Molecular mechanisms of the sedation and analgesia induced by xylazine on Wistar rats and PC12 cell

Jinghua ZHAO, Yiming ZHANG, Wenhan LIU, Yu CHEN, Daiyue CHANG, Xintong ZHANG, Tian CHANG, Qi WANG, Tao LIU and Li GAO

Heilongjiang Key Laboratory for Laboratory Animals and Comparative Medicine, College of Veterinary Medicine, Northeast Agriculture University, No. 600 Chang Jiang Road, Xiangfang District, Harbin 150030, China

Abstract: In veterinary clinics, xylazine is commonly used as a sedative, analgesic agent that produces muscle relaxation. In this study, we aimed to explore the mechanism of action of xylazine both in vivo and in vitro. After determining the optimal dose of xylazine, 35 male Wistar rats were divided into seven groups (n=5 per group), including a control group (saline) and xylazine administration groups. Then, at six time points after xylazine administration indicators were evaluated for changes. Moreover, PC12 cells were co-cultured with xylazine, and extracellular regulated protein kinase (ERK) siRNA and protein kinase A (PKA) siRNA were transfected into cells to identify changes of relevant indicators. Our data showed that xylazine influenced the level of adenosine triphosphate (ATP) ase and cyclic adenosine monophosphate (cAMP), and regulated the expression of GluR1, ERK, PKA, cAMP-response element binding protein (CREB), and brain derived neurotrophic factor (BDNF) in the nervous system. However, xylazine did not significantly affect the expression of GluR2 and protein kinase C (PKC). Together, these results indicated that xylazine might exert sedation and analgesia by regulating the PKA/ERK/CREB signaling pathway.

Key words: analgesia, PC12 cells, rat, sedation, xylazine

Introduction

Xylazine is commonly used in veterinary clinics for sedation and analgesia of animals. Xylazine can be used in combination with other agents to reduce the anaesthetic dose requirements for induction and maintenance of general anesthesia [11]. Previous studies have focused on the clinical effects of xylazine, however there are few reports that have focused on the underlying mechanism involved.

In the central nervous system, the AMPA receptor (AMPAR) mediates rapid excitatory synaptic transmission, and its dynamic expression in the postsynaptic membrane is associated with induction and maintenance of long-term potentiation (LTP) and long-term inhibition [20]. The AMPAR is a tetramer, containing of four subunits (GluR1–4). The AMPAR plays an important role in synaptic plasticity, and is involved in the induction and development of pain [14]. In previous studies, it has been indicated that GluR1 protein expression is reduced shortly after exposure to 1.8% isoflurane, however isoflurane increased GluR1 protein expression by inhibiting ubiquitination 7 days after exposure to anesthesia [22]. The GluR2 subunit plays a very important role in AMPAR activity through phosphorylation, and the lack of GluR2 leads to a decrease in synaptic strength [8]. Pro-
tein kinase A (PKA), protein kinase C (PKC), and extracellular regulated protein kinase (ERK) family protein kinases have been identified to play an important role in regulating nociceptive levels in the spinal dorsal horn. In a previous study, it was demonstrated that when culturing spinal dorsal horn neurons, protein kinase agonists regulated neuronal excitability and plasticity [12].

Cyclic adenosine monophosphate (cAMP)-response element binding protein (CREB) is a player in a variety of intracellular signaling pathways. Its phosphorylation level is directly related to the proliferation, differentiation, and apoptosis of nerve cells, and can promote gene expression of immediate early genes (IEGs), then regulated proteins associated with learning memory, cognition, LTP, and synaptic plasticity [9, 15]. The cascade of many upstream signals can lead to CREB phosphorylation, including the cAMP-PKA cascade, calmodulin-independent kinases II and IV (CaMKII/IV), and phospholipase C (PLC)–PKC cascade [13, 18]. CREB integrates different signals in multiple cascade signaling pathways, thereby making protein signaling a complex and flexible network system that regulates different target genomes at different developmental stages of neurons [17]. Sevoflurane-nitrous oxide resulted in down-regulation of the cAMP/CREB signaling pathway, causing cognitive deficits in aged rats and an increase in neuronal apoptosis [26].

