Modulation of Norepinephrine Release by Galanin in Rat Medulla Oblongata

Kazushi Tsuda, Seiko Tsuda, Ichiro Nishio, Yoshiaki Masuyama, and Menek Goldstein

Galanin is a biologically active neuropeptide composed of 29 amino acids that was isolated from porcine upper intestine.1 The galanin-like immunoreactivity in the brain is demonstrated not only in pigs, but also in rats, monkeys, and humans.2,3 Immunohistochemical studies have shown that galanin-immunoreactive neurons are present in the brain and spinal cord as well as in neuronal structures in several peripheral systems.2 Skofitsch and Jacobowitz4 have observed the quantitative distribution of galanin-like immunoreactivity in rat central nervous system and reported that high concentrations were determined in the median eminence, hypothalamus, locus coeruleus, medulla oblongata, and the caudal spinal trigeminal nucleus.

Recent evidence has suggested that galanin might actively participate in the central control of blood pressure and other cardiovascular functions because a high concentration of galanin has been found in the dorsal cardiovascular centers, particularly in the nucleus tractus solitarii of rat medulla oblongata.5 Häröstrand et al6 have observed that intracisternally injected galanin in the nanomolar range induced a significant hypotensive response in anesthetized rats and further reported that the combined treatment of galanin with neuropeptide Y resulted in a more prolonged hypotensive action. In several areas, galanin has been shown to coexist with other peptides or amines, such as γ-aminobutyric acid, norepinephrine, dopamine, serotonin, and acetylcholine.6-9 In many cases, the presence of coexisting peptides is believed to influence the release of classic neurotransmitters, although little is understood about the interactions between galanin and these transmitters at either presynaptic and postsynaptic sites. Nördstrom et al2-5 have reported that galanin significantly inhibits dopamine release from the rat median eminence and proposed that this peptide could act as a dopaminergic neuromodulator in this region. Fisone et al10 have found that galanin inhibits acetylcholine release in the ventral hippocampus of the rat both in vivo and in vitro. Recently, our colleagues have demonstrated that noradrenergic neurons containing galanin in locus coeruleus preferentially project to the hypothalamus, cerebral cortex, brain stem, and spinal cord of rats.9 Additionally, we have reported that galanin reduced the...
stimulation-evoked norepinephrine release in hypothalamus of Sprague-Dawley rats and further observed that galanin might stimulate the presynaptic α2-adrenergic receptors in the hypothalamus.10

It is now well known that the α2-adrenergic receptors are coupled with the inhibitory guanosine triphosphate (GTP)-binding protein (G, protein), which participates in the receptor-mediated transmembrane signaling by modulating adenylate cyclase activity.11,12 Pertussis toxin (islet activating protein) has been reported to inactivate the G protein by adenylate diphosphate (ADP) ribosylation of the α subunit, and this toxin has been widely used to determine the involvement of the G protein in the receptor-mediated inhibition of adenylate cyclase or in the overall cellular responses elicited by activation of the receptors.13,14

The presence of a high density of galanin in the nucleus tractus solitarii5 may support the idea that the peptide has a modulatory action on catecholamine release in this region and has a significant role in cardiovascular regulations. In the present study, in order to gain further insight into the regulatory mechanisms of galanin on central sympathetic nervous activity, we investigated the influences of galanin on norepinephrine release in rat medulla oblongata and further examined the effects of the α2-adrenergic agonist and antagonist as well as the effects of inactivation of the G protein by pertussis toxin on the modulation of norepinephrine release in this region. In the second series of the experiments to test the possibility of abnormal peptidergic regulation of central norepinephrine release in hypertension, we studied whether galanin-mediated regulation of norepinephrine release might be altered in the medulla oblongata of spontaneously hypertensive rats (SHR).

Methods

Animals

Male Sprague-Dawley (SD) rats (weight, 200–250 g) from Taconic Farms, Germantown, N.Y., were used for the fundamental investigation of the effects of galanin in rat medulla oblongata. Male SHR (9–10 weeks old; Taconic Farms) were studied in comparison with age-matched male Wistar-Kyoto (WKY) rats (Taconic Farms). The body weight of the SHR was 197.5±2.0 g (n=6) and that of WKY rats was 177.3±3.5 mm Hg in SHR (n=6) and 114.7±6.2 mm Hg in WKY rats (n=6).

All rats were maintained and housed in a temperature- and humidity-controlled room. The rats were fed regular pelleted food and tap water ad libitum for at least 1 week before the experiment.

