Modulation of G Protein-Coupled Receptors by an Estrogen Receptor that Activates Protein Kinase A

ANDRE H. LAGRANGE, OLINNE K. RØNNEKLEIV, and MARTIN J. KELLY
Department of Physiology and Pharmacology, Oregon Health Sciences University, Portland, Oregon 97201
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SUMMARY
17β-Estradiol (E2) rapidly (<20 min) attenuates the ability of μ-opioids to hyperpolarize guinea pig hypothalamic (β-endorphin) neurons. In the current study, we used intracellular recordings from guinea pig hypothalamic slices to characterize the receptor and intracellular effector system mediating the rapid effects of E2. E2 acted stereospecifically with physiologically relevant concentration dependence (EC50 = 8 nM) to cause a 4-fold reduction in the potency of a μ-opioid agonist to activate an inwardly rectifying K+ conductance. Using Schid analysis to estimate the affinity of the μ-opioid receptor for an antagonist (naloxone), we found that estrogen did not compete for the μ-opioid receptor or alter the affinity of the μ receptor. Both the nonsteroidal estrogen diethylstilbestrol and the "pure" antiestrogen ICI 164,384 blocked the actions of E2, the latter with a subnanomolar affinity. The protein synthesis inhibitor cycloheximide did not block the estrogenic uncoupling of the μ-opioid receptor from its K+ channel, implying a nongenomic mechanism of action by E2. The actions of E2 were mimicked by the protein kinase A (PKA) activators forskolin and cAMP, Sp-isomer triethylammonium salt. Furthermore, the selective PKA antagonists cAMP, Rp-isomer triethylammonium salt and KT5720, which have different chemical structures and modes of action, both blocked the effects of E2. Thus, estrogen binds to a specific receptor that activates PKA to rapidly uncouple the μ-opioid receptor from its K+ channel. Because we have previously shown that γ-aminobutyric acidg receptors are also uncoupled by estrogen, this mechanism of action has the potential to alter synaptic transmission via G protein-coupled receptors throughout the brain.

Classically, the ER is thought to act by increasing transcription at estrogen-response elements (1). However, it has become clear that ER actions are much more complex, involving multiple accessory proteins (2) and complex interactions with other intracellular systems (e.g., protein kinases) (3). Furthermore, there is compelling evidence for the existence of nonclassic steroid receptors, some of which are in the plasma membrane (4–7). Finally, numerous rapid (<30 min), presumably nongenomic effects of E2 are found in the brain and other tissues (8–11); however, the pharmacology and cellular mechanisms of these effects are often poorly understood. Thus, despite the recent progress toward understanding the complexity of E2 actions, it remains unclear how these diverse actions work together to regulate cellular physiology.

One well-characterized and vital action of E2 is regulation of reproduction through negative feedback on the HPG axis. In vivo and in vitro studies in several species have shown that E2 rapidly (<30 min) suppresses GnRH/luteinizing hormone release (12–14). Although this estrogenic inhibition is thought to involve β-endorphin neurons that are presynaptic to GnRH cells (15), the cellular mechanism by which β-endorphin neurons mediate the rapid regulation by estrogen of GnRH secretion remains unknown. However, β-endorphin preferentially binds to μ-opioid receptors (16), and the vast majority (>90%) of hypothalamic neurons, including GnRH cells (17), are hyperpolarized by μ-opioid activation of inwardly rectifying K+ currents (18). Furthermore, a brief (20 min) exposure to E2 rapidly reduces μ-opioid potency in β-endorphin but not GnRH neurons (17, 18). The EC50 value of the μ-opioid agonist DAMGO after the application of E2 is nearly 4-fold greater than control values with no change in the efficacy. 17α-Estradiol is a biologically inactive isomer of E2 that is identical to the native steroid except for the configuration of a single hydrogen atom. The inability of this compound to mimic the effects of E2 helped confirm the specificity of this response. Finally, we have also shown that the actions of E2 occur at physiologically relevant concentrations.

