

1 **Role of Kisspeptin and Kiss1R in the Regulation of Prolactin Gene Expression in**
2 **Rat Somatolactotroph GH3 Cells**

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23

1 **Abstract**

2 Hypothalamic kisspeptin is a known principal activator of gonadotropin-
3 releasing hormone neurons and governs the hypothalamic-pituitary-gonadal axis.
4 Previous reports have shown that kisspeptin is also released into the hypophyseal portal
5 circulation and directly affects the anterior pituitary. In this study, we examined the direct
6 effect of kisspeptin on pituitary prolactin-producing cells. The rat pituitary
7 somatolactotroph cell line GH3 expresses the kisspeptin receptor (Kiss1R); however, in
8 these cells, kisspeptin failed to stimulate prolactin-promoter activity. When GH3 cells
9 overexpressed Kiss1R, kisspeptin clearly increased prolactin-promoter activity, with a
10 concomitant increase in extracellular signal-regulated kinase (ERK) and cAMP/protein
11 kinase A (PKA) signaling pathways. In the experiments using GH3 cells overexpressing
12 Kiss1R, kisspeptin did not potentiate thyrotropin-releasing hormone (TRH)-induced
13 prolactin-promoter activity, but it potentiated the pituitary adenylate cyclase-activating
14 polypeptide-induced prolactin-promoter activity, with a concomitant enhancement of
15 ERK and PKA signaling pathways. Although the basal and TRH-induced prolactin-
16 promoter activities were not modulated by increasing amounts of Kiss1R expression in
17 GH3 cells, kisspeptin-stimulated prolactin-promoter activity was increased by the amount
18 of Kiss1R overexpression. Endogenous *Kiss1r* mRNA expression in GH3 cells was
19 significantly increased by treatment with estradiol (E2) but not by TRH. In addition,
20 kisspeptin's ability to stimulate prolactin-promoter activity was restored after E2
21 treatment in non-transfected GH3 cells.

22 Our current observations suggest that kisspeptin might have a direct effect on
23 prolactin expression in the anterior pituitary prolactin-producing cells under the influence
24 of E2, which may regulate Kiss1R expression and function.

1 **Introduction**

2 Kisspeptin, which is encoded by the *Kiss1* gene, is known for its principal role
3 in reproductive function by regulating the hypothalamic-pituitary-gonadal axis, and it
4 primarily controls gonadotropin-releasing hormone (GnRH) neurons in the hypothalamus
5 [1]. The *Kiss1* gene and the kisspeptin receptor (Kiss1R) are broadly distributed in the
6 brain. In rodents, kisspeptin neurons are located in the two different hypothalamic areas,
7 the anteroventral periventricular nucleus (AVPV) and the arcuate nucleus (ARC).
8 Kisspeptin neurons in the AVPV region, in which the *Kiss1* gene is upregulated by
9 estradiol (E2), are known to be involved in the E2-induced GnRH/luteinizing hormone
10 (LH) surge, whereas ARC kisspeptin neurons, which coexpress neurokinin B (NKB) and
11 dynorphin (Dyn) and in which E2 downregulates the *Kiss1* gene, maintain pulsatile
12 release of GnRH [2-5]. In addition to the two major populations, there are other
13 populations of kisspeptin neurons in the hypothalamus, such as those in the ventromedial
14 hypothalamus and paraventricular nucleus [6,7]. Extrahypothalamic kisspeptin neurons
15 have also been detected in bed nucleus of the stria terminalis and median amygdala [6,8].

16 Kisspeptin produced by the hypothalamus is known to be released into the
17 peripheral circulation because kisspeptin has been detected in the hypophyseal portal
18 blood [9]. This observation implies that the hypothalamic peptide kisspeptin directly
19 modulates hormone secretion from the anterior pituitary as a hypothalamic factor. In
20 addition, kisspeptin and Kiss1R are expressed in peripheral organs outside the central
21 nervous system [10,11]. The pituitary gland also expresses the *Kiss1* gene and Kiss1R
22 [12], suggesting that pituitary hormones might also be under the influence of kisspeptin
23 in an autocrine and/or paracrine fashion.

24 The anterior pituitary gland is composed of five major different hormone-

1 secreting cells: corticotrophs, thyrotrophs, gonadotrophs, somatotrophs, and lactotrophs.
2 These cells synthesize and secrete adrenocorticotrophic hormone (ACTH), thyroid-
3 stimulating hormone (TSH), gonadotropins (LH and follicle-stimulating hormone [FSH]),
4 growth hormone (GH), and prolactin under the influence of relatively specific
5 hypothalamic peptides such as corticotropin-releasing hormone, thyrotropin-releasing
6 hormone (TRH), GnRH, and GH-releasing hormone. In addition to the primary
7 secretagogues, several in vitro studies support the hypothesis that hypothalamic
8 kisspeptin can also act at the pituitary level and modulate pituitary function. In rat, bovine,
9 and porcine pituitary cultures, kisspeptin stimulates the release of GH, prolactin, and LH
10 [13-15]. However, the first studies using cultured rat pituitary cells and anterior pituitary
11 fragments did not demonstrate any direct effect on gonadotropin secretion [16,17]. In
12 addition, in vitro experiments using baboon pituitary cell cultures produced no evidence
13 that ACTH and TSH release are modulated by kisspeptin, although LH and GH release
14 was reported to be stimulated in this culture [18]. As for the gonadotropin regulation by
15 kisspeptin in pituitary gonadotrophs, we have previously reported that kisspeptin had a
16 direct effect on the mouse pituitary gonadotroph cell line L β T2 and increased both LH β -
17 and FSH β -subunit-promoter transcriptional activities [19].

18 Previous studies suggest that kisspeptin might have a direct effect on pituitary
19 prolactin-producing cells. Kisspeptin increases the prolactin release from cultured bovine
20 anterior pituitary cells, but its effect was less potent than that of TRH [20]. However, in
21 another study using rat anterior pituitary cell cultures, kisspeptin failed to modulate
22 prolactin release [21]. In addition, kisspeptin has been shown to stimulate prolactin
23 secretion and gene expression by directly acting at the pituitary level in goldfish [22];
24 however, the capacity of this peptide to modulate prolactin has not been confirmed in in

1 vivo studies using goats [23].

2 In this study, we focused on the direct effect of kisspeptin on prolactin-producing
3 pituitary cells. We utilized GH3 cells, which are a clonal strain of rat pituitary tumor and
4 can synthesize and secrete both prolactin and GH [24]. We confirmed the presence of
5 Kiss1R in these cells, and examined the direct effect of kisspeptin in these cells.

6

1 **Materials and Methods**

2 **Materials**

3 The following chemicals and reagents were sourced as follows: fetal bovine
4 serum (FBS) and trypsin (GIBCO, Invitrogen, Carlsbad, CA); Dulbecco's modified
5 Eagle's medium (DMEM), penicillin-streptomycin, TRH (Sigma-Aldrich, St. Louis,
6 MO); pituitary adenylate cyclase-activating polypeptide 38 (PACAP38, Peptide Institute,
7 Osaka, Japan); kisspeptin-10 (KP10) (ANA SPEC, Fremont, CA); serum response
8 element (SRE) and cAMP-response element (CRE) firefly luciferase reporter genes
9 (pSRE-Luc and pCRE-Luc) and pCI-neo (Promega, Madison, WI).

10

11 **Cell culture**

12 GH3 cells were plated in 35-mm tissue culture dishes and incubated in high-
13 glucose DMEM containing 10% heat-inactivated FBS and 1% penicillin-streptomycin at
14 37°C in a humidified atmosphere of 5% CO₂ in air. After 24 h, the culture medium was
15 changed to high-glucose DMEM containing 1% heat-inactivated FBS and 1% penicillin-
16 streptomycin and incubated without (control) or with test reagents for the indicated times.

