Thyrotropin Receptor Stimulates Internalization-Independent Persistent Phosphoinositide Signaling

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ABSTRACT

The thyrotropin (thyroid-stimulating hormone (TSH)) receptor (TSHR) is known to acutely and persistently stimulate cAMP signaling and at higher TSH concentrations to acutely stimulate phosphoinositide signaling. We measured persistent signaling by stimulating TSHR-expressing human embryonic kidney-EM293 cells with TSH and measuring cAMP or inositol monophosphate (IP1) production, a measure of phosphoinositide signaling, 60 min or longer after TSH removal. In contrast to persistent cAMP production, persistent IP1 production increased progressively when TSH exposure was increased from 1 to 30 min, whereas the rates of decay of persistent signaling were similar. A small-molecule agonist and a thyroid-stimulating antibody also caused persistent IP1 and cAMP signaling. A small-molecule inverse agonist and a neutral antagonist inhibited TSH-stimulated persistent IP1 production, whereas the inverse agonist but not the neutral antagonist inhibited persistent cAMP production. As with persistent cAMP production, persistent IP1 production was not affected when TSHR internalization was inhibited or enhanced. Moreover, Alexa546-TSH-activated TSHR internalization was not accompanied by persistent IP1 production when TSHR internalization was inhibited or enhanced. Thus, transient exposure to high concentrations of TSH causes persistent phosphoinositide and cAMP signaling that is not dependent on internalization. To our knowledge, this is the first demonstration of persistent activation by any G protein-coupled receptor (GPCR) via the Gαq pathway and of two G protein-mediated pathways by any GPCR.

Introduction

Although G protein-coupled receptors (GPCRs) are able to signal independently of G proteins, the major pathways for GPCR signaling involve coupling of the activated receptor to one or more G proteins (Woehler and Ponimaskin, 2009). The human thyrotropin (thyroid-stimulating hormone (TSH)) receptor (TSHR) has been shown to couple to several G proteins (Laugwitz et al., 1996), including the stimulatory G protein (Gαs), which activates adenylyl cyclase to produce cAMP (cAMP pathway), and Gαq, which activates phospholipase C to produce inositol-1,4,5-trisphosphate (1,4,5-P3) (phosphoinositide pathway). The Gαq-mediated stimulation of cAMP formation has been regarded as the principal intracellular signaling mechanism mediating the action of TSH. However, recently Kero et al. (2007) demonstrated that the Gαq/G11-mediated signaling pathway is required for TSH-induced thyroid hormone synthesis and release in the adult and that the lack of Gαq/G11 leads to hypothyroidism. Additional support for an essential physiological role of Gαq/G11 proteins in mediating the regulation of thyroid function was demonstrated by a TSHR germline mutation that preferentially affected the phosphoinositide pathway (Grasberger et al., 2007).

ABBRVIATIONS: GPCR, G protein-coupled receptor; TSH, thyroid-stimulating hormone; TSHR, thyroid-stimulating hormone receptor; IP1, inositol monophosphate; I-1,4,5-P3, inositol-1,4,5-trisphosphate; YFP, yellow fluorescent protein; HBSS, Hanks’ balanced salt solution; IBMX, 3-isobutyl-1-methylxanthine; HEEK, human embryonic kidney; βAr2, β-arrestin-2; NCGC00161870, N-[4-[[3-(furan-2-ylmethyl)-4-oxo-1,2-dihydroquinazolin-2-yl]-2-methoxyphenyl]methoxy]phenyl]acetamide; NCGC00161856, 2-[5-[[2,6-dimethylphenoxo]methyl]-4-methoxyphenyl]-3-(furan-2-ylmethyl)-1,2-dihydroquinazolin-4-one; NCGC00229600, 2-[3-[[2,6-dimethylphenoxo]methyl]-4-methoxyphenyl]-3-(pyridin-3-ylmethyl)-2,3-dihydroquinazolin-4(1H)-one.
Persistently signaling can be caused by a small-molecule agonist of TSHR and by a thyroid-stimulating antibody.

Materials and Methods

Cell Culture and Transfection. The generation of a HEK-EM293 cell line stably expressing human TSHR (HEK-TSHR cells) or human TRH receptor were described previously (Engel et al., 2006; Neumann et al., 2009). Cells were grown in Dulbecco’s modified Eagle’s medium supplemented with 10% fetal bovine serum, 100 U/ml penicillin, and 100 μg/ml streptomycin and 250 μg/ml hygromycin B (both from Invitrogen, Carlsbad, CA) at 37°C in a humidified 5% CO₂ incubator.