Drugs

The α2-agonist 5-bromo-6-(2-imidazolin-2-ylamino)-quinoxaline (UK 14,304) and clonidine were received from Pfizer Inc., New York, and Boehringer Ingelheim KG, Ingelheim, Germany, respectively. The α2-antagonist, 2-(1-hydroxyethyl)-1-imidazolin-2-methyl HC1 (RX 781094) was received from RPI Corp., Mt. Prospect, Ill. Galanin was donated by Dr. David Schlesinger (Cell Biology and Kaplan Cancer Center, New York Medical Center, New York). Purified pertussis toxin (islet activating protein) was purchased from List Biological Laboratories Inc., Campbell, Calif. All other drugs used were standard laboratory reagents of analytical grade.

Experimental Procedure

The rats were decapitated, and the whole medulla oblongata was rapidly dissected on ice according to the method described previously.15 The frontal section was cut from the level of the nucleus nervi facialis to the pyramidal decussation.15 The isolated medulla oblongata was sliced at 0.3-mm thickness with a tissue chopper (Brinkmann Instruments, Inc., Westbury, N.Y.), rotated 90°, and sliced again (0.3×0.3 mm). The sliced tissues were washed three times with 2 ml Krebs-Ringer bicarbonate buffer (in mM: NaCl 118.0, KCl 4.80, CaCl2 1.20, KH2PO4 1.15, MgSO4 1.20, NaHCO3 25.0, glucose 11.1, ascorbic acid 0.11, and disodium EDTA 0.04 saturated with a 95% O2–5% CO2 mixture at 37°C, pH 7.4). The slices were incubated with 2 ml buffer containing 0.1 μM of 3Hnorepinephrine (specific activity 40.8 Ci/mmol; New England Nuclear Research Products, Boston, Mass.) for 20 minutes at 37°C. After the slices (5–6 slices) were rinsed with fresh buffer, they were transferred to a superfusion chamber (volume 200 μl), jacketed with 37°C water and suspended between two platinum electrodes (25 mm apart, 2 mm long). The slices were continuously superfused with Krebs-Ringer bicarbonate buffer at a rate of 0.7 ml/min. The superfuse was collected after 60 minutes of superfusion when basal outflow of tritium had stabilized to a constant level. Samples of superfuse were collected at 7-minute intervals until the end of the experiment (at 130 minutes). For electrical stimulation, trains of unipolar and rectangular pulses (1 Hz, 20 mA, 2-msec duration for 2 minutes) were delivered with a stimulator (model S4K, Grass Instrument Co., Quincy, Mass.).

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The amount of tritium released in each sample was calculated by dividing the total tritium collected in each sample by the total tritium present in the tissue at the time of the sample collection (the tritium released into superfuse after that point plus the tritium remaining in the tissue at the end of the experiment) and was expressed as a percentage of fractional release. Basal overflow during the two prestimulation periods (b1 and b2, respectively) was evaluated from the tritium collected in the two 7-minute samples just before SI and S2. The overflow of tritium evoked by nerve stimulation was calculated by subtracting the basal overflow during the 7-minute prestimulation period from the value in samples collected during the 2-minute stimulation period and 5 minutes after the electrical stimulation (total 7 minutes). The tritium content of the first fraction collected ranged consistently from 5,000 to 7,000 disintegrations per minute and the tritium remaining in the
Galanin and Norepinephrine Release

In the first series of the experiment, we studied the effects of galanin in combination with UK 14,304, clonidine, RX 781094, and pertussis toxin on the [3H]norepinephrine release in SD rats. In the control experiment, S1 and S2 were performed in the absence of any added drugs. The effects of galanin, UK 14,304, and clonidine were evaluated only in S2, with S1 serving as an internal control. Superfusion with galanin, UK 14,304, and clonidine was initiated 14 minutes before S2 and maintained until the end of the experiment. The effects of the drugs on the stimulation-evoked [3H]norepinephrine release were determined by comparing the S2/S1 ratios (fractional release ratios during S2 and S1) obtained in control slices with the values in slices treated with the tested drugs in S2. Control superfusion chambers and chambers with several concentrations of the drugs were run in parallel.

To examine the effects of blockade of \( \alpha_2 \)-adrenergic receptors, RX 781094 (1 \times 10^{-8} \text{ M}) was added to the superfusion medium 28 minutes before S1 and maintained until the end of the experiment. To inactivate the G protein, the slices of medulla oblongata were preincubated for 1 hour at 37°C in 95% O2-5% CO2 atmosphere in a mixture of 1,380 \( \mu \text{l} \) Krebs-Ringer bicarbonate buffer and 120 \( \mu \text{l} \) 0.01 M sodium phosphate buffer that contained 0.05 M NaCl and 12 \( \mu \text{g} \) pertussis toxin (concentration 8 \( \mu \text{g/ml} \)). In the control experiment, the slices were incubated in the same buffer mixture without pertussis toxin.