17

18 **Western blot analysis**

19 GH3 cell extracts were lysed on ice with RIPA buffer (phosphate-buffered saline
20 [PBS], 1% NP-40, 0.5% sodium deoxycholate, 0.1% sodium dodecyl sulfate [SDS])
21 containing 0.1 mg/mL phenylmethylsulfonyl fluoride, 30 mg/mL aprotinin, and 1 mM
22 sodium orthovanadate, scraped for 20 s, and centrifuged at 14,000 × g for 10 min at 4°C.
23 Protein concentration in the cell lysate supernatants was measured using the Bradford
24 method. Denatured protein (10 µg per well) was resolved in 10% SDS polyacrylamide

1 gel electrophoresis (SDS-PAGE) gels according to standard protocols. Protein was
2 transferred onto polyvinylidene difluoride membranes (Hybond-P PVDF, Amersham
3 Biosciences, Little Chalfont, UK), which were blocked for 2 h at room temperature in
4 Blotto (5% milk in Tris-buffered saline). Membranes were incubated with anti-Kiss1R
5 antibody (1:200 dilution; Santa Cruz Biotechnology, Inc., Dallas, TX) in Blotto overnight
6 at 4°C and washed 3 times for 10 min per wash with Tris-buffered saline/1% Tween.
7 Subsequent incubation with horseradish peroxidase-conjugated monoclonal antibody was
8 performed for 1 h at room temperature in Blotto, and additional washes were performed
9 appropriately. Following enhanced chemiluminescence detection (Amersham
10 Biosciences), membranes were exposed to X-ray film (Fujifilm, Tokyo, Japan). Extracts
11 from rat anterior pituitary tissue were used as positive control, whereas extracts from
12 COS7 cells, which are devoid of Kiss1R, were used as negative control [25].

13

14 **Receptor overexpression**

15 The human GPR54 (Kiss1R) vector was generously provided by Dr. Ursula
16 Kaiser (Brigham and Women's Hospital and Harvard Medical School, Boston, MA) and
17 the PACAP type I receptor (PAC1R)-expressing vector (HA-tagged PAC1R/pEF-BOS in
18 pCAM17) was kindly provided by Prof. A. Baba (Osaka University) [26]. Cells were
19 transiently transfected via electroporation with either Kiss1R or PAC1R expression
20 vectors. An empty vector (pCI neo) served as the mock control.

21

22 **Transfections and luciferase assays**

23 The prolactin promoter reporter construct used was generated by fusing
24 -609/+12 of the prolactin gene to the firefly luciferase cDNA in pGL3 (PRL-Luc), as

1 previously described [27]. To determine the extracellular signal-related kinase (ERK)-
2 and cAMP/protein kinase A (PKA)-mediated signaling activity, pSRE-Luc (2.0 µg/well;
3 contains tandem repeats of the *Sre* enhancer [×4] upstream of the firefly luciferase gene)
4 and pCRE-Luc (2.0 µg/well; contains tandem repeats of the CRE enhancer [×4] upstream
5 of the firefly luciferase gene) were applied. GH3 cells were transiently transfected by
6 electroporation [28] with 2.0 µg/dish of reporter construct and 0.1 µg of pRL-TK
7 (Promega), which expresses *Renilla* luciferase, and plated in 35-mm tissue culture dishes.
8 When Kiss1R and PAC1R were expressed in GH3 cells, Kiss1R- and PAC1R-expressing
9 vectors were transiently transfected together with these luciferase expression vectors.
10 After stimulation, cells were washed with ice-cold PBS and lysed with Passive Lysis
11 Buffer (Promega). Cell debris was pelleted by centrifugation at 14,000 × g for 10 min at
12 4°C, and firefly luciferase and *Renilla* luciferase activities were measured in the
13 supernatants with the Dual-Luciferase Reporter Assay System using a luminometer (TD-
14 20/20) (Promega) according to the manufacturer's protocol. Firefly luciferase activity was
15 normalized to *Renilla* luciferase activity to correct for transfection efficiency, and the
16 results are expressed as the fold increase compared to the unstimulated control. All
17 experiments were performed independently, three times, each with triplicate samples.

18

19 **RNA preparation, reverse transcription, RT-PCR, and real-time quantitative RT-** 20 **PCR**

21 Total RNA from untreated or treated GH3 cells was extracted using
22 commercially available TRIzol-S (GIBCO BRL Life Technologies) according to the
23 manufacturer's instructions. Total RNA of female rat anterior pituitary tissue, which was
24 excised under deep sodium pentobarbital anesthesia, was used as positive control. This

1 protocol was approved by the committee of the Experimental Animal Center for
2 Integrated Research in Shimane University (IZ27-82). To obtain cDNA, 1.0 µg of total
3 RNA was reverse transcribed using an oligo-dT primer (Promega), and was prepared
4 using a First-Strand cDNA Synthesis Kit (GIBCO, Invitrogen) in reverse transcription
5 (RT) buffer. The preparation was supplemented with 10 mM dithiothreitol, 1 mM each
6 dNTP, and 200 units of RNase inhibitor/human placenta ribonuclease inhibitor
7 (Ribonuclease Inhibitor, Code No. 2310, Takara, Tokyo, Japan) in a final volume of 10
8 µl. The reaction was incubated at 37°C for 60 min. For the detection of *Kiss1r* mRNA,
9 after PCR amplification using primers for *Kiss1r* (sense: 5'-
10 CTGCCACAGACGTCACCTTTC-3', antisense: 5'-ACATACCAGCGGTCCACACT-3')
11 [29], amplicons were electrophoresed in a 2.0% agarose gel and visualized with ethidium
12 bromide staining. cDNAs from rat anterior pituitary tissues and COS7 cells were used as
13 positive and negative controls, respectively. Quantification of *Kiss1r* and *Prl* mRNA was
14 obtained through real-time quantitative PCR (ABI Prism 7000, Perkin Elmer Applied
15 Biosystems, Foster City, CA) following the manufacturer's protocol (User Bulletin No.
16 2), and utilizing Universal ProbeLibrary Probes and FastStart Master Mix (Roche
17 Diagnostics, Mannheim, Germany). Using specific primers for *Kiss1r* [29] and *Prl* (sense:
18 5'-AATGACGGAAATAGATGATTG-3', antisense: 5'-
19 CCAGTTATTAGTTGAAVAGA-3') [27], the simultaneous measurement of the mRNA
20 of interest and GAPDH mRNA permitted normalization of the amount of cDNA added
21 per sample. For each set of primers, a no-template control was included. The thermal
22 cycling conditions were 95°C for 10 min for denaturation, followed by 40 cycles of 95°C
23 for 15 s and 60°C for 1 min. The cycle threshold (Ct) was determined using PRISM 7000
24 software and post-amplification data were analyzed using the delta-delta Ct method with

1 Microsoft Excel.

2

3 **Statistical analysis**

4 All experiments were independently repeated at least three times. Each
5 experiment in each experimental group was performed using either triplicate samples
6 (luciferase assay) or duplicate samples (real-time RT-PCR). Briefly, when we determined
7 the mRNA expression, two samples were assayed in duplicate. Six averages from three
8 independent experiments were statistically analyzed. For the luciferase assay, three
9 samples were assayed in one experiment, and three averages were statistically analyzed.
10 Data are expressed as the mean \pm standard error of the mean. Statistical analysis was
11 performed using one-way ANOVA and Bonferroni's post hoc test. $P < 0.05$ was
12 considered statistically significant.