Xylazine is a typical α2 adrenergic receptor agonist, and its receptor can affect the level of Na+, K+-ATPase activity of rat kidney, and the expression of ERK/MAPK/CREB and AMPAR signaling pathways of neurons [2, 29, 30]. However, the effects of xylazine on ATPase and cAMP content, AMPAR, related protein kinase, and transcription factors in the central nervous system are still unknown. Therefore, in this study, we investigated the mechanism of xylazine both in vitro and in vivo. In brief, rats were given xylazine and the expression of related indicators was determined at different time points. In vitro studies and gene interference studies were performed on PC12 cells, and the effects of PKA and ERK1/2 sites on the signaling pathway after xylazine exposure were explored. To provide guidance for clinical applications, the mechanism of action was studied at the molecular level.

### Materials and Methods

#### Animals

Male Wistar rats, 8–10 weeks, weighing 225–265 g, were purchased from the Animal Experiment Center of the Second Hospital of the Harbin Medical University (Harbin, China). Rats were housed in the laboratory for 2 weeks prior to the experiment to accommodate the laboratory environment. All procedures involving animals were approved by the Laboratory Animal Care and Use Committee of Northeast Agricultural University (Harbin, China) and performed in accordance with relevant guidelines (Approval number: 1025).

#### Determination of the dose of xylazine for sedation and analgesia

This study was performed at three concentrations of xylazine: 35 mg/kg, 70 mg/kg, and 140 mg/kg (JiLin HuaMu Animal Pharmaceutical Co., Ltd., Changchun, China) for which xylazine was given by intraperitoneal administration (n=10 rats per dose). The percentage of righting reflex was observed after intraperitoneal administration of xylazine. If the righting reflex disappeared after the administration of xylazine, and rats did not respond with slight stimulation (clamping and acupuncture in the tail and claws), we considered that the rats entered sedation and analgesia. We combined the rats’ ratio of sedation and analgesia and if heart rate and respiratory rate drastically reduced to determine the optimal use dose. For moribund rats, euthanasia was carried out by cervical dislocation.

#### Animals groups and sample collection

Male Wistar rats were intraperitoneally injected with xylazine at a dose of 70 mg/kg (injection volume was 5 ml/kg body weight) and divided into 7 groups (n=5 per group): control group (normal saline group, C), 8 min after administration of xylazine (X1), righting reflex just disappeared (X2), righting reflex disappeared for 30 min (X3), righting reflex disappeared for 60 min (X4), righting reflex just recovered (X5), and righting reflex recovered for 30 min (X6). Rats in the control group were given normal saline intraperitoneally at a volume of 5 ml/kg. Rats in the control group were examined 8 min after injection of normal saline. Rats in the experimental groups were sampled at corresponding time points after injection of xylazine. Rats were sacrificed by cervical dislocation, the hippocampus was removed, and stored at −80°C.
**PC12 nerve cells and groupings**

PC12 nerve cells were obtained from the BeNa culture collection Co. (Beijing, China) and divided into 5 groups: blank control group (C), negative control group (Y), xylazine group (X), ERK siRNA group (ERKi), and PKA siRNA group (PKAi).

**Cell transfection**

Transfection experiments were performed using the Lipofectamin™ 2000 kit (Beyotime Institute of Biotechnology, Shanghai, China). Prior to transfection, PC12 cells were seeded in 96-well plates at a density of 4–5 × 10⁴ cells. Next, siRNA was added to serum-free medium (Opti-MEM) and mixed gently, then, Opti-MEM culture medium was diluted with the appropriate amount of Lipofectamine™ 2000 and allowed to stand for 5 min at room temperature. Lipofectamine™ 2000 and siRNA diluent were mixed (total volume 100 µl). The mixture was gently mixed and allowed to stand at room temperature for 20 min before adding the mixture to the cells. Cells were incubated at 37°C for 24–48 h, then harvested and used for RT-PCR and Western blot analysis.