In the second series of the experiment, the effects of galanin on the stimulation-evoked release of [3H]norepinephrine were examined in the slices of medulla oblongata of SHR as compared with WKY rats.

Statistics

Values are expressed as mean±SEM. Differences between the means of the drug treatment and their corresponding controls were determined by one-way analysis of variance (ANOVA). To compare the means of the different study groups, the Wilcoxon rank-sum test was used. To examine the differences between SHR and WKY rats, statistical analyses were performed with the two-way ANOVA. A value of \( p < 0.05 \) was accepted as the level of significance.

Results

Effects of Galanin Alone and in Combination With UK 14,304, Clonidine, and RX 781094 on the Tritiated Norepinephrine Release in Medulla Oblongata of Sprague-Dawley Rats

In the control experiments, the stimulation-evoked [3H]norepinephrine release in S1 and S2 does not differ significantly (S2/S1 ratio, 0.937±0.043, \( n = 6 \)). Table 1 shows the effects of galanin on the release of [3H]norepinephrine in slices of medulla oblongata of SD rats. Galanin strongly inhibited the stimulation-evoked [3H]norepinephrine release in a concentration-dependent manner (IC50 value, 1.5±0.4 \times 10^{-7} \text{ M}, \( n = 6 \)), although the basal release of [3H]norepinephrine was not changed by these concentrations of the peptide.

To evaluate whether \( \alpha_2 \)-adrenergic receptors are associated with the inhibitory action of galanin, we studied the effects of galanin in slices exposed to \( \alpha_2 \)-adrenergic receptor agonists (UK 14,304 and clonidine). Exposure of slices to UK 14,304 and clonidine before S2 resulted in the reduction of S2/S1 ratio (Table 1). In a separate experiment, we examined the effects of \( \alpha_2 \)-adrenergic receptor antagonist (RX 781094) on the inhibition of [3H]norepinephrine release by galanin. Exposure of

**Table 1.** Inhibitory Effects of Galanin, UK 14,304, and Clonidine on [3H]Norepinephrine Release in Medulla Oblongata of Sprague-Dawley Rats

<table>
<thead>
<tr>
<th>Drugs added before S2</th>
<th>Fractional Release (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$S_1$</td>
</tr>
<tr>
<td>Control ($n = 6$)</td>
<td>1.230±0.035</td>
</tr>
<tr>
<td>Gal $1 \times 10^{-8}$ M ($n = 6$)</td>
<td>1.298±0.023</td>
</tr>
<tr>
<td>Gal $1 \times 10^{-7}$ M ($n = 6$)</td>
<td>1.245±0.041</td>
</tr>
<tr>
<td>Gal $1 \times 10^{-6}$ M ($n = 6$)</td>
<td>1.374±0.061*</td>
</tr>
<tr>
<td>UK $1 \times 10^{-6}$ M ($n = 5$)</td>
<td>1.215±0.044</td>
</tr>
<tr>
<td>UK $1 \times 10^{-4}$ M ($n = 6$)</td>
<td>1.269±0.047</td>
</tr>
<tr>
<td>UK $1 \times 10^{-4}$ M+Gal $1 \times 10^{-4}$ M ($n = 6$)</td>
<td>1.205±0.048</td>
</tr>
<tr>
<td>Clon $1 \times 10^{-4}$ M ($n = 5$)</td>
<td>1.192±0.075</td>
</tr>
<tr>
<td>Clon $1 \times 10^{-4}$ M ($n = 5$)</td>
<td>1.178±0.047</td>
</tr>
<tr>
<td>Clon $1 \times 10^{-4}$ M+Gal $1 \times 10^{-4}$ M ($n = 7$)</td>
<td>1.201±0.053</td>
</tr>
</tbody>
</table>

Slices were electrically stimulated at 1 Hz (20 mA, unipolar rectangular pulses for 2-msec duration for 2 minutes). Galanin (Gal), UK 14,304 (UK), and clonidine (Clon) were added 14 minutes before S2. Fractional release during S1 and S2 were calculated by subtracting basal outflow from the total outflow of tritium during stimulation period (2-minute stimulation and after 5 minutes) and is expressed as percentage of the tritium content of the tissue at the onset of stimulation. S1, first electrical stimulation; S2, second electrical stimulation; b1, prestimulation period before S1; b2, prestimulation period before S2; S2/S1, fractional release ratio during S2 and S1; b2/b1, fractional release ratio during b2 and b1. Data are represented as mean±SEM.