13

14

1 **Results**

2 **Expression of Kiss1R and the effect of kisspeptin on prolactin-promoter activity in** 3 **GH3 cells**

4 First, we examined whether GH3 cells express Kiss1R. RT-PCR analysis using
5 specific primers for *Kiss1r* revealed that *Kiss1r* mRNA could be detected in the extracts
6 from rat anterior pituitary tissues as well as GH3 cells (Fig. 1A). *Kiss1r* mRNA was not
7 detected in COS7 cells, which are a fibroblast-like cell line derived from monkey kidney.
8 Western blotting analysis using anti-Kiss1R antibody revealed that Kiss1R protein was
9 also expressed in GH3 cells (Fig. 1B). Next, we examined the direct effect of kisspeptin
10 on prolactin expression using GH3 cells. Stimulating the GH3 cells with increasing
11 concentrations of kisspeptin failed to modulate the transcriptional activity of the prolactin
12 promoter. TRH, a known prolactin secretagogue, stimulated the prolactin promoters 3.02
13 \pm 0.18-fold ($P < 0.01$) in these cells (Fig. 2A). Because endogenous Kiss1R did not
14 respond to exogenous kisspeptin, we overexpressed Kiss1R in the GH3 cells. When GH3
15 cells were transfected with Kiss1R-expressing vectors, the cells clearly responded to
16 kisspeptin and increased the activity of the prolactin promoter. In Kiss1R-overexpressing
17 GH3 cells, kisspeptin stimulation significantly increased prolactin-promoter activity
18 compared to the untreated cells: 1.69 \pm 0.09-fold ($P < 0.05$) at 10 nM and 2.49 \pm 0.11-
19 fold ($P < 0.01$) at 1 μ M kisspeptin (Fig. 2B).

20

21 **Effect of kisspeptin on SRE- and CRE-promoter activity in GH3 cells overexpressing** 22 **Kiss1R**

23 To examine the signaling pathways activated by kisspeptin in Kiss1R-
24 overexpressing GH3 cells, we performed SRE- and CRE-luciferase promoter assays. SRE

1 is a DNA domain in the promoter region that binds to ERK-mediated transcription factors,
2 and SRE-promoter activity reflects ERK-mediated signaling pathway activity. The CRE
3 promoter is a known target of the CRE-binding protein, and the CRE-luciferase reporter
4 system reflects the activity of the cAMP/PKA signaling pathway. In mock-transfected
5 GH3 cells, neither the SRE nor the CRE promoter was activated by kisspeptin stimulation
6 (data not shown). When Kiss1R was overexpressed in these cells, both SRE- and CRE-
7 promoters were dramatically activated by kisspeptin. At 1 μ M kisspeptin stimulation,
8 SRE- and CRE- promoters were activated 66.46 ± 15.19 -fold and 94.42 ± 9.62 -fold,
9 respectively, relative to the control (Fig. 3A and B).

11 **Effect of kisspeptin on TRH- or PACAP-induced prolactin-promoter activity**

12 TRH is a principal secretagogue for prolactin. In addition, PACAP participates
13 in prolactin regulation [30]. To clearly observe the effect of both kisspeptin and PACAP,
14 both receptors were overexpressed for the experiments. In GH3 cells overexpressing both
15 Kiss1R and PAC1R, kisspeptin and TRH similarly stimulated prolactin-promoter activity
16 by 2.60 ± 0.10 -fold and 3.18 ± 0.45 -fold, respectively, compared with the unstimulated
17 controls, but combined treatment with kisspeptin and TRH did not enhance their
18 individual effects (TRH alone, 3.18 ± 0.45 -fold vs. kisspeptin+TRH, 2.87 ± 0.53 -fold;
19 not significant). However, PACAP stimulated prolactin-promoter activity to a greater
20 degree compared to that stimulated by kisspeptin (4.32 ± 0.39 -fold), and combined
21 stimulation with kisspeptin and PACAP significantly further increased prolactin-promoter
22 activity compared with that by kisspeptin or PACAP alone (PACAP alone, 4.32 ± 0.39 -
23 fold vs. kisspeptin + PACAP, 5.20 ± 0.11 -fold; $P < 0.01$) (Fig. 4). Next, we determined
24 the SRE- and CRE-promoter activities stimulated by kisspeptin, TRH, and PACAP.

1 Kisspeptin dramatically increased SRE-promoter activity (99.79 ± 10.27 -fold) compared
2 with that by TRH stimulation (6.44 ± 0.70 -fold) in Kiss1R- and PAC1R-overexpressing
3 GH3 cells. Combined stimulation with kisspeptin and TRH failed to potentiate the effect
4 of kisspeptin alone (105.47 ± 19.62 -fold). PACAP stimulated SRE-promoter activity to a
5 lesser degree than that stimulated by kisspeptin (14.88 ± 1.30 -fold), and combined
6 stimulation with kisspeptin and PACAP significantly increased the SRE-promoter activity
7 compared with that stimulated by kisspeptin alone (kisspeptin alone, 99.79 ± 10.27 -fold
8 vs. kisspeptin+PACAP, 150.91 ± 23.71 -fold; $P < 0.05$) (Fig. 5A). The patterns of CRE-
9 promoter activity stimulation were distinct from those of the SRE promoter. Both
10 kisspeptin and TRH significantly increased CRE-promoter activity 26.73 ± 0.91 -fold and
11 71.69 ± 4.24 -fold, respectively, and combined stimulation with kisspeptin and TRH did
12 not enhance the effect of TRH alone (TRH alone, 71.69 ± 4.24 -fold vs. kisspeptin+TRH,
13 89.66 ± 2.60 -fold; not significant). PACAP more potently activated CRE-promoter
14 activity, 798.28 ± 50.06 -fold, compared with kisspeptin or TRH. Although TRH-induced
15 CRE-promoter activity was not modified in the presence of kisspeptin, PACAP-
16 stimulated CRE-promoter activity was significantly potentiated in the presence of
17 kisspeptin (PACAP alone, 798.28 ± 50.06 -fold vs. kisspeptin+PACAP, $1,182.67 \pm 58.97$ -
18 fold; $P < 0.01$) (Fig. 5B).

19

20 **Effect of increasing amounts of Kiss1R-expressing vector transfection in GH3 cells** 21 **on kisspeptin- and TRH-induced prolactin-promoter activity**

22 Next, we examined how the cell responses changed according to Kiss1R
23 expression levels. GH3 cells were transfected with different amounts of Kiss1R
24 expression vector and stimulated with kisspeptin. The basal activity and TRH- or

1 kisspeptin-induced fold induction of prolactin-promoter activity were compared. Basal
2 activity of the prolactin promoter was unchanged by transfection of increasing amounts
3 of Kiss1R expression vector (Fig. 6A). TRH-induced fold induction of prolactin-promoter
4 activity was not modified by the dose of transfected Kiss1R expression vector (Fig. 6B).
5 However, kisspeptin-stimulated prolactin-promoter activity was significantly higher in
6 the cells transfected with 2.0 and 4.0 μg of Kiss1R vector (3.75 ± 1.27 -fold and $2.44 \pm$
7 0.58 -fold, respectively) compared with that in cells transfected with 1.0 μg of Kiss1R
8 vector (1.66 ± 0.25 -fold) (Fig. 6C).

9

10 **Effect of E2 on Kiss1R expression and function**

11 Next, we examined how endogenous *Kiss1r* mRNA is regulated in GH3 cells.
12 TRH (100 nM) did not stimulate *Kiss1r* gene expression in GH3 cells. However,
13 treatment of cells with 100 nM E2 significantly increased *Kiss1r* mRNA expression,
14 which was increased 1.72 ± 0.2 -fold compared with untreated cells (Fig. 7A). *Kiss1r*
15 mRNA was not increased by concentrations of E2 lower than 100 nM (data not shown).
16 Furthermore, we found that GH3 cells acquired responsiveness to kisspeptin after the 48-
17 h treatment with 100 nM E2. GH3 cells that were not overexpressing Kiss1R were treated
18 with E2 for 48 h and then stimulated with kisspeptin. In E2-treated GH3 cells, but not in
19 untreated GH3 cells, kisspeptin significantly increased *Prl* mRNA expression 1.90 ± 0.16 -
20 fold compared to unstimulated cells (Fig. 7B).