**Measurement of cell viability using cell counting kit-8**

Cell viability was measured using the CCK-8 kit (Beyotime Institute of Biotechnology, Shanghai, China). A total of 100 µl (approximately 1 × 10⁵ cells) of cell suspension was added to wells of a 96-well plate. The plate was pre-incubated in the incubator for 24 h. Then, 100 µl of cell culture medium containing different concentrations of xylazine (0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4 µg/ml) was added to the plate. CCK-8 solution was added to each well at 3 h after adding xylazine, and incubated for 1–4 h. The absorbance at 450 nm was measured using a microplate reader (Bio-Tek Instruments, Thermo Fisher Scientific, Winooski, VT, USA). When the activity of PC12 cells reached about 50%, the concentration of xylazine was considered optimal.

**RT-PCR**

RNA was extracted from the rat hippocampus or PC12 cells using the trizol method. RNA was converted to cDNA using the TaKaRa reverse transcription kit (TaKaRa Biomedical Technology Co., Ltd., Beijing, China), stored at −20°C, then subjected to real-time quantitative PCR reaction. In brief, the reaction mixture consisted of 2 µl cDNA, 0.5 µl upstream primer, 0.5 µl downstream primer, 10 µl fluorescent dye (protected from light) and 7 µl DEPC H₂O and was centrifuged, then placed into the LightCycler 96 (Roche Life Sciences, Shanghai, China). Data was calculated using the 2⁻ΔΔCt method.

**Western blot analysis**

The hippocampus of rats as well as PC12 cells was lysed and total proteins were extracted. Then, gel electrophoresis was performed. Primary antibody dilution ratio: GluR1, GluR2, p-ERK1/2/ERK1/2, p-PKA/PKA, p-PKC/PKC, p-CREB/CREB and brain derived neurotrophic factor (BDNF), diluted 1:2,000 (Absin Bioscience Inc., Shanghai, China), incubated overnight at 4°C. After washing with TBST, membranes were incubated with goat anti-rabbit IgG-HRP (1:3,000) at room temperature for 65 min. The expression of GluR1, GluR2, p-ERK1/2/ERK1/2, p-PKA/PKA, p-PKC/PKC, p-CREB/CREB, and BDNF proteins was visualized by an Amer sham Imager 600 (General Electric Co., Pittsburgh, PA, USA). Image results were analyzed using Image J software (National Institutes of Health, Bethesda, MD, USA).

**Detection of related enzyme activities in hippocampus**

Levels of Na⁺-K⁺-ATPase, Ca²⁺-Mg²⁺-ATPase, and cAMP were determined using ATPase and cAMP kits (Nanjing jiancheng Bioengineering Institute, Nanjing, China). Tissue homogenates were placed in PBS, then centrifuged for 5 min (5,000 r/min) at 4°C. Supernatant was collected and enzyme activities were tested according to the kit instructions.

**Statistical analysis**

Statistical analysis was performed using GraphPad Prism 7.0 software (GraphPad Software Inc., San Diego, CA, USA). After normal distribution and homogeneity test of variance, data were analyzed by one-way ANOVA and Tukey’s Post Hoc test. Test results were expressed as the mean ± SD. P<0.05 was considered statistically significant.

### Results

**Identifying the optimal dose of xylazine in rats**

In this study, we evaluated the effect and lethal ratio of xylazine after administration in rats. At a xylazine dose of 35 mg/kg, the ratio of sedation and analgesia was 40%, and at a dose of 70 mg/kg, the ratio of sedation
and analgesia was 90% and no rats were moribund. However, at a dose of 140 mg/kg, the ratio of sedation and analgesia was 100%, and four rats moribund. Based on these findings, we selected 70 mg/kg as the optimal dose of xylazine in rats (Table 1).

CCK-8 test in PC12 cells

The CCK-8 study showed that when a xylazine dose of 1.0 µg/ml was used in cells, the cell viability was 61%. Therefore, 1.0 µg/ml of xylazine was used in vitro studies (Fig. 1).