Cells were transiently transfected with β-arrestin-2 (βarr2) or K44A (both kindly provided by Dr. Catherine Berlot, Weis Center for Research, Geisinger Medical Center, Danville, PA) in 24-well plates (7.5 × 10⁴ cells/well) with 0.2 μg of DNA/well or on poly(D-lysine)-coated cover slips (40 × 10⁴ cells/cm²) with 0.3 μg of DNA using FuGENE6 reagent (Roche Diagnostics, Indianapolis, IN). Experiments were performed 48 or 72 h after transfection.

cAMP Production. Cells seeded into 24-well plates at a density of 2.2 × 10⁵ cells/well were cultured for 24 h. Then they were washed three times with 0.5 ml of 37°C HBBS and incubated in HBBS/10 mM LiCl at 37°C. Confocal (1.3 numerical aperture objective and are represented by slices at midpoint cell thickness. Detector gains and microscope parameters remained unchanged throughout all experimental conditions. Quantitative colocalization analysis was performed using Zeiss Zen software. Each region of interest within a confocal acquisition was assigned to include an entire cell. At least 5 unique images and 13 regions of interest were analyzed for each experimental condition. Pearson’s correlation coefficient (R) and Manders’ overlap coefficient (R) were calculated (Zinchuk and Zinchuk, 2008).

Statistical Analysis. The data were analyzed by Student’s t test or one-way analysis of variance; P < 0.05 was considered significant.

Results

We used IP1 production to quantify activation of the phosphoinositide pathway because I-1,4,5-P₃ is rapidly metabolized to IP1, and IP1 can be trapped in the presence of LiCl, which inhibits the IP1 mono phosphatase. This is similar to quantifying the cAMP pathway by measuring cAMP in the presence of IBMX, which inhibits the cAMP phosphodiesterase. Figure 1 illustrates that TSHR activation quickly leads to stimulation of the production of cAMP and IP1 in HEK-TSHR cells and confirms the observation reported previously that much lower concentrations of TSH stimulate cAMP production compared with those required for stimulation of IP1 production (Van Sande et al., 1990). TSH rapidly stimulated cAMP production with an EC₅₀ = 0.75 mM/ml and IP1 pro-
duction with an estimated EC_{50} \approx 71 \text{ mU/ml}. Indeed, the estimated EC_{50} for IP1 production is probably an underestimate because maximal stimulation may not have been achieved. We, therefore, needed to use high concentrations of TSH to stimulate both pathways simultaneously.

Figure 2 illustrates the experimental protocol we used to measure persistent TSH signaling. Cells were exposed to TSH (pretreatment), washed four times, and incubated in buffer alone (washout) and then incubated in buffer with IBMX or LiCl for measurement of cAMP or IP1 production, respectively. We had found previously that the level of activation of persistent cAMP signaling in HEK-TSHR cells by 10 \text{ mU/ml} TSH increased between 1 and 5 min and then remained constant for up to 30 min (Neumann et al., 2010a). Figure 3 illustrates the time courses of acquisition of persistent signaling by the cAMP and IP1 pathways stimulated by 100 \text{ mU/ml} TSH. This high concentration of TSH caused maximal persistent cAMP production after 1 min of stimulation. In contrast, the level of persistent IP1 production increased progressively with increasing time of exposure to 100 \text{ mU/ml} TSH over the 30-min period. We showed previously that HEK-293EM cells expressing human receptors for lutetinizing hormone/chorionic gonadotropin or follicle-stimulating hormone do not exhibit persistent cAMP production (Neumann et al., 2010a). We found that HEK-293EM cells expressing human receptors for thyrotropin-releasing hormone do not exhibit persistent IP1 production (data not shown). Thus, not all GPCRs exhibit persistent signaling in this cell model.

Figure 4 illustrates the time courses of loss of persistent cAMP and IP1 production stimulated by 100 \text{ mU/ml} TSH. Both cAMP and IP1 production fell progressively at rates of approximately 3% per hour and had returned to pretreatment basal levels after 23 h.