21

22

1 **Discussion**

2 The importance of hypothalamic kisspeptin in the regulation of hypothalamic
3 GnRH neurons has been well documented, but accumulating evidence suggests that
4 kisspeptin also plays a role as a hypophysiotropic hormone and acts directly within the
5 pituitary gland. As for prolactin control by kisspeptin at the pituitary level, previous in
6 vivo studies showed divergent responses. Central intracerebroventricular injection of
7 kisspeptin reduced the prolactin release in both male and female mice [31], while Szawka
8 et al. observed an increase in prolactin by the same kisspeptin stimulation [21].
9 Stimulatory effects of kisspeptin on prolactin expression and release are also observed in
10 the goldfish pituitary [22], but not in goats [23]. It was also reported that kisspeptin could
11 inhibit dopamine neurons in the hypothalamus and modulate prolactin output [21].

12 In this study, we sought to clarify the action of kisspeptin at the single population
13 of prolactin-producing lactotrophs to evaluate the direct effect of kisspeptin on the
14 anterior pituitary cells. Because of the difficulty of isolating single-cell populations of
15 pituitary lactotrophs from anterior pituitary cells, we used the rat somatolactotroph cell
16 line, GH3. These cells are a clonal strain of rat pituitary tumor and can synthesize and
17 secrete both prolactin and GH [24]. GH3 cells respond to TRH and increase their
18 synthesis and secretion of prolactin, but TRH reduces the synthesis of GH [24,27]. We
19 found that GH3 cells express Kiss1R. Because GH3 cells are a pituitary prolactin-
20 producing cell model, it is plausible that normal prolactin-producing cells in the pituitary
21 gland express Kiss1R and are directly influenced by hypothalamic kisspeptin.
22 Unexpectedly, GH3 cells did not respond to kisspeptin and failed to modulate the
23 transcriptional activity of the prolactin promoter. We sometimes encounter similar
24 problems when we use immortalized-cell models. The pituitary gonadotroph cell line

1 L β T2 expresses Kiss1R, but these cells do not respond to kisspeptin without Kiss1R
2 overexpression [19]. Similarly, the mouse GnRH-producing cell model GT1-7 expresses
3 Kiss1R, but kisspeptin failed to induce responses in these cells without Kiss1R
4 overexpression [32]. We postulate that endogenous Kiss1R is reduced or not functional,
5 probably due to cell immortalization or multiple passages in these immortalized-cell
6 models. Thus, we used GH3 cells overexpressing Kiss1R as a prolactin-producing cell
7 model in our experiments to determine the effect of kisspeptin.

8 When GH3 cells overexpressed Kiss1R, they clearly responded to kisspeptin and
9 increased prolactin-promoter activity. These observations clearly demonstrated that the
10 kisspeptin/Kiss1R system in prolactin-producing cells has the ability to stimulate
11 prolactin expression. Both SRE- and CRE-reporter luciferase activities were increased by
12 kisspeptin stimulation in GH3 cells overexpressing Kiss1R, suggesting that the
13 overexpressed Kiss1R coupled with Gq and Gs proteins and increased both ERK and
14 cAMP/PKA signaling pathways. Previous studies revealed that kisspeptin can activate a
15 variety of signals via Kiss1R, which includes Gq protein-involved activation of
16 phospholipase C (PLC) and subsequent accumulation of inositol triphosphate (IP3),
17 intracellular Ca²⁺ mobilization, and activation of protein kinase C. Kisspeptin also
18 activates ERK, P38 MAPK, and PI3K/Akt [33]. Although early studies showed that
19 Kiss1R does not couple with Gs protein and does not increase cAMP accumulation
20 [11,34], it was subsequently shown that kisspeptin can increase cAMP accumulation in
21 goldfish pituitary cells [35] and in GnRH-producing GT1-7 cells [32].

22 Being the principal prolactin secretagogue, TRH could of course stimulate
23 prolactin-promoter activity in our experiments. The hypothalamic peptide PACAP also
24 works as a prolactin-stimulating factor [36]. Interestingly, combined stimulation with

1 kisspeptin and TRH failed to potentiate their individual effects on the prolactin promoter;
2 however, the combination of kisspeptin and PACAP further stimulated prolactin-
3 promoter activity compared to that stimulated individually. The TRH receptor couples
4 with Gq protein and activates PLC-mediated signaling pathways, which includes IP3
5 accumulation or Ca²⁺ mobilization [37]. PACAP receptors, such as the PACAP type I
6 receptor, mainly couple with Gs protein, which binds to adenylate cyclase, leading to the
7 accumulation of cAMP and subsequent activation of PKA [38]; PACAP has also been
8 shown to activate ERK signaling pathways in a PKA-dependent manner [28]. We
9 presume that combined treatment with kisspeptin and TRH did not enhance their
10 prolactin-producing ability because Kiss1R and the TRH receptor share common
11 signaling pathways that are mainly initiated by Gq protein and PLC. Indeed, stimulation
12 of SRE- and CRE-promoter activities was not potentiated by the combined treatment with
13 kisspeptin and TRH. In contrast, prolactin-promoter activity could be enhanced by
14 combined stimulation with kisspeptin and PACAP, with concomitant enhancement of
15 SRE- and CRE-promoter activities, hypothetically because the main signal transduction
16 systems are distinct between Kiss1R and the PACAP receptor.

17 GH3 cells express Kiss1R, but they did not respond to kisspeptin. Interestingly,
18 the function of endogenous Kiss1R in these cells was recovered in the presence of 100
19 nM E2. In addition, we found that the same concentration of E2 could increase the
20 expression of Kiss1R in these cells. Although it is still unclear whether our experiments
21 actually reflect the physiological situation, our current observations imply that E2 has
22 some roles in prolactin-producing cells by modulating the expression and function of
23 Kiss1R. The importance of E2 in the functional effects of kisspeptin was previously
24 described. In ewes, primary pituitary cell cultures responded to kisspeptin and increased

1 LH secretion only when the cells were obtained during the follicular phase of the estrous
2 cycle, while no response was seen in cells from the luteal phase or from ovariectomized
3 animals [9]. In an ovariectomized rat model, pre-exposure to E2 was effective in
4 achieving maximal LH release in response to kisspeptin [39]. Similarly, the effect of
5 kisspeptin on gonadotropin release in women is greater in the preovulatory phase but
6 lower in the follicular phase of the menstrual cycle [40]. In addition, an in vitro study
7 using GnRH-producing GT1-7 cells demonstrated that E2 induced Kiss1R expression
8 [41].

9 The prolactin-inducing ability of kisspeptin was altered by the amount of Kiss1R
10 expression vector transfected into the GH3 cells. In short, kisspeptin-stimulated prolactin-
11 promoter activity increased with increasing amounts of Kiss1R vector. A similar
12 phenomenon was also observed in gonadotropin-producing cells. The mouse gonadotroph
13 cell line L β T2 expresses Kiss1R and increasing Kiss1R expression potentiates the ability
14 of kisspeptin to increase LH β -subunit promoter transcriptional activity [19]. Although the
15 amount of Kiss1R vector did not modify the basal and TRH-induced transcriptional
16 capacities of the prolactin promoter in this study using GH3 cells, the basal activity of
17 both LH β - and FSH β -subunit promoters in L β T2 cells was modified [19]. The increase
18 in Kiss1R number under the influence of E2 might introduce some other influences on
19 prolactin-producing cells.