Effect of xylazine on enzyme activity in the rat hippocampus

The relevant enzyme activity in the rat hippocampus was determined after xylazine administration. The results showed that the level of Ca\(^{2+}\)-Mg\(^{2+}\)-ATPase and Na\(^+\)-K\(^+\)-ATPase in groups X1 and X2 was significantly lower when compared to that of group C (P<0.05), however it was increased in X3. No significant trends were observed in groups X3, X4, X5, and X6. The cAMP enzyme content in group X2 was significantly lower compared to that in group C (P<0.05), and the lowest content was observed in X2. No significant differences were observed between the other groups and group C (Fig. 2).

Results of related gene expression in the rat hippocampus after xylazine administration

The related genes expression of the rat hippocampus was determined after xylazine administration. We found that mRNA expression of GluR1 was significantly lower in groups X3, X4, X5, and X6 when compared to that in group C (P<0.05). No significant changes were observed between groups X3, X4, X5, and X6 in expression levels of GluR1 mRNA. The mRNA expression level of PKA was significantly lower (P<0.05) in groups X3, X4, X5, and X6 when compared with group C, and was the lowest in X3, and showed a gradual increasing trend. The mRNA expression of BDNF was significantly lower in groups X3, X4, and X5 compared to group C (P<0.05), and reached the lowest expression in X3, then returned to the normal level in X6. The mRNA expression of GluR2, ERK, PKC, and CREB were not significantly different from that of group C (P>0.05), and no significant changes were observed between each time point (Fig. 3).

Results of related protein expression of the rat hippocampus after xylazine administration

After xylazine administration, the rat protein level of GluR1, GluR2, p-ERK1/2/ERK1/2, p-PKA/PKA, p-PKC/PKC, p-CREB/CREB, and BDNF in the hippocampus was determined. It was found that the protein expression of GluR1 was significantly lower in groups X1, X2, X3, X4, X5, and X6 groups compared to group C (P<0.05). The lowest level was observed in X4, and then slowly increased. PKA levels were significantly changed in groups X3, X4, and X5 compared to group C (P<0.05), and the lowest level was observed in X3. The level of p-PKA was significantly different in X3 compared with group C (P<0.05). The level of p-ERK was significantly lower in groups X2 and X3 compared to group C (P<0.05), and reached the lowest level in X3.

Table 1. Results of the dose screening experiment on rats (n=10)

| Groups (n=10) | Xylazine (mg/kg) | Righting reflex | Moribund state | Sedation ratio |
|--------------|-----------------|----------------|----------------|---------------|
|              |                 | Yes | No |                |               |
| 1            | 35              | 6   | 4  | 0              | 40%           |
| 2            | 70              | 1   | 9  | 0              | 90%           |
| 3            | 140             | 0   | 10 | 4              | 100%          |

The righting reflex disappeared more than 1 min was judged as positive.

Fig. 1. The viability of the PC12 cells was determined using the CCK-8 assay. PC12 cells were incubated with different concentrations of xylazine (0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, and 1.4 µg/ml) for 3 h. Data was obtained from three independent experiments. Compared with xylazine (0 µg/ml), *P<0.05.
The mechanism of xylazine

The effect of xylazine on related gene expression levels in PC12 cells

The mRNA expression level of ERK was significantly decreased in groups X and ERKi when compared with group C ($P<0.05$). Moreover, the mRNA expression level of PKA was significantly decreased in groups X and PKAi when compared with group C ($P<0.05$). The gene expression level of ERK and PKA was significantly decreased in groups ERKi and PKAi when compared with group X ($P<0.05$). The gene expression level of CREB in groups X, ERKi, and PKAi was lower compared to that of group C ($P<0.05$), and expression of the CREB gene in groups ERKi and PKAi was significantly lower compared to that in group X ($P<0.05$). Furthermore, the mRNA expression level of BDNF in groups X, ERKi, and PKAi was significantly lower compared to that in group C ($P<0.05$), and that in group ERKi was significantly lower compared to that in group X ($P<0.05$). No significant differences were observed between group PKAi and group X (Fig. 5).
Fig. 4. Results of related protein expression in the rat hippocampus after xylazine administration. Rats in group C were intraperitoneally injected with normal saline, and rats in groups X1–X6 were sampled for hippocampus at six different time points after xylazine administration. Indexes were determined by Western blot analysis (A). Densitometric analyses are depicted in (B–L). Compared with group C, *P<0.05.