* \( p < 0.05 \) compared with the corresponding control.

**t** \( p < 0.05 \) compared with the experiment of UK 14,304 (1 \times 10^{-4} \text{ M}) or clonidine (1 \times 10^{-4} \text{ M}) alone.

Tissue ranged from 100,000 to 150,000 dpm. Because more than 85% of tritium released during stimulation represents unmetabolized [3H]norepinephrine, we have expressed the fractional release of tritium as [3H]norepinephrine.

The effects of the drugs on the stimulation-evoked [3H]norepinephrine release were determined by comparing the S2/S1 ratios (fractional release ratios during S2 and S1) obtained in control slices with the values in slices treated with the tested drugs in S2. Control superfusion chambers and chambers with several concentrations of the drugs were run in parallel.
slices to RX 781094 before S1 increased the stimulation-evoked [3H]norepinephrine release (fractional release during S1, 1.705±0.049%, n=6; during S2, 1.646±0.053%, n=6; S2/S1 ratio, 0.947±0.010, n=6). The data in Figure 1 show that the inhibition by galanin was significantly attenuated in the presence of RX 781094.

Effects of Pertussis Toxin on the Inhibition of Tritiated Norepinephrine Release by Galanin and UK 14,304 in Medulla Oblongata of Sprague-Dawley Rats

The a2-adrenergic receptors are negatively linked to adenylate cyclase via the G protein. We therefore examined whether the inactivation of the G protein by pertussis toxin may alter the inhibitory action of galanin on the stimulation-evoked [3H]norepinephrine release. The fractional release of [3H]norepinephrine release during electrical stimulation was not changed by the treatment of pertussis toxin. However, the inhibitory effect of galanin on [3H]norepinephrine release was significantly attenuated in slices pretreated with pertussis toxin (Table 2). Similarly, the inhibitory action of UK 14,304 on [3H]norepinephrine release was also reduced in the pertussin toxin–treated slices (Table 2).

**Effects of Galanin on Tritiated Norepinephrine Release in Medulla Oblongata of Spontaneously Hypertensive Rats and Wistar-Kyoto Rats**

The stimulation-evoked [3H]norepinephrine release from slices of medulla oblongata was not significantly different between SHR and WKY rats (percent fractional release during S1: SHR, 1.239±0.033% of total tissue radioactivity, n=6; WKY, 1.396±0.063%, n=6). The basilar release of tritium also did not differ between SHR and WKY rats (percent fractional release during S1: SHR, 2.798±0.034% of total tissue radioactivity, n=6; WKY, 2.661±0.029%, n=6). As shown in Figure 2, galanin significantly reduced the stimulation-evoked [3H]norepinephrine release both in SHR and WKY rats. The suppression by galanin was significantly more attenuated in SHR than in WKY rats (S2/S1 ratio: galanin 1×10−7 M: SHR, 0.883±0.050, n=6; WKY, 0.534±0.010, n=6, p<0.05; galanin 1×10−6 M: SHR, 0.542±0.013, n=6; WKY, 0.217±0.019, n=6, p<0.05).

**Discussion**

Galanin is colocalized with classic neurotransmitters such as norepinephrine, dopamine, or acetylcholine in specific neuronal systems in the brain.2-7-9 We therefore investigated the effects of galanin on norepinephrine release and its interactions with a2-adrenergic receptors in rat medulla oblongata. The results of the present study demonstrate that galanin inhibited the stimul-

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**Table 2. Effects of Pertussis Toxin on Galanin-Induced and UK 14,304-Induced Reduction in Stimulation (1 Hz)-Evoked [3H]Norepinephrine Release in Medulla Oblongata of Sprague-Dawley Rats**