20 Regarding the inconsistencies between previous reports on the action of
21 kisspeptin and our current observations of the effect of E2 on kisspeptin/Kiss1R functions,
22 it is plausible that conflicting results concerning the direct effect of kisspeptin on prolactin
23 secretion and gene expression depend on the hormonal milieu of the experimental models.
24 Developmental stage, male versus female, or day of the estrous cycle of the experimental

1 female animals might determine the sensitivity of pituitary lactotrophs to kisspeptin in
2 the in vivo studies. Furthermore, kisspeptin may not only directly affect lactotrophs, but
3 may also influence other regulators of prolactin. Indeed, it was reported that dopamine
4 neurons, known negative regulators of prolactin, receive synaptic input from kisspeptin
5 neurons and modulate prolactin secretion [21,42,43]. Furthermore, a recent study using a
6 female rat model demonstrated that kisspeptin stimulation of prolactin release requires
7 estrogen receptor α [44]. On the other hand, experiments using pituitary cell cultures were
8 also influenced by many other local factors within the anterior pituitary because primary-
9 culture cells contained multiple different cell types including at least 5 different hormone-
10 secreting cells. In addition, as with the in vivo studies, the characteristics of pituitary cells
11 would be dissimilar depending on the species, developmental stage, sex difference, or the
12 day of the estrous cycle when the cells were obtained. The culturing periods prior to using
13 the cells might also influence the responsiveness of the cells to kisspeptin because the
14 disappearance of E2 after removing pituitaries from the animals could diminish the
15 function of Kiss1R in the pituitary cells.

16 In this study, we used somatolactotroph GH3 cells overexpressing Kiss1R to
17 examine the direct effect of kisspeptin on prolactin-producing cells. We found that
18 Kiss1R is expressed in a pituitary prolactin-producing cell model and obtained evidence
19 that kisspeptin has a direct effect on this cell by stimulating prolactin production.
20 Furthermore, we showed that E2 plays an important role in modulating kisspeptin's effect
21 on these cells. We realize that our current study and results do not completely reflect the
22 physiological condition of prolactin-producing cells in vivo. However, these prolactin-
23 producing cells originating from rat express Kiss1R, suggesting that normal lactotrophs
24 in the pituitary gland express Kiss1R. In addition, from the observations that Kiss1R was

1 functional in GH3 cells (by artificial Kiss1R overexpression or E2 treatment) and that
2 kisspeptin could stimulate intracellular signaling and stimulate prolactin gene expression,
3 we could speculate that normal lactotrophs, which express functional Kiss1R, would
4 respond to kisspeptin and increase prolactin production. In our current study using clonal
5 prolactin-producing cells, the cells were not influenced by any other factors except
6 kisspeptin when we stimulated them with kisspeptin. Our current observations suggest an
7 important role of kisspeptin/Kiss1R in the regulation of pituitary lactotroph functions.

8 9 **Compliance with Ethical Standards**

10 **Funding**

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12 Ministry of Education, Culture, Sports, Science and Technology of Japan (No. 17K11237).

14 **Conflict of interest**

15 The authors declare that they have no competing interests.

17 **Ethical approval**

18 All applicable international, national, and/or institutional guidelines for the care and use
19 of animals were followed.

21 **Informed consent**

22 For this type of study, formal consent is not required.

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27

28

1 **Figure Legends**

2 Fig. 1. Expression of Kiss1R in GH3 cells.

3 (A) Total RNA from GH3 cells and rat anterior pituitary tissues were prepared and RT-
4 PCR was carried out for 40 cycles using *Kiss1r*-specific primers. PCR products were
5 resolved in a 2.0 % agarose gel and visualized with ethidium bromide staining. (B) Cell
6 lysates (10 µg) from GH3 cells and rat anterior pituitary tissues were analyzed by SDS-
7 PAGE followed by immunoblotting and incubation with antibody against Kiss1R. The
8 bands were visualized using horseradish peroxidase-conjugated secondary antibody.
9 Tissues from rat anterior pituitary and extracts from COS7 cells were used as positive and
10 negative controls, respectively.

11

12 Fig. 2. Effect of kisspeptin on the activity of the prolactin (PRL) promoter.

13 GH3 cells were transfected without (mock) (A) or with 2.0 µg of Kiss1R-expressing
14 vector (B), together with pRL-TK (0.1 µg) plus 2.0 µg of PRL-Luc vector. At 48 h after
15 transfection, cells were treated with increasing doses of kisspeptin (Kp10) for 6 h. A
16 firefly luciferase assay was performed to examine prolactin-promoter activity, which was
17 normalized to *Renilla* luciferase activity, and is expressed as the fold induction over the
18 unstimulated controls. Data are expressed as the mean ± standard error of the mean (three
19 independent experiments were performed using triplicate samples). **P* < 0.05, ***P* < 0.01
20 vs. control.

21

22 Fig. 3. Effect of kisspeptin on SRE- and CRE-promoter activities.

23 GH3 cells were transfected with 2.0 µg of Kiss1R-expressing vector, together with pRL-
24 TK (0.1 µg) and 2.0 µg of SRE-Luc (A) or CRE-Luc (B) vector. Forty-eight hours after

1 transfection, cells were treated with increasing amounts of kisspeptin (Kp10) for 6 h. A
2 firefly luciferase assay was performed to examine SRE- and CRE-promoter activity,
3 which was normalized to *Renilla* luciferase activity and is expressed as the fold induction
4 over the unstimulated controls. Data are expressed as the mean \pm standard error of the
5 mean (three independent experiments performed using triplicate samples). $**P < 0.01$ vs.
6 control.

7

8 Fig. 4. Effect of kisspeptin, TRH, and PACAP on prolactin-promoter activity.

9 GH3 cells were transfected with 2.0 μ g of Kiss1R-expressing and 2.0 μ g of PAC1R-
10 expressing vectors, together with 2.0 μ g of PRL-Luc and pRL-TK (0.1 μ g) vectors. Forty-
11 eight hours after transfection, cells were treated with 100 nM kisspeptin (Kp10), 100 nM
12 TRH, 100 nM PACAP, or both Kp10 and TRH or Kp10 and PACAP for 6 h. A firefly
13 luciferase assay was performed to examine prolactin-promoter activity, which was
14 normalized to *Renilla* luciferase activity and is expressed as the fold induction over the
15 unstimulated controls. Data are expressed as the mean \pm standard error of the mean (three
16 independent experiments performed using triplicate samples). $*P < 0.05$, $**P < 0.01$ vs.
17 control. The difference between PACAP and PACAP + Kp10 treatment was statistically
18 significant ($P < 0.01$). n.s., difference was not statistically significant.

19

20 Fig. 5. Effect of kisspeptin, TRH, and PACAP on SRE- and CRE-promoter activities.

21 GH3 cells were transfected with 2.0 μ g of Kiss1R-expressing and 2.0 μ g of PAC1R-
22 expressing vectors, together with pRL-TK (0.1 μ g) and 2.0 μ g of SRE-Luc (A) or CRE-
23 Luc (B) vectors. Forty-eight hours after transfection, cells were treated with 100 nM
24 kisspeptin (Kp10), 100 nM TRH, 100 nM PACAP, or both Kp10 and TRH or Kp10 and

1 PACAP for 6 h. A firefly luciferase assay was performed to examine SRE- and CRE-
2 promoter activity, which was normalized to *Renilla* luciferase activity and is expressed
3 as the fold induction over the unstimulated controls. Data are expressed as the mean \pm
4 standard error of the mean (three independent experiments performed using triplicate
5 samples). $**P < 0.01$ vs. control. The difference in SRE-promoter activity between Kp10
6 and PACAP + Kp10 treatment was statistically significant ($P < 0.05$). The difference in
7 CRE-promoter activity between PACAP and PACAP + Kp10 treatment was statistically
8 significant ($P < 0.01$). n.s., difference was not statistically significant.

9

10 Fig. 6. Effects of Kiss1R overexpression on the basal levels and the kisspeptin- and TRH-
11 induced fold induction of prolactin-promoter activity.