Fig. 5. The effect of xylazine on related gene expression level in PC12 cells. PC12 cells were divided into five groups: blank control group (C), negative control group (Y), xylazine group (X), extracellular regulated protein kinase (ERK) siRNA group (ERKi), and protein kinase A (PKA) siRNA group (PKAi). Compared with group C, *P<0.05. Compared with group X, ▲P<0.05.
The effect of xylazine on related protein expression levels in PC12 cells

The protein expression level of ERK and p-ERK was significantly lower in group ERKi compared to that in group C ($P<0.05$), and the ERK level in group ERKi was significantly lower compared to that in group X ($P<0.05$). In addition, the p-ERK level in group PKAi was significantly reduced compared to group X ($P<0.05$). The protein expression level of PKA, CREB, and BDNF in groups X, ERKi, and PKAi was significantly lower compared to that in group C ($P<0.05$). Moreover, the level of p-CREB in group PKAi was significantly decreased from that in group C ($P<0.05$), and the PKA protein expression in group PKAi was significantly decreased from that in group X ($P<0.05$). The expression of p-PKA protein in group ERKi was significantly increased from group X ($P<0.05$). The expression of CREB protein in the group PKAi was significantly lower compared to that in group X ($P<0.05$). No significant differences in the protein expression of BDNF were observed between groups ERKi and PKAi when compared to group X (Fig. 6).

Discussion

It has previously been published that some rats are anesthetized at a dose of 87 mg/kg of ketamine and 13 mg/kg of xylazine, and increasing that dose 3-fold is still considered significantly safe in rats [24]. In order to eliminate interference of other anesthetics for detection of the mechanism of xylazine, we used single xylazine in rats in this experiment. We found that when the dose of xylazine in rats was 140 mg/kg, severe inhibition of the central nervous system, cardiovascular system and
respiratory system was observed, resulting in a significant decrease in heart rate and respiration, finally leading to moribundity. Due to individual differences, 4 rats died in this study, and 6 rats finally woke up when the dose of xylazine was 140 mg/kg. We found that 70 mg/kg of xylazine achieved a safe and stable sedation and analgesia effect. and duration lasted for 3–4 h (see Supplementary Table S1 and Supplementary Fig. S1). We also found rats injected with mixture of ketamine (75 mg/kg) and xylazine (20 mg/kg) were anesthetized for 90 min (see Supplementary Table S2). In in vitro studies, most anesthetics produce cytotoxic effects when administered at an anesthetic dose, including ketamine and isoflurane [3, 21]. We used 1.0 µg/ml as the working concentration of xylazine in vitro experiments with cell viability of 61%, because the drug-induced cell activity did not have a practical research value when it was too high or too low. Thus, a drug dose was chosen that produced modest cellular activity.

ATPase is a protease that is present in tissue cells and organelle membranes. ATPase plays an important role in material transport, energy conversion, information transmission, maintenance of cell membrane integrity, and tissue metabolism. Related studies on the relationship between anesthesia and information transduction has shown that various anesthetics caused changes in Na⁺-K⁺-ATPase and Ca²⁺-Mg²⁺-ATPase activities in several brain regions during anesthesia [6, 23]. Propofol inhibited ATP-sensitive potassium channels in cardiomyocytes, and this inhibition was attenuated by intracellular MgADP and protons [27]. The results of our study showed that levels of Na⁺-K⁺-ATPase, Ca²⁺-Mg²⁺-ATPase, and cAMP in the rat hippocampus decreased to the lowest in X2, but increased in X3 after xylazine administration. It could be speculated that xylazine mainly affected related enzymes in the early stage of sedation and analgesia. After entering deep sedation, the content of related enzymes did not significantly change.