We determined whether other TSHR agonists—a small-molecule agonist C2 [NCGC00161870; N-[4-fluoro-3-(furanylmethyl)-4-oxo-1,2-dihydroquinazolin-2-yl]-2-methoxyphenyl[ methoxy][phenyl]acetamide] (Neumann et al., 2009) and a thyroid-stimulating antibody M22 (Sanders et al., 2004)—would cause persistent signaling. We used maximally effective doses of C2 and M22 as determined previously (Sanders et al., 2004; Neumann et al., 2009) and showed that they were maximally effective because the two doses gave similar levels of stimulation. We found qualitatively similar effects of C2 and M22 on persistent cAMP and IP1 signaling. Figure 5 illustrates that C2 and M22 are full agonists for cAMP production.
duction when added immediately and stimulated persistent cAMP signaling to similar levels as TSH. In contrast, C2 and M22 are partial agonists for short-term IP1 production and stimulated persistent IP1 signaling to proportionately lower levels than TSH. Thus, C2 and M22 are functionally selective agonists (Strange, 2008) at TSHR and stimulate persistent signaling to levels concordant with their efficacies for short-term stimulation.

We showed previously that a small-molecule inverse antagonist of TSHR, 2-(3-(2,6-dimethylphenoxymethyl)-4-methoxyphenyl)-3-(pyridin-3-ylmethyl)-2,3-dihydroquinazolin-4(1H)-one (NCGC00229600; compound 1), partially inhibited persistent cAMP signaling (Neumann et al., 2010b). We have developed a small-molecule neutral antagonist for TSHR, NCGC00242595 (compound 2). Supplemental Fig. 1 illustrates the structure and synthetic scheme of 2, and Supplemental Fig. 2 illustrates that 2 does not inhibit basal signaling by TSHR but inhibits TSH-stimulated signaling and is therefore a neutral antagonist. 2 inhibited cAMP production immediately stimulated by an EC50 dose of TSH by 55% with an EC50 of 2.7 μM. Figure 6 illustrates that 1 inhibited persistent cAMP production by 34% and persistent IP1 production by 89%, whereas 2 had no effect on persistent cAMP production but inhibited persistent IP1 production by 84%. Thus, both 1 and 2 inhibited persistent IP1 production, but only 1 inhibited persistent cAMP production.

Because we had provided evidence previously that persistent cAMP production stimulated by TSH did not depend on TSHR internalization (Neumann et al., 2010a; but see Calebiro et al., 2009), we determined whether persistent IP1 production was affected by TSHR internalization. We measured IP1 production in cells in which internalization was inhibited by expressing the dominant-negative dynamin mutant protein (K44A) or was enhanced by the expression of βArr2 in these cells (Neumann et al., 2010a). Figure 7 illustrates that both expression of βArr2, which increased acid-resistant 125I-bTSH binding from 12 (control) to 59%, and of K44A, which had no effect on acid-resistant 125I-bTSH binding, had no effect on basal, on short-term TSH stimulation of, on TSH-activated persistent stimulation of, or on restimulation by TSH of IP1 production. [The lack of effect of K44A expression on acid resistant binding in these cells confirms our previous findings (Neumann et al., 2010a) and the conclusion that not all acid-resistant binding is caused by internalization (Jones and Hinkle, 2008).] Most importantly, inducing robust TSHR internalization with βArr2 (see below) did not affect TSH stimulation of the phosphoinositide pathway.

To further address the issue of whether TSHR internalization...
tion is necessary for persistent phosphoinositide pathway activation, we visualized TSH-bound TSHRs using Alexa Fluor 546-tagged TSH (Alexa-TSH) in HEK-TSHR cells expressing Goαq-YFP (Hughes et al., 2001) (Fig. 8). There was no apparent TSHR internalization in HEK-TSHR cells or in HEK-TSHR cells expressing K44A (data not shown) but robust internalization in HEK-TSHR cells expressing βArr2, as has been reported previously (Frenzel et al., 2006; Neumann et al., 2010a). However, Goαq-YFP remained at the surface of all cells including cells expressing βArr2 (Fig. 8). Quantitative analysis confirmed that there was a high level of colocalization of Alexa-TSH/TSHR and Goαq-YFP on the surface of control cells not expressing βArr2 but no significant colocalization (Pearson’s correlation coefficient) or a marked loss in colocalization (Manders’s overlap coefficient) in cells expressing βArr2. Thus, HEK-TSHR cells do not internalize TSH-bound TSHRs but can be made to internalize TSHRs after expression of βArr2, but Goαq-YFP does not colocalize with TSHRs. These findings, together with those in Fig. 7, show that persistent IP1 production stimulated by TSHR does not require TSHR (or Goαq) internalization.