ABBREVIATIONS: E2, 17β-estradiol; DES, diethylstilbestrol; ER, estrogen receptor; BSA-E2, bovine serum albumin/estrogen; PKA, cAMP-dependent protein kinase; HPG, hypothalamic-pituitary-gonadal axis; GnRH, gonadotropin-releasing hormone; DAMGO, [δ-Ala²,δ-MePhe⁵,Gly⁷]-enkephalin; αCSF, artificial cerebrospinal fluid salt solution; Rp-cAMP, cAMP, Rp-isomer, triethylammonium salt; Sp-cAMP, cAMP, Sp-isomer triethylammonium salt; HEPES, 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid; AC, adenylate cyclase; RIA, radioimmunoassay.
In the current study, we characterized the receptor and intracellular effector system mediating the rapid attenuation by E₂ of μ-opioid response. Because PKA activation uncouples purified μ receptors from their G proteins (19), we investigated the possibility that a protein kinase mediates the rapid actions of estrogen. We found that PKA stimulators mimicked the effects of E₂ and that two different PKA antagonists with different chemical structures and mechanisms of action blocked the effects of E₂.

**Materials and Methods**

**Animals.** Female guinea pigs (Topeka; 350–600 g) that were born and raised in our colony were maintained on a 14-hr light/10-hr dark lighting schedule (lights on 6:30 a.m. to 8:30 p.m.) and were ovariectomized while under anesthesia with ketamine (33 mg/kg) and xylazine (6 mg/kg) 6–10 days before each experiment. Serum estrogen levels as determined by RIA (steroid RIA core, P30 HD18185) were <12 pg/ml (sensitivity of the RIA was 2.5 pg/ml) at the time of death. Each animal was decapitated between 9:00 and 10:00 a.m.; the brain was removed, the hypothalamus was dissected, and coronal slices of 450-μm thickness were cut with a vibratome (18). A single slice was submerged in an oxygenated (95% O₂/5% CO₂) solution (aCSF) at 35 ± 1°C; the solution flowed through at a rate of 1.5 ml/min and contained 124 mM NaCl, 5 mM KCl, 1.25 mM NaH₂PO₄, 2 mM MgSO₄, 2 mM CaCl₂, 26 mM NaHCO₃, 10 mM dextrose, and 10 mM HEPES.

**Drugs.** All drugs and chemicals were from Sigma Chemical (St. Louis, MO) unless otherwise specified. All drugs were dissolved in aCSF and then superfused over the slice. Drug changes were made using a manual three-way stopcock. Tetrodotoxin (1 M) was added to all drug solutions before application to ensure a postsynaptic effect. The μ-opioid responses were measured with the selective agonist DAMGO (20 nM–24 μM; Peninsula Laboratories, Belmont, CA; Ref. 16) and antagonized with naltrexone (20–320 nM; Ref. 16). E₂, DES, and ICI 164,384 were stored at 4°C in a 100% methanol solution to ensure purity. E₂, DES, and BSA-E₂ were from Steraloids (Wilton, NH), and ICI 164,384 (N-[n-butyl-11-3,17β-dihydroxyestr-1-3,5(10)-tri-en-7α-y1]-N-methylundecanamide) was the generous gift of Dr. Alan Wakeling (Zeneca Pharmaceuticals, Cheshire, UK). The E₂ had been recrystallized to ensure purity. E₂, DES, and ICI 164,384 were stored at 4°C; the solution flowed through at a rate of 1.5 ml/min and contained 124 mM NaCl, 5 mM KCl, 1.25 mM NaH₂PO₄, 2 mM MgSO₄, 2 mM CaCl₂, 26 mM NaHCO₃, 10 mM dextrose, and 10 mM HEPES.