12 GH3 cells were transfected with 1.0 to 4.0 μg of Kiss1R-expressing vector together with
13 2.0 μg of PRL-Luc and pRL-TK (0.1 μg) vectors. Forty-eight hours after transfection,
14 cells were treated with 100 nM TRH (B) and 100 nM kisspeptin (Kp10) (C) for 6 h. A
15 firefly luciferase assay was performed to examine prolactin (PRL) promoter activity,
16 which was normalized to *Renilla* luciferase activity and expressed as basal (A) and the
17 fold induction over unstimulated controls in the mock-transfected group. The fold
18 induction of TRH-stimulated (B) and Kp10-stimulated (C) cells over unstimulated cells
19 was calculated. Data are expressed as the mean \pm standard error of the mean (three
20 independent experiments performed using triplicate samples). $**P < 0.01$ vs. mock
21 control. The differences between the 1.0 μg and higher amounts of Kiss1R-expressing
22 cells in Kp10-induced prolactin-promoter activity were statistically significant ($P < 0.05$).

23

24 Fig. 7. Effects of estradiol on *Kiss1r* mRNA expression and receptor function.

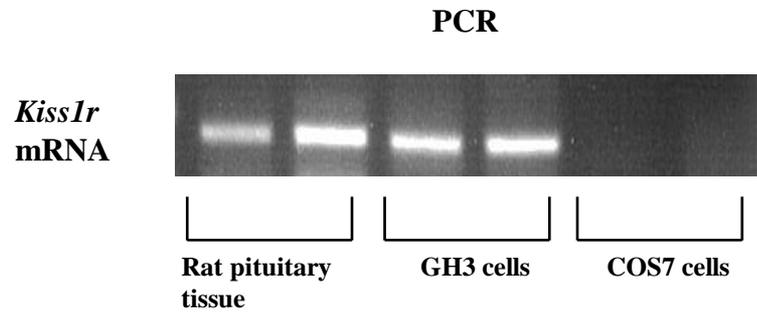
1 (A) GH3 cells were treated with 100 nM TRH and 100 nM estradiol (E2) for 48 h. *Kiss1r*
2 mRNA levels were measured by quantitative real-time PCR after mRNA extraction and
3 reverse transcription. (B) GH3 cells were pre-treated in the presence or absence of 100
4 nM E2 for 48 h, and then stimulated with kisspeptin (Kp10) for an additional 48 h.
5 Prolactin (*Prl*) mRNA levels were measured by quantitative real-time PCR after mRNA
6 extraction and reverse transcription. Samples for each experimental group were run in
7 duplicate and normalized to GAPDH mRNA levels. Results are expressed as the fold
8 induction over unstimulated cells and presented as the mean \pm standard error of the mean
9 of three independent experiments, each performed with duplicate samples. * $P < 0.05$, **
10 $P < 0.01$ vs. control.

11

12

Fig. 1

A



B

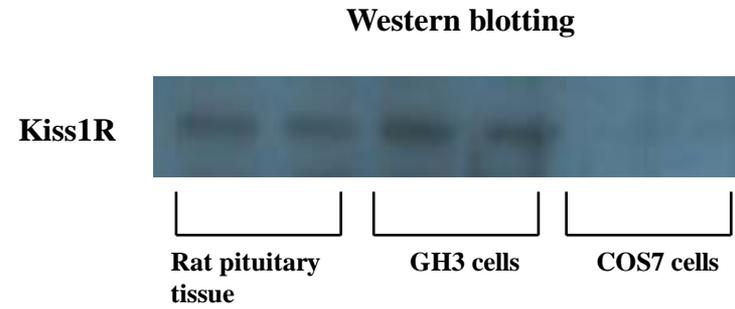


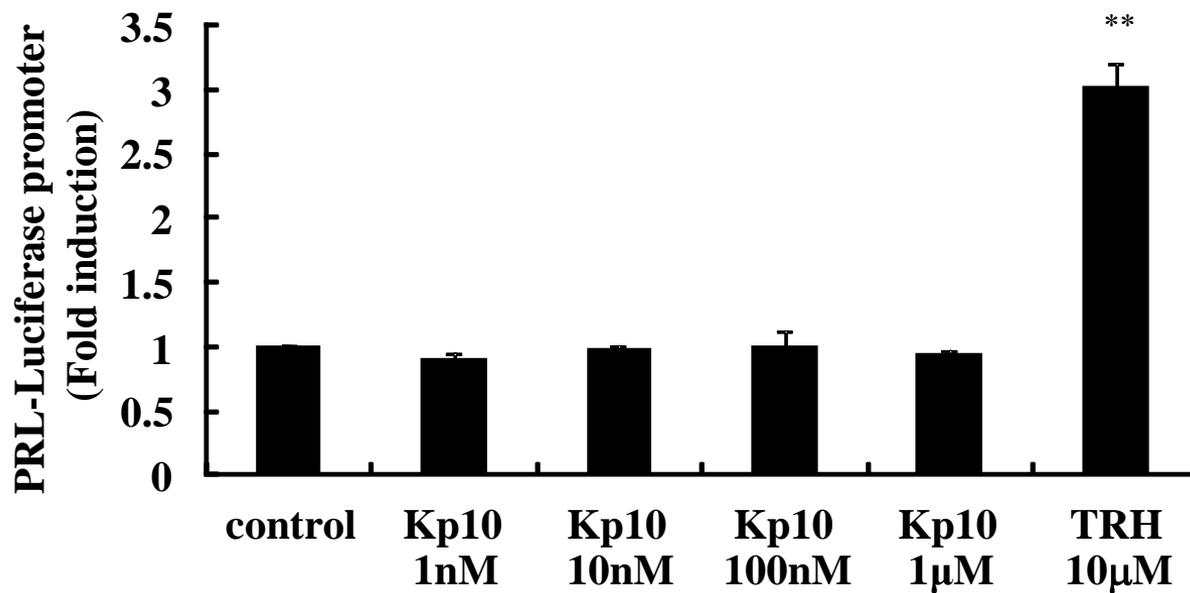
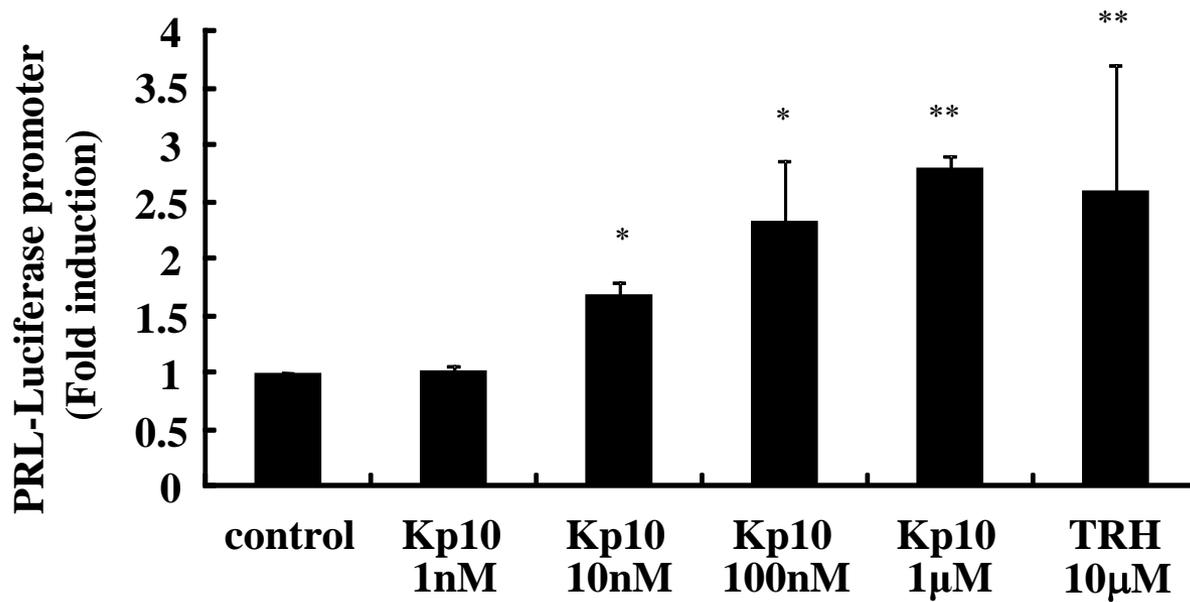
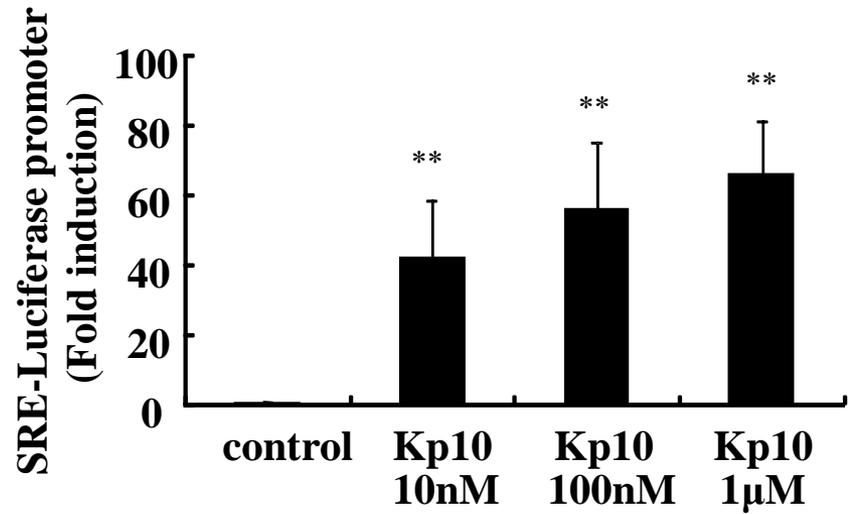
Fig. 2**A****B**