Fig. 7. Dominant-negative dynamin mutant protein (K44A) or βArr2 had no effect on persistent IP1 production. HEK-TSHR cells were transfected with empty plasmid (Mock); plasmid to express βArr2 or plasmid to express K44A. A, acid-resistant [125I]-TSH binding. After 48 h, specific [125I]-TSH binding (HBSS wash) and [125I]-TSH binding after acid wash were measured and acid-resistant binding calculated as described under Materials and Methods. βArr2 increased acid-resistant binding (p < 0.001) whereas K44A had no effect (p > 0.1). The bars are the mean ± S.E. of duplicate measurements in three experiments. B, IP1 production. After 48 h, the cells were incubated without (Control) or with 100 mU/ml TSH at 37°C. After 30 min (pretreatment), the cells were washed and incubated in HBSS/HEPES with LiCl alone or LiCl and 100 mU/ml TSH at 37°C for 30 min (production). The cells were lysed and IP1 content was measured in the cell lysates. Control-Control, no pretreatment/no treatment during production phase; Control, TSH; no pretreatment, TSH added during production phase; TSH-Control, TSH pretreatment/no treatment during production phase (persistent signaling); TSH-TSH, TSH pretreatment/TSH treatment during production phase. There was no increase in IP1 production in cells expressing βArr2 (p > 0.1) nor a decrease in IP1 production in cells expressing K44A (p > 0.1). The bars are the mean ± S.E. of duplicate measurements in three experiments.

Discussion

We show herein that TSHR activation by TSH leads to persistent signaling by the phosphoinositide pathway and by the cAMP pathway, which was reported previously (Calebiro et al., 2009; Neumann et al., 2010a). As shown previously (Van Sande et al., 1990) and confirmed herein, the potency of TSH to activate the phosphoinositide pathway was approximately 100-fold lower than that needed to activate the cAMP pathway. Therefore, it was necessary to use high TSH concentrations to activate the cAMP and phosphoinositide pathways simultaneously. We measured persistent activation of the phosphoinositide pathway using a protocol similar to the one we used for measurement of persistent cAMP signaling (Neumann et al., 2010a). For the cAMP pathway, we pre-treated HEK-TSHR cells with TSH, washed the cells to remove TSH, and incubated the cells in medium without TSH for 1 h. After incubation without TSH (washout), we measured cAMP production as the amount of cAMP accumulated during 30- to 60-min incubations in the presence of IBMX, which inhibits cAMP degradation (Fig. 2). For the phosphoinositide pathway, we performed the same pretreatment, washes, and washout incubation and then added LiCl to inhibit IP1 degradation by the IP1 phosphatase because I-1,4,5-P3 is rapidly metabolized to IP1, and there is no effective inhibitor of I-1,4,5-P3 metabolism. We measured IP1 production as the amount of IP1 accumulated during a 30- to 60-min incubation in the presence of LiCl. We are, therefore, able to make direct quantitative comparisons between persistent signaling in these two pathways.

We showed that the time courses of acquisition of persistent signaling activated by TSH were different for the cAMP and phosphoinositide pathways. Acquisition of persistent cAMP production was very rapid, whereas persistent IP1 production was progressive over 30-min exposure to TSH. We believe that these different findings were most likely caused by the need to occupy a smaller fraction of TSHRs to generate...
maximal cAMP production and a higher fraction of TSHRs to generate maximal IP1 production. Indeed, our finding that persistent cAMP production was not increased (Neumann et al., 2010a) but IP1 production was increased further upon re-exposure to TSH (Fig. 7) may have been because not all TSHR binding sites were occupied during the pretreatment exposure to TSH. By contrast, decay of persistent cAMP and IP1 production were similar (3% per hour) and may reflect an intrinsic mechanism of inactivation of TSH/TSHR complexes.

In the previous reports of persistent cAMP signaling by activated TSHRs, the only agonist used was TSH (Calebiro et al., 2009; Neumann et al., 2010a). In this study, we activated TSHR with TSH; a small-molecule agonist, C2 (Neumann et al., 2009); and a thyroid-stimulating antibody, M22 (Sanders et al., 2004). We found qualitatively similar effects of C2 and M22 on persistent cAMP and IP1 signaling. Both C2 and M22 are full agonists for cAMP production when added immediately and stimulated persistent cAMP signaling to levels similar to those of TSH, whereas C2 and M22 are partial agonists for short-term IP1 production and stimulated persistent IP1 signaling to proportionately lower levels than TSH. Thus, both C2 and M22 exhibit functionally selective short-term signaling (Strange, 2008). It had been shown previously that some thyroid-stimulating antibodies exhibit functionally selective signaling at TSHR (Morshed et al., 2009, 2010). It is noteworthy that there was a clear parallelism between the efficacies of these agonists to immediately and persistently stimulate cAMP and IP1 production. These findings are consistent with the idea that the activatory conformation achieved after binding a given agonist to stimulate second-messenger formation immediately is retained during persistent signaling. One hypothesis that is compatible with this idea is that the persistently signaling complex is composed of agonist/activated TSHR/Gα subunit. Another possibility is that the persistently signaling complex is activated TSHR/Gα subunit but does not contain agonist.

