intake and gastric emptying in rats: Differential role of corticotropin-releasing factor2 receptor. Endocrinology. 2009; 150(11): 4911–4919.
45. Tse YC, Yung KKL. Cellular expression of ionotropic glutamate receptor subunits in subpopulations of neurons in the rat substantia nigra pars reticulata. Brain Research. 2000; 854(1–2): 57–69.
46. Uner A, Gonçalves GHM, Li W, et al. The role of GluN2A and GluN2B NMDA receptor subunits in AgRP and POMC neurons on body weight and glucose homeostasis. Molecular metabolism. 2015; 4: 678–691.
47. Uner A, Keçik O, Quaresma PGF, et al. Role of POMC and AgRP neuronal activities on glycaemia in mice. Scentific reports. 2019; 9(1): 13068.
48. Yosten GLC, Redlinger L, Samson WK. Evidence for a Role of Endogenous Nesfatin-1 in the Control of Water Drinking. Journal of Neuroendocrinology. 2012; 24(7): 1078–1084.
49. Yosten GLC, Samson WK. Nesfatin-1 exerts cardiovascular actions in brain: Possible interaction with the central melanocortin system. American Journal of Physiology - Regulatory Integrative and Comparative Physiology. 2009; 297(2): 330–336.
50. Yosten GLC, Samson WK. The anorexigenic and hypertensive effects of nesfatin-1 are reversed by pretreatment with an oxytocin receptor antagonist. American Journal of Physiology - Regulatory Integrative and Comparative Physiology. 2010; 298(6).
51. Yuan JH, Chen X, Dong J, et al. Nesfatin-1 in the lateral parabrachial nucleus inhibits food intake, modulates excitability of glucosensing neurons, and enhances UCP1 expression in brown adipose tissue. Frontiers in Physiology. 2017; 8: 1–11.
52. Zhao J bing, Zhang Y, Li G zhao, et al. Activation of JAK2/STAT pathway in cerebral cortex after experimental traumatic brain injury of rats. Neuroscience Letters. 2011; 498(2): 147–152.

Table-I. The percentages of c-Fos-positive nesfatin-1 neurons relative to all nesfatin-1 neurons in all groups (mean±standard deviation). P values pertain to the comparison with the refeeding and glucose-injected groups.

	c-Fos expression (%)	
	Nesfatin-1 neurons	**P**
Fasting	1.00±0.94	= 0.00
Refeeding	66.65±9.82	
CNQX+Refeeding	25.15±17.22	< 0.009
Glucose Control	1.13±0.66	< 0.01
Glucose	55.7±21.46	
CNQX+Glucose	6.32±9.60	< 0.01