Anesthetics alter the expression of neurotransmitters and neurotrophic factors, and then act on membrane receptors, such as the neurotrophic factor tyrosine kinase receptor type 2 (TrkB), AMPA receptor, and N-methyl-D-aspartic acid (NMDA) receptor, which then regulates almost all proteins in the body through gene regulation, thereby changing the homeostasis of the neuronal circuit [28]. After remifentanil injection, GluR1 expression was increased and GluR2 expression was decreased in the dorsal horn of the spinal cord. It was hypothesized that GluR1 and GluR2 transport may be one of the reasons of hyperalgesia caused by remifentanil [25]. Acute administration of morphine altered the subcellular distribution of AMPAR subunit (GluR1 and GluR2) in mouse neuronal dendrites [4]. After xylazine administration, the gene expression of GluR1 in the hippocampus significantly decreased in groups X3, X4, X5, and X6 when compared to group C. In addition, the protein expression was significantly decreased, but the changes in gene and protein expression of GluR2 were not significant. Therefore, we hypothesized that xylazine affected the transport of GluR1 and GluR2 in the central nervous system. Alternatively, it only affected GluR1, but had no effect on GluR2. Further exploration will be needed to confirm this.

An increase in the activity of PKA can result in CREB activation, which can occur both on the cell surface and in the nucleus [7]. After xylazine administration, the protein expression of p-ERK, PKA, and p-PKA in the hippocampus was significantly decreased, however no significant effect on the gene and protein expression of PKC was observed. We suspected that the PKC pathway did not participate in the regulation of xylazine, or PKC-mediated expression mechanism had not been activated at the testing time during this study. In vitro studies using PC12 nerve cells also showed that xylazine inhibited the expression of ERK and PKA sites.

The in vitro studies showed that CREB may be involved in the regulation of cell proliferation of neural progenitor [9]. Activation of the cAMP-CREB cascade signaling pathway promotes proliferation, maturation, and survival of hippocampal neonatal neurons and plays a key role in many other aspects of the nervous system, however it does not play a key role in the maturation of mature neurons [10]. CREB is phosphorylated at the Ser-133 site in a neurotrophic-dependent manner (see Fig. 7). Destruction of the Creb1 gene in the brains of developing and adult mice induces neuron apoptosis after mitosis, therefore it is speculated that there is a direct relationship between neurodegenerative diseases and CREB, such as Alzheimer’s disease and depression [16].

BDNF is the most abundant and widely expressed neurotrophic factor in the mammalian nervous system, and is an important target protein of p-CREB, which ultimately changes various biological effects [1]. Many studies have confirmed that activation of the cAMP-CREB pathway increased the expression of BDNF in the
MECHANISM OF XYLAZINE

359

It has previously been suggested that neurotrophic proteins, such as BDNF may be located downstream of CREB rather than upstream, and CREB regulates the expression of neurotrophic factors, eventually resulting in complex biological effects [5]. In this study, we found that expression of the BDNF gene and protein in the hippocampus was significantly decreased after xylazine administration, and the protein expression of CREB and p-CREB was also significantly decreased. However, gene expression was not significantly changed, therefore it was speculated that xylazine played a role in post-transcriptional regulation in the CREB site. Cell experiments showed that the expression of CREB and BDNF genes and protein decreased after xylazine administration, thereby further validating the key role of CREB and BDNF in the nervous system. Using gene interference technology, it was verified that ERK1/2 and PKA could regulate the expression of CREB and affect the downstream index of CREB, indicating that xylazine produced sedation and analgesia by inhibiting ERK/PKA/CREB pathway. Thus, this study could provide guidance for the study of other related drugs.

Conflict of Interest

There is no conflict of interest.

Acknowledgments

This study was funded by the National Natural Science Foundation of China (31572580 and 31372491).

References

1. Alhaider, I.A., Aleisa, A.M., Tran, T.T. and Alkadhi, K.A. 2011. Sleep deprivation prevents stimulation-induced increases of levels of P-CREB and BDNF: protection by caffeine. Mol. Cell. Neurosci. 46: 742–751. [Medline] [CrossRef]

2. Aperia, A., Ibarra, F., Svensson, L.B., Klee, C. and Greengard, P. 1992. Calcineurin mediates alpha-adrenergic stimulation of Na⁺,K⁺-ATPase activity in renal tubule cells. Proc. Natl. Acad. Sci. USA 89: 7394–7397. [Medline] [CrossRef]