Fig. 3

A



B

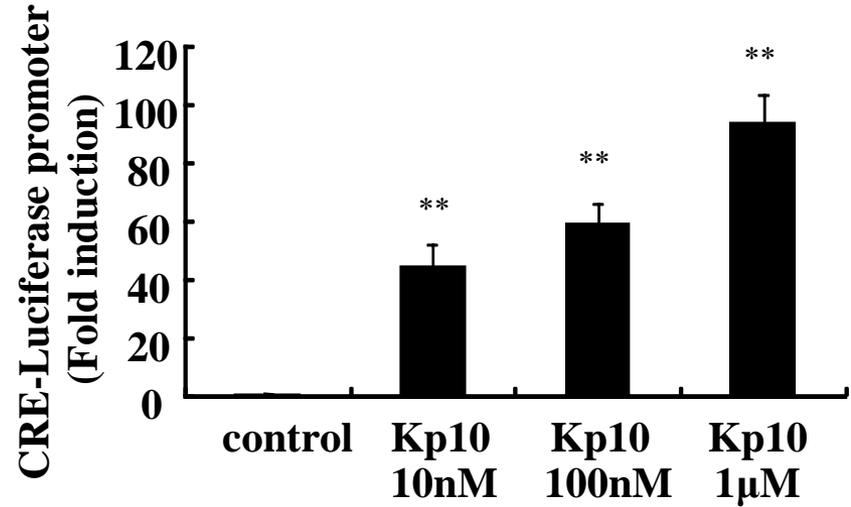


Fig. 4

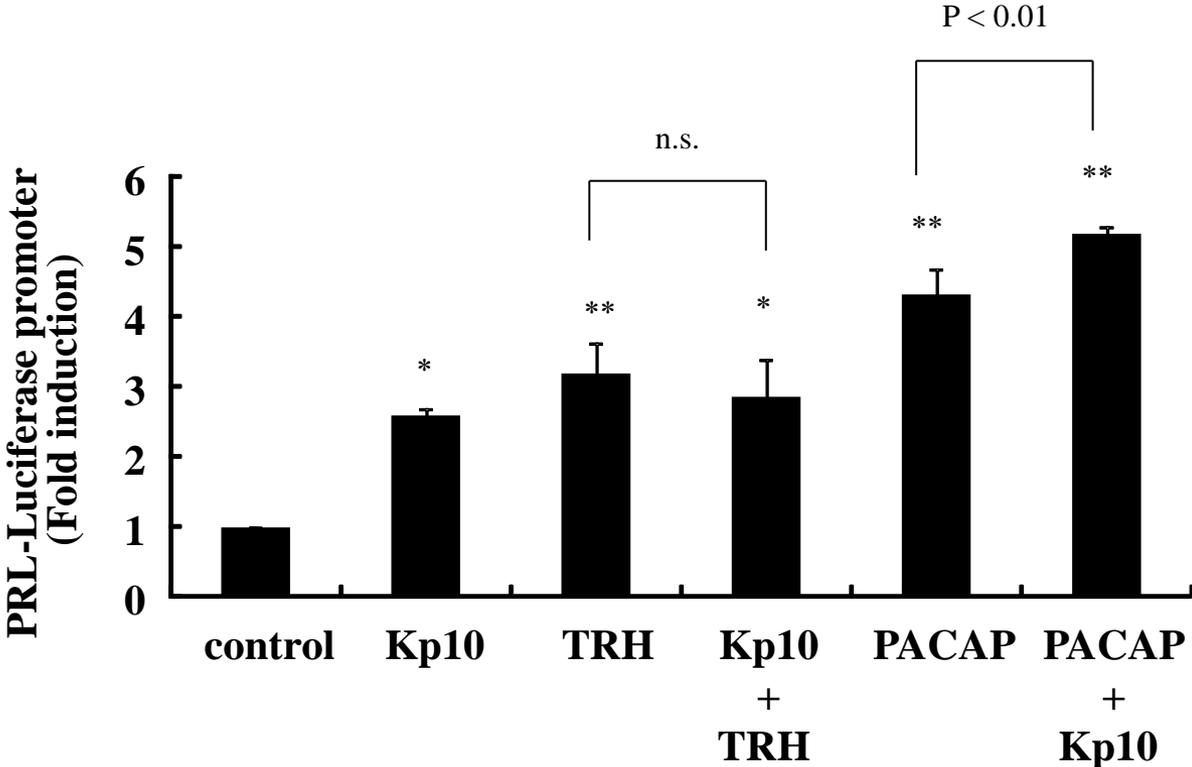


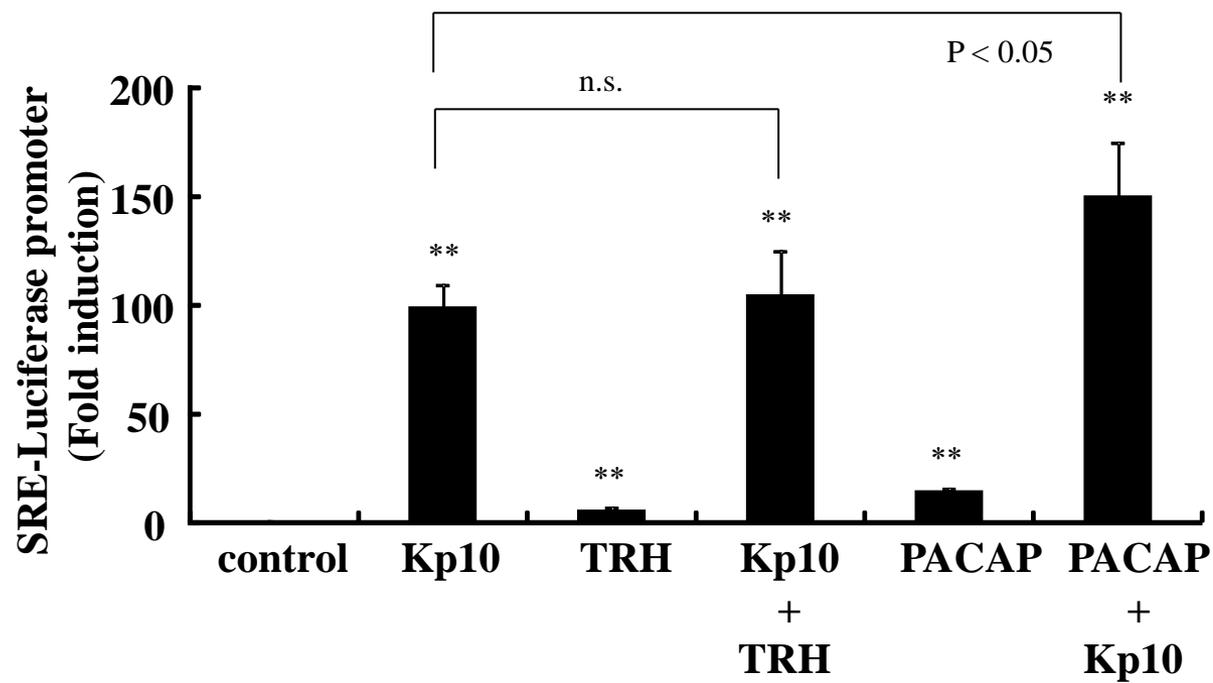
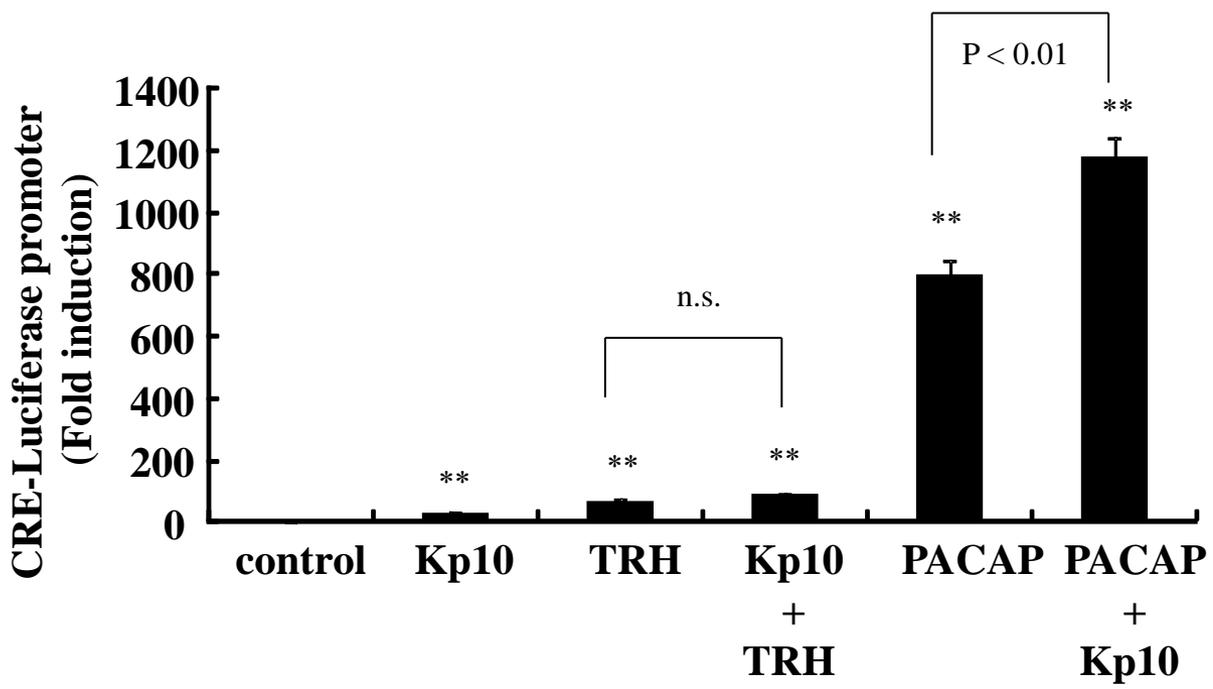