**Electrophysiology.** Intracellular recordings were made from arcuate neurons using techniques similar to those previously described (18). Microelectrodes were made from borosilicate glass micropipettes (1-mm o.d.; Dagan, Minneapolis, MN) and were filled with a 3% bicuculline solution in 1.75 M KCl and 0.025 M Tris, pH 7.4; resistances varied from 100 to 250 MΩ. Intracellular potentials were amplified, and current was passed through the electrode using an Axoclamp 2A (Axon Instruments, Burlingame, CA). Current and voltage traces were recorded on a chart recorder (model 2200; Gould, Cleveland, OH), digitized at 83 Hz, and stored on an IBM PC clone with Axotape software (Axon Instruments). Voltage-current relationships were obtained by applying a series of depolarizing and hyperpolarizing current pulses (1-msec, 50 pA) used to monitor input resistance. Arrow, membrane potential was current-clamped to the predrug resting potentials to verify that DAMGO caused a decreased input resistance. B, After washout of the drugs, a cumulative concentration-response curve was performed (●) and compared with pre-E₂ control responses to DAMGO (○). Line through data, computer-generated fit to the logistic equation. C, Current-voltage plot performed by applying current steps (1 sec, 0.2 Hz) before (○) and during (●) E₂ showed that this steroid did not alter resting conductances.

**Immunocytochemistry.** Hypothalamic slices that had been incubated with aCSF (time in aCSF, 3–6 hr) or were superfused with 1 or 2 nM ICI 164,384 for 15 min before E₂, the response to E₂ was calculated using the following relation: (DAMGO EC₅₀ after E₂)/DAMGO EC₅₀ before E₂). The data were computer fitted to the logistic equation to generate an E₂ concentration-response curve.
taining immunoreactive ERs, the cells within 250 μm² on each section were counted under fluorescent illumination using an eyepiece square grid reticule on a Leitz Laborlux microscope. Two or three sections from the arcuate area of each slice were counted without knowledge of the treatment groups. The total number of cells that were counted from the different sections were averaged, and the mean number of cells was used for further analysis.

**Statistical analysis.** Numerical data are expressed as mean ± standard error. Electrophysiological data were compared using an unpaired two-tailed Welch t test, except as noted. A value of p < 0.05 was considered significant. The mean DAMGO EC₅₀ value (114 ± 9 nm, 65 cells) after E₂ (including both E₂-sensitive and -insensitive cells) was significantly different from controls (p < 0.0001) and was compared with the DAMGO EC₅₀ values after E₂ plus kinase/estrogen antagonists with the use of a Mann-Whitney test to evaluate those agents. In the immunocytochemical studies, statistical differences among these groups were determined using an analysis of variance with a Tukey-Kramer post hoc test.

**Results**

**Estrogen rapidly attenuates the μ-opioid response in hypothalamic neurons.** E₂ rapidly (20 min) reduces the potency of the μ-opioid agonist DAMGO, causing a nearly 4-fold, parallel shift in the DAMGO dose-response curve in approximately one third of hypothalamic cells (53 cells) (18). To further characterize this time course, we applied submaximal concentrations of DAMGO and E₂ simultaneously (Fig. 1A). Although E₂ does not reduce the maximal response to DAMGO (18), it reduced the response to a submaximal μ-opioid concentration as the cell re-equilibrated to the lower potency state. The response to 100 nM DAMGO before E₂ was −9 mV hyperpolarization (82% maximum). However, when 20 nM E₂ was added, the DAMGO response was diminished within 7 min, and after ~12 min, the DAMGO response equilibrated to −4 mV (36% maximum response) below the resting membrane potential. There was no desensitization when this same cell was subsequently tested with higher concentrations of DAMGO (up to 300 nM for 18 min).³ In our preparation, the response to even higher DAMGO concentrations (1 μM) caused no obvious desensitization in hypothalamic cells (mean change = 0.12 ± 0.08 mV; 13 cells), and E₂ did not increase the desensitization to 1 μM DAMGO in E₂-sensitive cells (mean change = 0.15 ± 0.04 mV; 17 cells). Furthermore, we have shown previously that E₂ alters DAMGO potency without prior exposure to μ-opioids (18). Thus, the attenuated DAMGO response after E₂ does not appear to be due to homologous desensitization of the μ-opioid receptor.