3. Bakar, A.M., Park, S.W., Kim, M. and Lee, H.T. 2012. Isoflurane protects against human endothelial cell apoptosis by inducing sphingosine kinase-1 via ERK MAPK. Int. J. Mol. Sci. 13: 977–993. [Medline] [CrossRef]

4. Beckerman, M.A., Ogordnik, E. and Glass, M.J. 2013. Acute morphine associated alterations in the subcellular location of the AMPA-GluR1 receptor subunit in dendrites of neurons in the mouse central nucleus of the amygdala: comparisons and contrasts with other glutamate receptor subunits. Synapse 67: 692–704. [Medline] [CrossRef]

5. Bender, R.A., Lauterborn, J.C., Gall, C.M., Cariaga, W. and Baram, T.Z. 2001. Enhanced CREB phosphorylation in immature dentate gyrus granule cells precedes neurotrophin expression and indicates a specific role of CREB in granule cell differentiation. Eur. J. Neurosci. 13: 679–686. [Medline] [CrossRef]

6. Brazaluk, A.Z., Mozgovaia, E.N., Suchilina, S.P., Krapivina, O.V. and Alekseev, V.S. 1987. [Effect of combined anesthetics on the activity of various myocardium enzymes]. Ukr. Biokhim. Zh. 59: 79–82. (in Russian) [Medline]

7. Delghandi, M.P., Johannessen, M. and Moens, U. 2005. The cAMP signalling pathway activates CREB through PKA, p38 and MSK1 in NIH 3T3 cells. Cell. Signal. 17: 1343–1351. [Medline] [CrossRef]

8. Derkach, V.A., Oh, M.C., Guire, E.S. and Soderling, T.R. 2007. Regulatory mechanisms of AMPA receptors in syn-

Fig. 7. Adenylate cyclase (AC) is activated by stimulation of AMPA receptor (AMPAR), then regulates the second messenger of cAMP signaling. cAMP activates protein kinase A (PKA), protein kinase C (PKC), and extracellular regulated protein kinase (ERK), which leads to the release of related catalytic subunits. These subunits shuttle between nucleus and cytoplasm, phosphorylate cAMP-response element binding protein (CREB) at Ser133 site and regulate gene expression of brain derived neurotrophic factor (BDNF).
aptic plasticity. *Nat. Rev. Neurosci.* 8: 101–113. [Medline] [CrossRef]

9. Dworkin, S., Malaterre, J., Hollande, F., Darcy, P.K., Ramsay, R.G. and Mantamadiotis, T. 2009. cAMP response element binding protein is required for mouse neural progenitor cell survival and expansion. *Stem Cells* 27: 1347–1357. [Medline] [CrossRef]

10. Fujioka, T., Fujioka, A. and Duman, R.S. 2004. Activation of cAMP signaling facilitates the morphological maturation of newborn neurons in adult hippocampus. *J. Neurosci.* 24: 319–328. [Medline] [CrossRef]

11. Greene, S.A. 1999. Pros and cons of using α-2 agonists in small animal anesthesia practice. *Clin. Tech. Small Anim. Pract.* 14: 10–14. [Medline] [CrossRef]

12. Hu, H.J. and Gereau, R.W. 2003. ERK integrates PKA and PKC signaling in superficial dorsal horn neurons. II. Modulation of neuronal excitability. *J. Neurophysiol.* 90: 1680–1688. [Medline] [CrossRef]

13. Johannessen, M., Delghandi, M.P. and Moens, U. 2004. What turns CREB on? *Cell. Signal.* 16: 1211–1227. [Medline] [CrossRef]

14. Liu, S.Q. and Cull-Candy, S.G. 2000. Synaptic activity at calcium-permeable AMPA receptors induces a switch in receptor subtype. *Nature* 405: 454–458. [Medline] [CrossRef]

15. Lonze, B.E. and Ginty, D.D. 2002. Function and regulation of CREB family transcription factors in the nervous system. *Neuron* 35: 605–623. [Medline] [CrossRef]