<table>
<thead>
<tr>
<th>Drugs added before S2</th>
<th>S1</th>
<th>S2</th>
<th>S2/S1</th>
<th>b2/b1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pertussis toxin (+)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (n=6)</td>
<td>1.338±0.010</td>
<td>1.298±0.127</td>
<td>0.967±0.031</td>
<td>0.782±0.033</td>
</tr>
<tr>
<td>Gal 1×10−7 M (n=6)</td>
<td>1.348±0.027</td>
<td>1.132±0.031</td>
<td>0.841±0.035</td>
<td>0.817±0.025</td>
</tr>
<tr>
<td>Gal 1×10−6 M (n=6)</td>
<td>1.372±0.085</td>
<td>0.797±0.053</td>
<td>0.572±0.023</td>
<td>0.812±0.020</td>
</tr>
<tr>
<td>UK 1×10−4 M (n=6)</td>
<td>1.200±0.049</td>
<td>0.578±0.029</td>
<td>0.497±0.040</td>
<td>0.809±0.011</td>
</tr>
<tr>
<td>Pertussis toxin (−)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control (n=6)</td>
<td>1.328±0.031</td>
<td>1.245±0.032</td>
<td>0.937±0.036</td>
<td>0.799±0.010</td>
</tr>
<tr>
<td>Gal 1×10−7 M (n=6)</td>
<td>1.259±0.040</td>
<td>0.641±0.057</td>
<td>0.507±0.040</td>
<td>0.806±0.011</td>
</tr>
<tr>
<td>Gal 1×10−6 M (n=6)</td>
<td>1.357±0.047</td>
<td>0.446±0.027</td>
<td>0.334±0.024</td>
<td>0.815±0.016</td>
</tr>
<tr>
<td>UK 1×10−4 M (n=6)</td>
<td>1.249±0.034</td>
<td>0.255±0.044</td>
<td>0.184±0.038</td>
<td>0.815±0.021</td>
</tr>
</tbody>
</table>

Slices were pretreated with pertussis toxin (8 μg/ml), incubated with [3H]norepinephrine, and superfused as described in text. Effects of galanin (Gal) and UK 14,304 (UK) were expressed as S2/S1 ratios of tritium overflow evoked by the two stimulation periods. S1, first electrical stimulation; S2, second electrical stimulation; b1, prestimulation period before S1; b2, prestimulation period before S2; S2/S1, fractional release ratio during S2 and S1; b2/b1, fractional release ratio during b2 and b1. Values are mean±SEM.

*p<0.05 compared with the experiments in the presence of same concentrations of galanin or UK 14,304 alone.

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activation of α₂-adrenergic receptors. Additionally, the blockade of α₂-adrenergic receptors by RX 781094 diminished the inhibitory effects of galanin on norepinephrine release, which would support the hypothesis that galanin can act on α₂-adrenergic receptors in rat medulla oblongata. The possibility that galanin interacts with α₂-adrenergic receptors was further suggested by the evidence that galanin-induced feeding behavior in rats depended specifically on functional α₂-receptor sites. It was also shown that the effects of galanin on the release of luteinizing hormone releasing hormone in rat brain was blocked by phentolamine.

The signal transduction system via the α₂-adrenergic receptors is believed to be linked to the Gi protein of the membranes.

The present study showed that the α₂-agonists UK 14,304 and clonidine inhibited the stimulation-evoked [³H]norepinephrine release in medulla oblongata of spontaneously hypertensive rats (SHR) and Wistar-Kyoto (WKY) rats. Effects of galanin (1×10⁻⁷ M and 1×10⁻⁵ M) were expressed as S2/S1 ratios of tritium overflow evoked by the two stimulation periods. Galanin was added to the superfusion medium 14 minutes before S2 and maintained until the end of the experiment. Values are mean±SEM.

![Graph](http://hyper.ahajournals.org/)

**Figure 2.** Bar graph demonstrates effects of galanin (Gal) on stimulation (1 Hz)-evoked [³H]norepinephrine release in medulla oblongata of spontaneously hypertensive rats (SHR) and Wistar-Kyoto (WKY) rats. Effects of galanin (1×10⁻⁷ M and 1×10⁻⁵ M) were expressed as S2/S1 ratios of tritium overflow evoked by the two stimulation periods. Galanin was added to the superfusion medium 14 minutes before S2 and maintained until the end of the experiment. Values are mean±SEM.
hypertension. It would be possible that the quantitative abnormality might cause less sensitivity to exogenously applied galanin in medulla oblongata of SHR.

In summary, the results of the present study demonstrate that galanin inhibited stimulation-evoked norepinephrine release in rat medulla oblongata, and that a part of the mechanisms can be explained by the interactions with presynaptic α2-adrenergic receptors and the pertussis toxin–sensitive GTP-binding proteins in this region. Although the precise role of galanin in the pathogenesis of hypertension is still uncertain, the impaired modulation of norepinephrine release by galanin in medulla oblongata of SHR suggests the possible involvement of the peptide in the regulation of central sympathetic tone in hypertension.

References
Modulation of norepinephrine release by galanin in rat medulla oblongata.
K Tsuda, S Tsuda, I Nishio, Y Masuyama and M Goldstein

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