After the washout of DAMGO and E₂, a complete DAMGO concentration-response curve showed that the DAMGO EC₅₀ value (177 nm) was shifted from pre-estrogen controls (EC₅₀ = 59 ± 3 nm; 43 cells) (Fig. 1B). Furthermore, current/voltage relationships generated before and during the application of 20 nM E₂ alone showed that this steroid did not directly alter ion channels (Fig. 1C). Therefore, estrogen rapidly attenuates the DAMGO response by altering the potency at the μ-opioid receptor.

**Estrogen acts via a specific receptor.** The parallel, rightward shift in the DAMGO concentration-response curve induced by E₂ is consistent with a competitive block of the μ-opioid receptor, similar to what has been seen with pharmacological concentrations of E₂ (~200 μM; Ref. 22). This possibility was investigated using Schild analysis (20) to determine the affinity of the receptor for the opioid antagonist naloxone (16) before and after estrogen. As seen in Fig. 2, the Kᵣ value for naloxone in cells treated with 100 nm E₂ was not different from that of control cells. Furthermore, both Schild plots have a slope of −1.0, which is consistent with competitive blockade of the μ-opioid receptor with naloxone. This would not be true if E₂ were competing with both naloxone and DAMGO for the μ-opioid binding site (23). Thus, E₂ neither alters the affinity of the μ-opioid receptor for agonist nor competitively blocks it.

The receptor mediating the rapid effects of E₂ was further characterized using the antiestrogen ICI 164,384 and the nonsteroidal estrogen DES. Although DES binds to the classical ER and is an agonist for the genomic effects of E₂, this compound did not alter the response to μ-opioids (100 nm DES, DAMGO EC₅₀ = 69 ± 5 nm; seven cells). However, DES (100 nm) blocked the actions of 20 nm E₂ when these two compounds were super fused together (DAMGO EC₅₀ = 53 ± 4 nm; nine cells; p < 0.0001) (Fig. 3). Thus, DES acts as an estrogen agent, although it is an antagonist rather than an agonist in this system. To our knowledge, this is the first described system in which DES is an estrogen antagonist. However, a similar mixed agonist/antagonist action at classic ERs has been described for other nonsteroidal estrogens, such as tamoxifen (24). ICI 164,384 is a well-characterized, competitive estrogen antagonist (25). As seen in Fig. 4A, ICI 164,384 (100 nm) blocks E₂ (20 nm) action (DAMGO EC₅₀ = 61 ± 4 nm; seven cells; p < 0.0001). Further studies generated E₂ concentration-response curves by superfusing E₂ (1 nm to 1 μM; 53 cells) followed by a complete concentration-response profile to DAMGO. In several cases, multiple con-

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The nonsteroidal estrogen DES antagonized the effects of E₂. When DES (100 nM; nine cells) was superfused for 10 min before and during E₂ (20 nM, 20 min), the effects of E₂ were blocked. The DAMGO EC₅₀ value in this representative cell was 46 nM after the application of DES plus E₂. However, when E₂ alone was applied to the same cell, the DAMGO EC₅₀ value was increased to 194 nM. This is very similar to what ICI 164,384 to be 0.48 and 0.20 nM after treatment with 1 and 2 nM ICI 164,384, respectively. This is very similar to what Kₐ value (Fig. 3).

**Fig. 3.** The antiestrogen ICI 164,384 blocked the rapid effects of E₂. A, ICI 164,384 (100 nM; seven cells) was applied for 10–15 min before E₂ and then cosuperfused with E₂ (20 nM, 20 min). As represented by this cell, the resulting DAMGO EC₅₀ value was not different from that of controls. When E₂ was superfused alone, the DAMGO EC₅₀ value shifted from 50 nM (ICI 164,384 + E₂, A) to 166 nM (E₂ alone, B). Dashed line, summary of pre-E₂ DAMGO concentration-response curves (EC₅₀ = 59 ± 3 nM). Inset, Molecular structure of ICI 164,384. B, DAMGO concentration-response curves were performed before and after various concentrations of E₂ (1 nM–1 μM; 53 cells). The data were used to generate an E₂ concentration-response curve (Kᵣ = 7.5 nM). The addition of 1 nM ICI 164,384 (A, EC₅₀ = 23 nM; six cells) and 2 nM ICI 164,384 (B, EC₅₀ = 81 nM; eight cells), shifted E₂ concentration-response curve to the right.