16. Mantamadiotis, T., Lemberger, T., Bleckmann, S.C., Kern, H., Kretz, O., Martin Villalba, A., Tronche, F., Kellendonk, C., Gau, D., Kapfhammer, J., Otto, C., Schmid, W. and Schütz, G. 2002. Disruption of CREB function in brain leads to neurodegeneration. *Nat. Genet.* 31: 47–54. [Medline] [CrossRef]

17. Merz, K., Herold, S. and Lie, D.C. 2011. CREB in adult neurogenesis–master and partner in the development of adult-born neurons? *Eur. J. Neurosci.* 33: 1078–1086. [Medline] [CrossRef]

18. Nair, A., and Vaidya, V.A. 2006. Cyclic AMP response element binding protein and brain-derived neurotrophic factor: molecules that modulate our mood? *J. Biosci.* 31: 423–434. [Medline] [CrossRef]

19. Nibuya, M., Nestler, E.J. and Duman, R.S. 1996. Chronic antidepressant administration increases the expression of cAMP response element binding protein (CREB) in rat hippocampus. *J. Neurosci.* 16: 2365–2372. [Medline] [CrossRef]

20. Park, M., Penick, E.C., Edwards, J.G., Kauer, J.A. and Ehlers, M.D. 2004. Recycling endosomes supply AMPA re-ceptors for LTP. *Science* 305: 1972–1975. [Medline] [CrossRef]

21. Soriano, S.G., Liu, Q., Li, J., Liu, J.R., Han, X.H., Kanter, J.L., Bajic, D. and Ibla, J.C. 2010. Ketamine activates cell cycle signaling and apoptosis in the neonatal rat brain. *Anesthesiology* 112: 1155–1163. [Medline] [CrossRef]

22. Uchimoto, K., Miyazaki, T., Kamiya, Y., Mihara, T., Koyama, Y., Taguri, M., Imagawa, G., Takahashi, T. and Goto, T. 2014. Isoflurane impairs learning and hippocampal long-term potentiation via the saturation of synaptic plasticity. *Anesthesiology* 121: 302–310. [Medline] [CrossRef]

23. Vagin, I.E. and Kovrizhnykh, V.A. 1977. [Chemoluminescence during ATP hydrolysis by rat brain ATPase under the influence of agents of a narcotic nature]. *Farmakol. Toksikol.* 40: 28–31. (in Russian) [Medline]

24. Van Pelt, L.F. 1977. Ketamine and xylazine for surgical anesthesia in rats. *J. Am. Vet. Med. Assoc.* 171: 842–844. [Medline]

25. Wang, Z., Yuan, Y., Xie, K., Tang, X., Zhang, L., Ao, J., Li, N., Zhang, Y., Guo, S. and Wang, G. 2016. PICK1 regulates the expression and trafficking of AMPA receptors in remifentanil-induced hyperalgesia. *Anesth. Analg.* 123: 771–781. [Medline] [CrossRef]

26. Xiong, W.X., Zhou, G.X., Wang, B., Xue, Z.G., Wang, L., Sun, H.C. and Ge, S.J. 2013. Impaired spatial learning and memory after sevoflurane-nitrous oxide anesthesia in aged rats is associated with down-regulated cAMP/CREB signaling. *PLoS One* 8: e79408. [Medline] [CrossRef]

27. Yamada, H., Kawano, T., Tanaka, K., Yasui, S., Mawatari, K., Takahashi, A., Nakaya, Y. and Oshita, S. 2007. Effects of intracellular MgADP and acidification on the inhibition of cardiac sarcolemmal ATP-sensitive potassium channels by propofol. *J. Anesth.* 21: 472–479. [Medline] [CrossRef]

28. Yamashima, T. 2012. ‘PUFA-GPR40-CREB signaling’ hypothesis for the adult primate neurogenesis. *Prog. Lipid Res.* 51: 221–231. [Medline] [CrossRef]

29. Yuen, E.Y., Qin, L., Wei, J., Liu, W., Liu, A. and Yan, Z. 2014. Synergistic regulation of glutamatergic transmission by serotonin and norepinephrine reuptake inhibitors in prefrontal cortical neurons. *J. Biol. Chem.* 289: 25177–25185. [Medline] [CrossRef]