*CNQX – cyano-7-nitroquinoxaline-2,3-dione

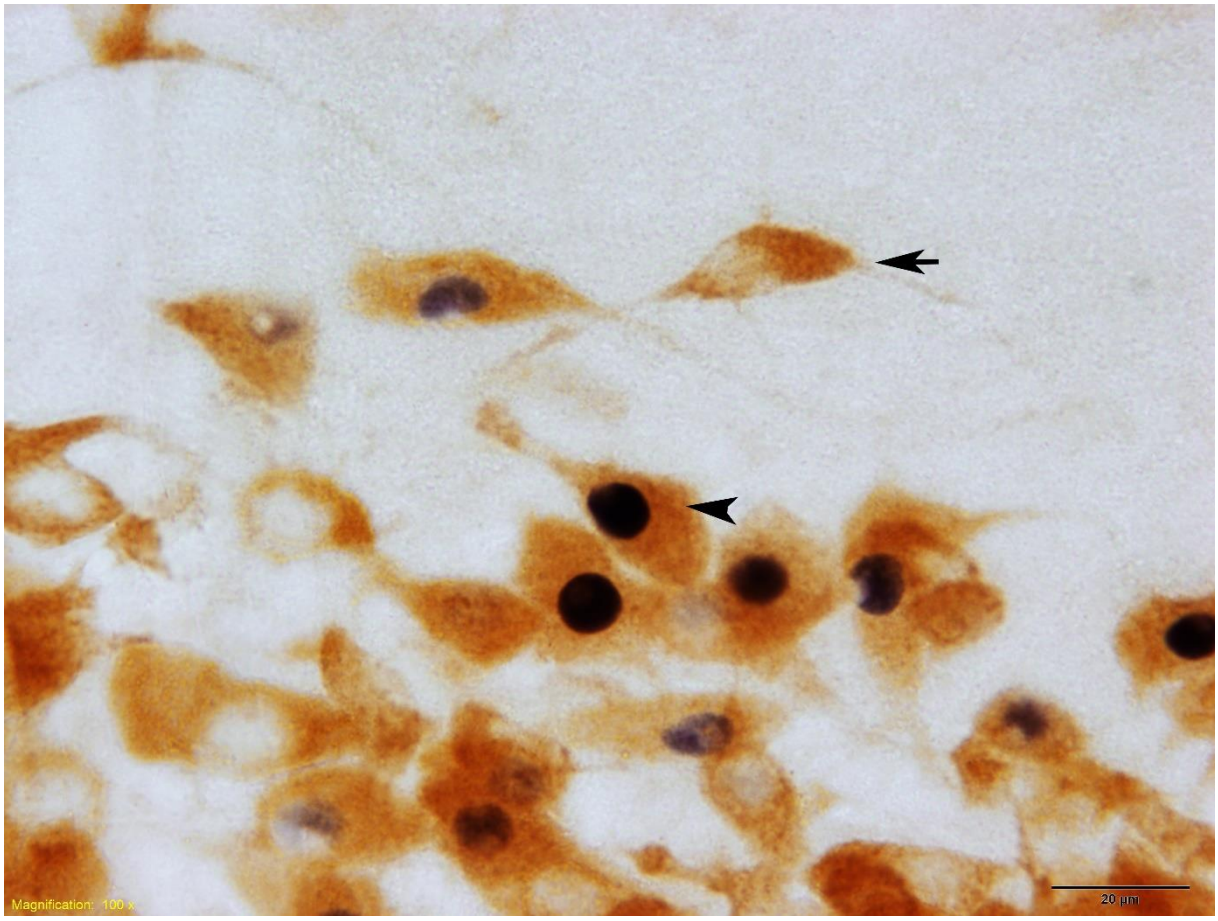