**Fig. 4.** The nonsteroidal estrogen DES antagonized the effects of E₂. When DES (100 nM; nine cells) was superfused for 10 min before and during E₂ (20 nM, 20 min), the effects of E₂ were blocked. The DAMGO EC₅₀ value in this representative cell was 46 nM after the application of DES plus E₂. However, when E₂ alone was applied to the same cell, the DAMGO EC₅₀ value was increased to 194 nM. This is very similar to what Kₐ value (Fig. 3).

**Inhibition of protein synthesis does not block the effects of E₂.** The question arises of what is the biochemical mechanism of the rapid effects of E₂. A genomic mechanism seems unlikely because E₂ requires ≥30–60 min to alter protein synthesis (26) and probably a longer time to affect cellular physiology. Moreover, cycloheximide did not block the rapid effects of E₂. Slices were superfused with 200 μM cycloheximide for 30 min before, during, and 30 min after E₂ (100 nM, 20 min). This treatment has been shown to block >90% of protein synthesis in brain slices (27) but was unable to block the effects of E₂ (DAMGO EC₅₀ = 115 ± 28 nM; eight cells with three cells having a DAMGO EC₅₀ value of >160 nM) (Fig. 5). To help confirm that this cycloheximide treatment did indeed block protein synthesis, we made use of the fact that E₂ causes a protein synthesis-dependent down-regulation of the ER (28). Consistent with these previous findings, we found that E₂ caused a robust decrease in the number of cells stained with an anti-ER antibody (77 ± 3 cells/250-μm² field in control slices versus 12 ± 4 cells in E₂-treated slices; p < 0.001) and that this effect was blocked with prior cycloheximide treatment (78 ± 7 cells; p < 0.001 versus controls; Fig. 6).

**PKA stimulators mimic the effects of E₂.** Research in other systems has shown that protein kinases can uncouple opioid receptors from their effector systems (19), and the rapid effects of E₂ have been shown to be mediated by increases in intracellular cAMP levels in neural (29) and non-neural (9) tissues. We tested the hypothesis that the rapid effects of estrogen are mediated by nongenomic stimulation of PKA. Stimulation of AC with forskolin (1–25 μM) decreased DAMGO potency (DAMGO EC₅₀ = 160–221 nM; six cells). Furthermore, direct PKA activation by superfusion of the nonhydrolyzable cAMP analog Sp-cAMP (Fig. 7A) mimicked E₂ action in a concentration-dependent manner. A concentration-response curve for Sp-cAMP (similar to the E₂ concentration-response curve shown in Fig. 4B) estimated the EC₅₀ value for Sp-cAMP to be 84 μM, with a maximal...
393% increase in the DAMGO EC50 value. Thus, activation of PKA either directly (Sp-cAMP) or via increasing intracellular cAMP levels (forskolin) mimicked the actions of E2.