To attempt to distinguish between these possibilities, we took advantage of our recent discovery of a small-molecule neutral antagonist of TSHR, 2 (Supplemental Figs. 1 and 2). In our previous report (Neumann et al., 2010a), we used another structurally related small-molecule inverse agonist [NCGC00161856, 2-[3-[(2,6-dimethylphenoxymethyl)ethyl]-4-methoxyphenyl]-3-(furan-2-ylmethyl)-1,2-dihydroquinazolin-4-one] and showed that it inhibited persistent cAMP production. These previous data allowed us to conclude that activated TSHR was necessary for persistent cAMP production but could not allow the determination of whether TSH was still present in the complex because an inverse agonist may inhibit signaling by the competition of agonist binding to receptors and by unoccupied receptors. Herein, we showed that both 1 and 2 markedly inhibited persistent IP1 production. Therefore, if 2 is a neutral antagonist at TSHR for IP1 production as it is for cAMP production, which is difficult to determine because basal IP1 production stimulated by TSHR is very low, then we may conclude that the complex that persistently signals includes the agonist-occupied, activated TSHR.

We confirmed that 1 inhibits persistent cAMP production but found that 2 did not. The explanation for the finding that 2 inhibits persistent IP1 signaling but persistent cAMP signaling may be because a lower fraction of TSHRs needs be bound by TSH to cause persistent cAMP signaling and a higher fraction for IP1 signaling. Another possibility is that there may be “spare receptors” for cAMP but not for IP1 signaling. We are currently performing experiments that may distinguish between these possibilities.

In the initial reports (Calebiro et al., 2009; Ferrandon et al., 2009; Mullershausen et al., 2009), persistent signaling by GPCRs with dissociable agonists was shown to correlate with their internalization. Indeed, for the parathyroid hormone receptor (Ferrandon et al., 2009), parathyroid hormone, which stimulated internalization, caused persistent cAMP signaling, whereas parathyroid hormone-related peptide, which did not cause internalization, did not. Evidence was also presented that persistent cAMP signaling was mediated by activated receptors within intracellular compartments. This mechanism was likened to the well established findings that some tyrosine kinase receptors signal intracellularly (Barbieri et al., 2004) and that some GPCRs signal via interactions with arrestin proteins that may be in intracellular vesicles (Hanyaloglu and von Zastrow, 2008). However, no direct evidence showing that persistent GPCR signaling was dependent on internalization was presented. We have reported that the TSHR could cause persistent cAMP signaling in HEK-TSHR cells, in which internalization did not occur or was inhibited, and that persistent cAMP signaling was not increased in HEK-TSHR cells in which internalization was induced by exo-genuously expressing βArR2 (Neumann et al., 2010a). We concluded, therefore, that persistent cAMP signaling was not dependent on internalization. Indeed, we showed that a small-molecule antagonist of TSHR (Neumann et al., 2010a) could inhibit persistent signaling and allow readded TSH to activate the receptor. We, therefore, hypothesized that persistently signaling TSHRs were not in endosomal vesicles but were in a compartment that was accessible to the TSHR antagonist and TSH. Herein, we present evidence that persistent signaling via the phosphoinositide pathway is independent of internalization also. We show that inhibiting or increasing internalization does not affect persistent IP1 production stimulated by TSH and that in cells in which TSHR internalization is increased, there is no detectable internalization of Gα,β-γ-YFP.