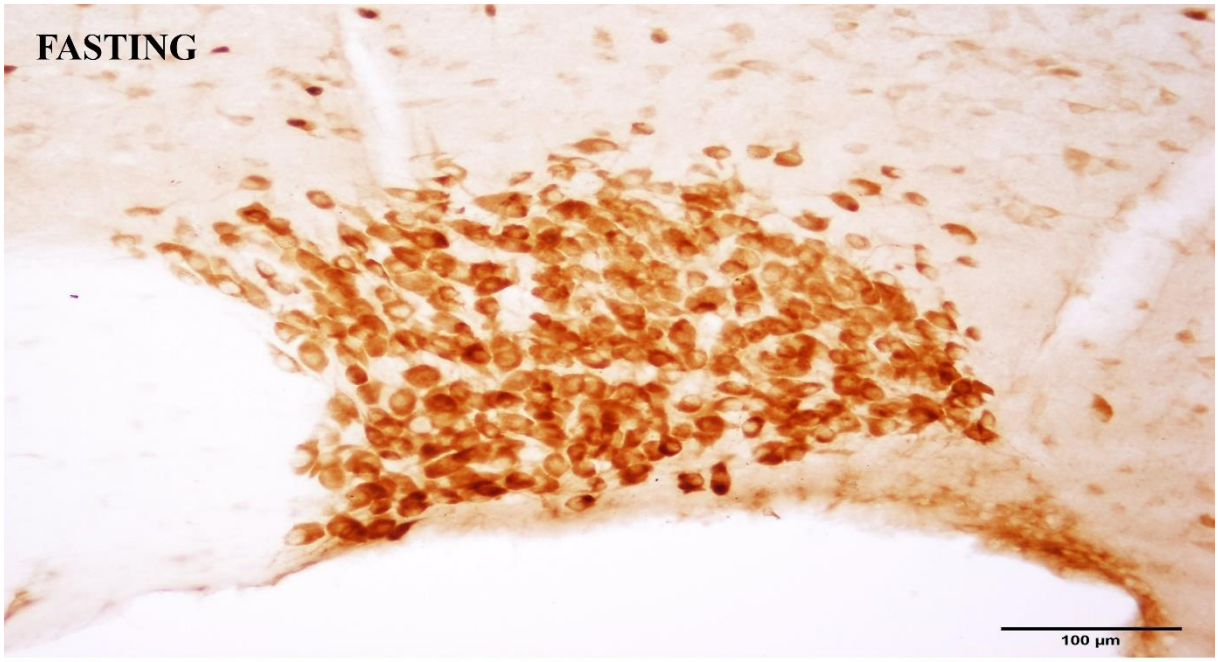
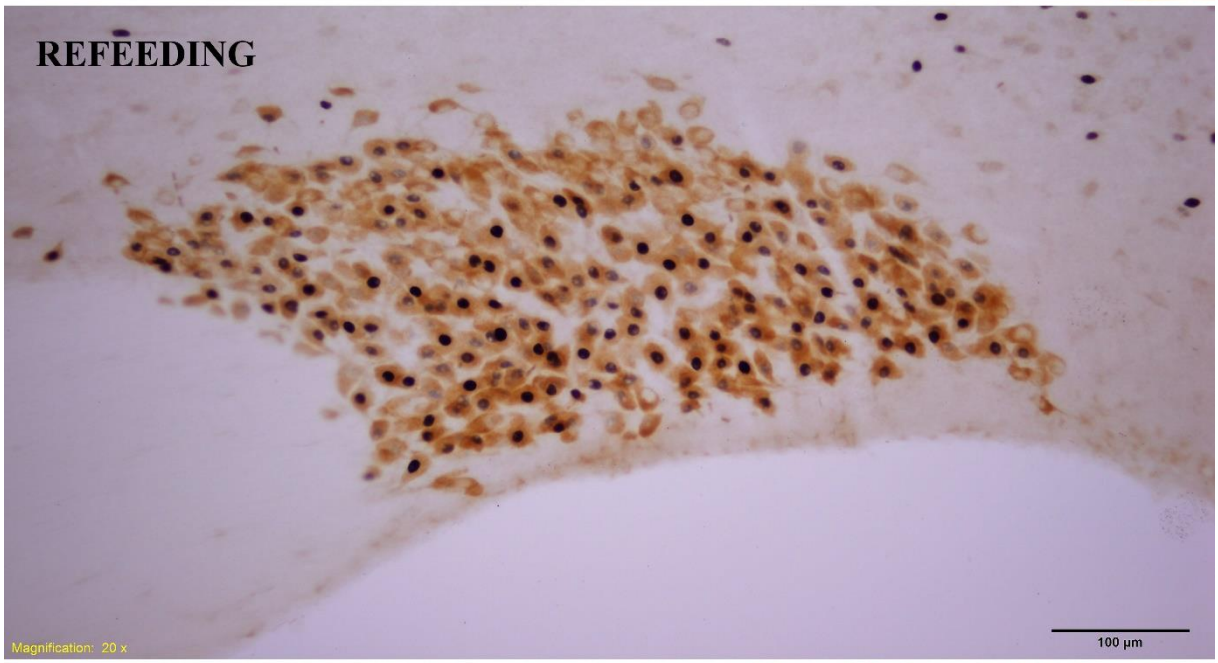