PKA inhibitors block the effects of E2. To further assess the involvement of protein kinases in modulating μ-opioid responses, the nonselective protein kinase inhibitor staurosporine (100 nM) was superfused before (10 min) and during (20 min) E2 (100 nM) (Fig. 7B). Staurosporine blocked the effects of E2, with a mean DAMGO EC50 value of 45 ± 6 nM (11 cells) that was significantly lower than in cells treated with E2 alone (p < 0.0001). Similarly, in an E2-sensitive cell (post-E2 DAMGO EC50 = 143 nM), application of staurosporine (10 nM) after E2 reduced the DAMGO potency (DAMGO EC50 = 46 nM). Thus, staurosporine both blocked the induction and reversed a previously established estrogenic modulation of μ-opioid potency. To confirm that PKA is the protein kinase mediating E2 action, we used chemically dissimilar compounds that selectively inhibit PKA through different mechanisms. Rp-cAMP is a nonhydrolyzable cAMP analog that blocks PKA activation by binding the regulatory subunit (30). In contrast, KT5720 is an analog of staurosporine that selectively inhibits PKA at its catalytic site (31). Prior application of either agent blocked E2 action. The DAMGO EC50 value (47 ± 7 nM; seven cells) in cells treated with KT5720 (60 nM) plus E2 (100 nM) was not different from that of controls but was significantly less than that of E2-treated cells (p < 0.0005). Similar effects were seen when Rp-cAMP (100 μM) was used instead of KT5720 (DAMGO EC50 = 57 ± 7 nM; eight cells; p < 0.0001). After these experiments, the same cells were superfused with E2 alone, which reduced the DAMGO potency, confirming the E2 sensitivity of these cells. Finally, the actions of E2 were reversed by Rp-cAMP and mimicked by Sp-cAMP in the same cell (Fig. 8). In a different cell, KT5720 also reversed the actions of E2. Thus, PKA inhibitors block the induction of the rapid actions of estrogen and reverse a previously established effect.

Discussion

The current results describe the receptor and intracellular effector system that mediates a novel action of E2 to rapidly alter synaptic transmission. E2 seems to act via a specific receptor because the actions of E2 are saturable, with a physiologically relevant concentration dependence and are not mimicked by the biologically inactive isomer 17α-estra-
This steroid did not compete for µ-opioid receptors. Furthermore, the lipophilic estradiol diffuses freely across cell membranes, but by covalently linking E₂ at its C6 position to BSA-E₂, the steroid is rendered cell-impermeant. Although this conjugate binds to extracellular E₂ receptors and is biologically active in other cell types (7), BSA-E₂ did not alter the response of hypothalamic neurons (eight cells) to µ-opioids.² Although the molecular structures of E₂ and DES are quite different, DES serves as an estrogenic agent at both the classic ER and the currently described ER. However, DES mimics the genomic effects of E₂, but this compound was an antagonist in our system. Although the currently described receptor is similar to the classic receptor, the pharmacodynamics of E₂ and the antagonism by DES imply that a different ER is mediating this effect. Perhaps these E₂ effects are mediated by one of the isoforms of the classic ER that have been found in the brain (4). Therefore, the currently described phenomenon may be mediated by a novel ER or a novel action of the classic ER.

PKA mediates the rapid modulation by estrogen of µ-opioid potency. PKA did not play a simply permissive role in E₂ action because PKA activators altered µ-opioid response in the absence of added steroid. Conversely, inhibition of PKA by two chemically and mechanistically different compounds confirmed that PKA is mediating (rather than merely mimicking) E₂ action. Finally, preliminary data indicate that treatment of hypothalamic slices with E₂, but not with 17α-estradiol, for 10 min stimulates ³²P-incorporation into a PKA substrate peptide.³ Although the estrogenic activation of PKA is clear, the mechanism of this stimulation remains to be determined.

**Fig. 7.** PKA is necessary and sufficient to alter µ-opioid potency. A, The effects of E₂ were mimicked by the PKA activator Sp-cAMP. DAMGO concentration-response curves were generated in this cell after superfusion of the slice with 50 µM Sp-cAMP (●, DAMGO EC₅₀ = 104 nM) and then subsequently with 150 µM Sp-cAMP (▲, DAMGO EC₅₀ = 175 nM). Dashed line with open circles, summary of pre-E₂ DAMGO concentration-response curves. A similar effect was seen in 3 of 10 cells. B, The rapid attenuation by estrogen of DAMGO potency is blocked by PKA inhibitors. When E₂-sensitive and -insensitive cells were combined, the DAMGO EC₅₀ value (114 ± 9 nM; 65 cells) was significantly higher than that of controls. Staurosporine (100 nM) and the more selective PKA inhibitors KT5720 (80 nM; seven cells) and Rp-cAMP (100 µM; eight cells) blocked the effects of E₂ (100 nM, 20 min) when these agents were superfused for 10 min before and during E₂. After the generation of these DAMGO concentration-response curves, E₂ was subsequently applied alone and shown to reduce DAMGO potency (data not shown), thus confirming that each of these kinase inhibitors blocked the actions of estrogen in E₂-sensitive neurons. Staurosporine caused a small but significant reduction in the DAMGO EC₅₀ value compared with that for controls. However, none of these agents had any other effect on either the passive or DAMGO-induced properties of these cells. ***, p < 0.0001; *, p < 0.01 compared with controls.