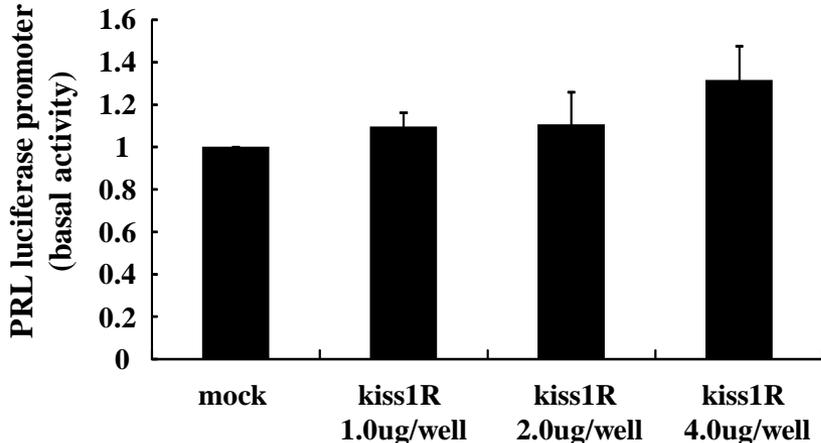
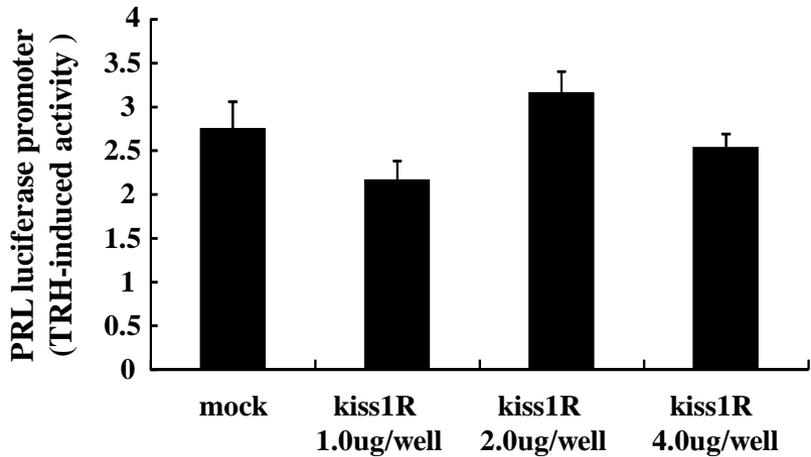
Fig. 5**A****B**

Fig. 6

A



B



C

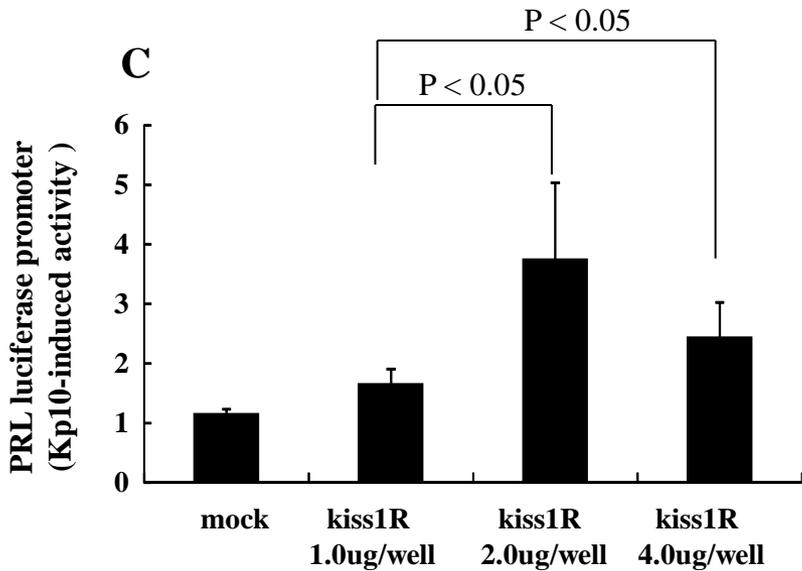


Fig. 7