Figure 1. Representative c-Fos-positive and c-Fos-negative nesfatin-1 neurons. The arrow-head indicates c-Fos positivity (black) in the nucleus of a nesfatin-1-positive (brown) neuron. The arrow indicates a representative c-Fos-negative nesfatin-1 neuron.


FASTING
100 µm


REFEEDING
Magnification: 20 x
100 µm

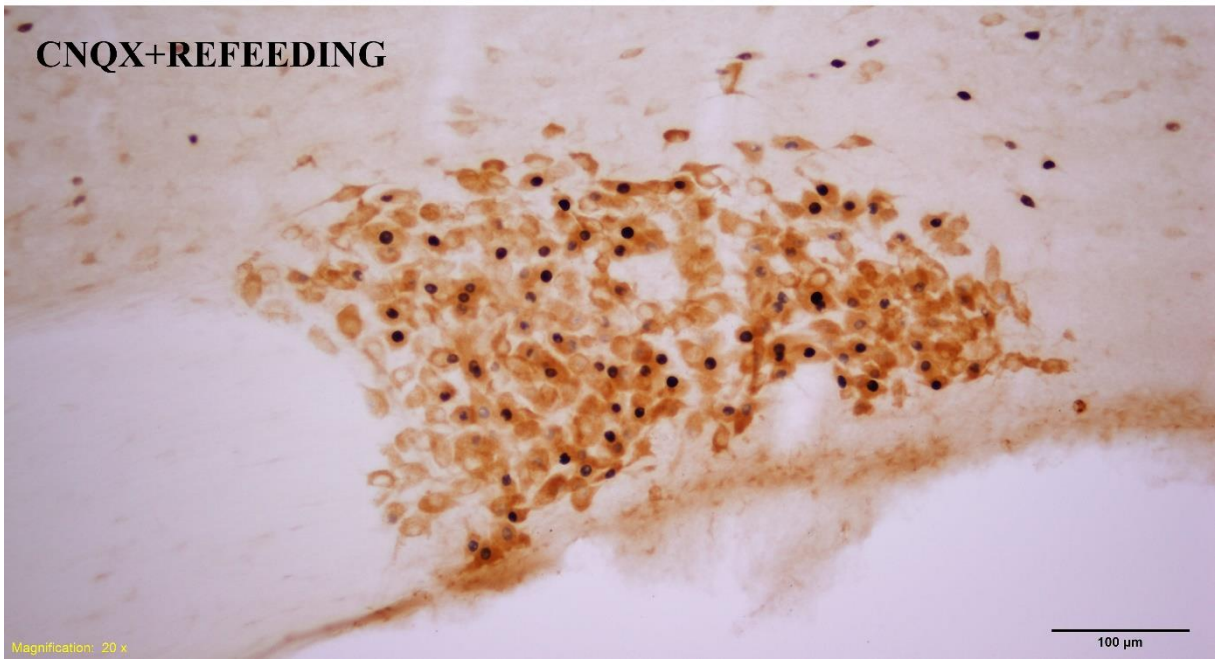

CNQX+REFEEDING
Magnification: 20 x
100 µm

Figure 2. Effect of CNQX, a non-NMDA glutamate antagonist, in subjects stimulated by refeeding after fasting. Double-immunohistochemical staining of c-Fos and nesfatin-1 in SON after 48 h fasting (upper panel), after 2h refeeding following 48 h fasting (middle panel) and CNQX-treated subjects before feeding (lower panel).