Even though the concentrations of TSH needed to stimulate the phosphoinositide pathway are higher than the levels found in the blood of healthy subjects, these levels may be found in tissues in which TSH-producing cells and TSHR-expressing cells are found together, such as the pituitary gland (Prumel et al., 2000) and epidermis (Bodó et al., 2010; Cianfarani et al., 2010). Moreover, thyrostimulin, another heterodimeric glycoprotein activator of TSHR that is believed to act in a paracrine fashion (Nakabayashi et al., 2002; Sun et al., 2010), may achieve concentrations sufficient to stimulate TSHR-mediated phosphoinositide signaling locally. Thyrostimulin has been shown to activate cAMP and calcium signaling, which is most likely initiated by coupling of TSHR to Gα (Nagasaki et al., 2006). Strong support for the idea that TSHR signaling via the phosphoinositide pathway is physiologically relevant was provided by the recent demonstrations that the Gq/G₁₁-mediated signaling pathway is required for TSH-induced thyroid hormone synthesis and release in the adult and that the lack of Gq/G₁₁ leads to hypothyroidism (Kero et al., 2007) and the finding that a
TSHR germline mutation that preferentially affected the phosphoinositide pathway affected thyroid gland function (Grasberger et al., 2007). Thus, we think that phosphoinositide signaling mediated by activation of TSHR is physiologically relevant.

In conclusion, we showed that TSHR activation by TSH leads to persistent signaling by both the cAMP and phosphoinositide pathways. To our knowledge, this is the first demonstration of persistent activation by any GPCR via the Gq pathway and of persistent signaling of two G protein-mediated pathways by any GPCR.

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References


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Thyrotropin Receptor Stimulates Internalization-independent Persistent Phosphoinositide Signaling

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Molecular Pharmacology

Name: 2-(3-((2,6-dimethylphenylthio)methyl)-4-methoxyphenyl)-3-(furan-2-ylmethyl)-2,3-dihydroquinazolin-4(1H)-one

Synthesis of 2-(3-((2,6-dimethylphenylthio)methyl)-4-methoxyphenyl)-3-(furan-2-ylmethyl)-2,3-dihydroquinazolin-4(1H)-one (WWH07-084)

To a solution of 3-(chloromethyl)-4-methoxybenzaldehyde (91.0 mg, 0.5 mmol, 1.0 equiv) and 2,6-dimethylbenzenethiol (68.4 mg, 0.5 mmol, 1.0 equiv) in 4 mL
acetonitrile was added potassium carbonate (0.55 g, 4.0 mmol, 8.0 equiv). The mixture was heated to 150 °C in the microwave for 10 min. After filtered off the solid and removed the solvent, 2-amino-N-(furan-2-ylmethyl)benzamide (107 mg, 0.5 mmol, 1.0 equiv) in 5 mL of EtOH was added followed by addition of Ytterbium trifluoromethanesulfonate (62 mg, 0.1 mmol, 0.2 equiv). The mixture was heated at 80 °C for 2 hours. Upon completion, the mixture was dried down and chromatographed on silica gel with 10-60% EtOAc/Hexanes gradient elution to give 2-(3-((2,6-dimethylphenylthio)methyl)-4-methoxyphenyl)-3-(furan-2-ylmethyl)-2,3-dihydroquinazolin-4(1H)-one (101.4 mg, 42%) as a white solid after triturating with diethyl ether. $^1$HNMR (400 MHz, DMSO-$d_6$) δ ppm 2.26 (s, 6 H), 3.56 (d, $J$=15.7 Hz, 1 H), 3.66 (s, 3 H), 3.72 (d, 1 H), 3.79 (d, 1 H), 5.12 (d, $J$=15.7 Hz, 1 H), 5.55 (d, $J$=2.2 Hz, 1 H), 6.25 (d, $J$=3.1 Hz, 1 H), 6.41 (dd, $J$=3.0, 1.9 Hz, 1 H), 6.59 (d, $J$=8.0 Hz, 1 H), 6.66 (t, $J$=7.5 Hz, 1 H), 6.78 - 6.94 (m, 2 H), 7.00 - 7.28 (m, 6 H), 7.59-7.66 (m, 2 H); LCMS: (electrospray + ve), m/z 485.2 (MH)$^+$, $t_R$ = 7.16 min, UV$_{254}$ = 98%.
 Supplementary Figure 2. 2 is a neutral antagonist of TSHR.
HEKTSHR cells were exposed to the noted concentrations of 2 in the absence of TSH but 20 min prior to 1 mM IBMX (Basal) or 20 min prior to the addition of a half-maximally effective concentration of TSH (1.8 nM) and 1 mM IBMX (TSH-stimulated). After an additional 40 min incubation in the presence of IBMX alone (Basal) or IBMX and TSH (TSH-stimulated), the cells were lysed and cAMP levels were measured by ELISA. 2 did not inhibit basal cAMP production but inhibited TSH-stimulated cAMP production with an IC_{50} of 2.7 µM.