be determined. However, the ability of Rp-cAMP to reverse E₂ action suggests that estrogenic activation of PKA involves increases in cAMP levels rather than direct stimulation of the kinase (10). Perhaps E₂ stimulates the activity of AC or inhibits a phosphodiesterase. Finally, it remains to be determined whether other intracellular effectors (e.g., protein kinase C) are also involved in transducing the rapid effects of estrogen. Nevertheless, along with the well-described genomic and plasma membrane-delimited actions of E₂, the present intracellular messenger broadens our understanding of how E₂ regulates cellular physiology.

In addition to heterologous control by E₂, PKA may be involved in homologous regulation of μ-opioid receptors. Chronic exposure to morphine causes a similar uncoupling of μ-opioid receptors from their potassium channels (32). Furthermore, μ-opioids inhibit AC, and chronic inhibition by morphine results in a compensatory up-regulation of AC and PKA (33). Changes in PKA have been correlated with the development of morphine tolerance and dependence (33). However, previous studies have been unable to show a PKA-specific reduction in the maximal μ-opioid potency in neurons. Perhaps the up-regulation of PKA seen with chronic morphine causes an uncoupling of μ receptors from their effector systems, similar to what has been shown for β-adrenergic receptors (36). Because β-endorphin neurons develop tolerance to chronic morphine (37) and are sensitive to rapid E₂ effects (18), it may be that acute E₂ and chronic morphine share some of the same mechanisms (i.e., increased PKA activity). Studies are under way to examine the effects of PKA modulators in morphine-tolerant animals.

In addition, the currently described phenomenon provides a cellular substrate for the rapid inhibition by estrogen of the HPG axis. We have found that both β-endorphin and GnRH neurons are hyperpolarized by μ-opioids (17, 18) and have proposed a model for negative feedback of estrogen on GnRH release. Because the μ receptor is an autoreceptor on β-endorphin neurons, a given β-endorphin cell would be hyperpolarized by its own neurotransmitter. Therefore, the rapid attenuation by E₂ of μ-opioid potency in β-endorphin neurons (18) would uncouple β-endorphin autoinhibition. This would cause increased opioid peptide release with subsequent inhibition of GnRH neuronal activity (17). Furthermore, modulation of μ-opioid potency occurs within a few minutes and requires nanomolar E₂ concentrations, whereas genomic actions of E₂ require hours to days to alter cellular physiology and act with subnanomolar potency (26, 38). Thus, E₂ may have different actions depending on the time and concentration of E₂, as has been predicted by research in animal models (39). Finally, because we have recently shown that E₂ can rapidly alter the potency at the γ-aminobutyric acid₄ receptor (40), estrogen may modulate a variety of G protein-coupled receptors that participate in regulation of the HPG axis.

The genomic effects of E₂ have often been assumed to be the sole pathway for steroid actions. The recent discovery of membrane-delimited estrogen actions has added to the complexity of E₂ physiology, resulting in a dichotomy between extremely rapid membrane effects and slow nuclear actions. Estrogenic activation of PKA is a mechanism for rapid alteration of synaptic transmission that may both complement and complete the other modes of E₂ action. These findings extend the range of E₂ actions from months to minutes and from the nucleus to the extracellular membrane. Although we must further characterize the pharmacology and physiology of these various actions and the interactions among them, we are beginning to develop a more comprehensive picture of how E₂ actually works.

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Send reprint requests to: Martin J. Kelly, Ph.D., Department of Physiology & Pharmacology, Oregon Health Sciences University, Portland OR 97201. E-mail: kellym@ohsu.edu