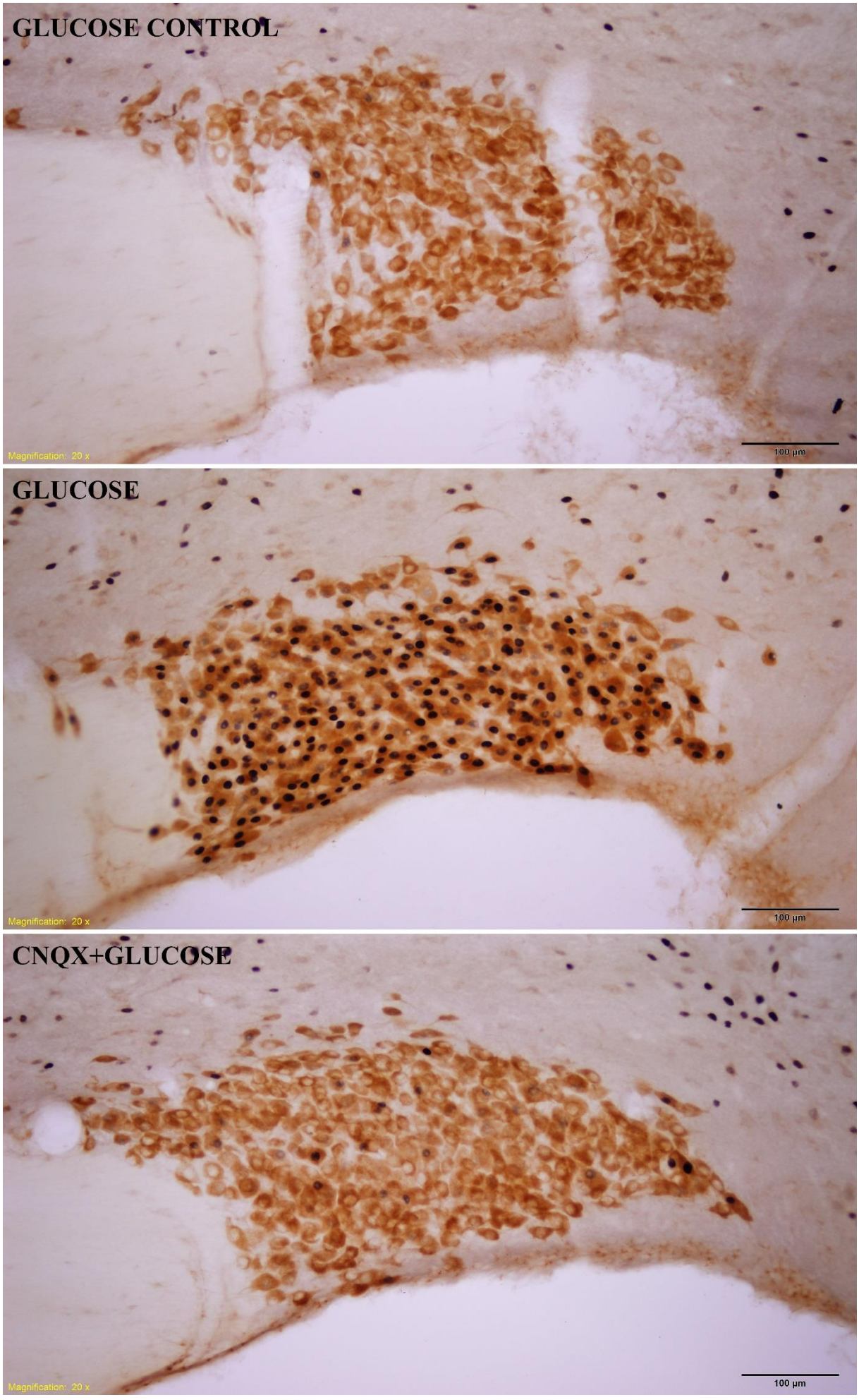

GLUCOSE CONTROL
Magnification: 20 x
100 µm
GLUCOSE
Magnification: 20 x
100 µm
CNQX+GLUCOSE
Magnification: 20 x
100 µm

Figure 3. Effect of CNQX, a non-NMDA glutamate antagonist, in subjects stimulated by glucose injection. Double-immunohistochemical staining of c-Fos and nesfatin-1 in SON, after 48 h fasting; saline injection (upper panel), glucose injection (middle panel) and CNQX-treated subjects before glucose injection (lower panel).

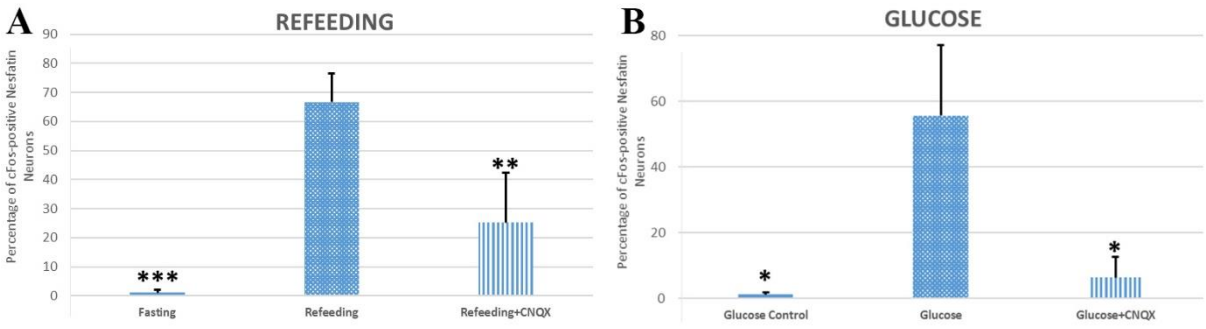


Figure 4. The percentages of c-Fos-positive nesfatin-1 neurons relative to all nesfatin-1 neurons. Effect of CNQX, a non-NMDA glutamate antagonist, in subjects stimulated by refeeding after fasting. There were significant differences between fasting-refeeding (***p < 0.001) groups and refeeding-antagonist groups (**p < 0.01) (**A**). Effect of CNQX, a non-NMDA glutamate antagonist, in subjects stimulated by glucose injection. There were significant differences between glucose control-glucose and glucose-antagonist (CNQX+glucose) groups (*p <0.05) (**B**).