Amiloride derivatives and a non-peptidic antagonist bind at two distinct allosteric sites in the human gonadotropin-releasing hormone receptor

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The human GnRH receptor has two distinct allosteric sites

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Text pages: 30

Number of tables: 4

Number of Figures: 10

Number of references: 40

Number of words in abstract: 258

Number of words in introduction: 529

Number of words in discussion: 1439

ABBREVIATIONS: CHO, Chinese hamster ovary; CHOhGnRHr_luc, human GnRH receptor and luciferase reporter gene transfected CHO cells; DCB, dichlorobenzamil; GnRH, gonadotropin-releasing hormone; GTP, guanosine-5’-triphosphate; HMA, 5-(N,N-hexamethylene)amiloride; MIBA, 5-(N-methyl-N-isobutyl)amiloride; NFAT-luc, Nuclear Factor Activated T-cell luciferase reporter gene; GPCRs, G protein-coupled receptors; FD-1, 5-(3,5,5,8,8-Pentamethyl-5,6,7,8-tetrahydro-naphthalen-2-yloxy)-furan-2-carboxylic acid (2,4,6-trimethoxy-pyrimidin-5-yl)-amide; PBS, phosphate-buffered saline; TAK-013, 5-(N-benzyl-N-methylaminomethyl)1-(2,6-difluorobenzyl)-6-[4-(3-methoxyureido)phenyl]-3-phenylthieno[2,3-d]pyrimidine-2,4(1H,3H)-dione
ABSTRACT

The interest in the allosteric modulation of G protein-coupled receptors has grown during the past decade. It has been shown that ligands acting at allosteric sites present in these important drug targets have the ability to modulate receptor conformations and fine-tune pharmacological responses to the orthosteric ligand. In the present study, allosteric modulation of the human GnRH receptor by amiloride analogues (e.g. HMA) and a non-peptide antagonistic furan derivative (FD-1) was studied. Firstly, the compounds’ ability to influence the dissociation of a radiolabeled peptide agonist (\(^{125}\)I-triptorelin) from human GnRH receptors stably expressed in CHO cell membranes was investigated. HMA and FD-1, but not TAK-013, another non-peptide antagonist, were shown to increase the dissociation rate of \(^{125}\)I-triptorelin, revealing their allosteric inhibitory characteristics. The simultaneous addition of HMA and FD-1 resulted in an additive effect on the dissociation rate. Secondly, in a functional assay it was shown that HMA was a non-competitive antagonist and that FD-1 had both competitive and non-competitive antagonistic properties. Equilibrium displacement studies showed that the inhibition of \(^{125}\)I-triptorelin binding by FD-1 was not affected by HMA. Furthermore, the potency of HMA to increase radioligand dissociation was not affected by the presence of FD-1. Simulation of the data obtained in the latter experiment also indicated neutral cooperativity between the binding of HMA and FD-1. Taken together, these results demonstrate that HMA and FD-1 are allosteric inhibitors that bind at two distinct, non-cooperative, allosteric sites. This presence of a second allosteric site may provide yet another opportunity for the discovery of new ligands for the human GnRH receptor.
The gonadotropin-releasing hormone (GnRH) receptor belongs to the rhodopsin-like subfamily (class A) of G protein-coupled receptors (GPCRs) (Millar et al., 2004). Activation of the GnRH receptor results in the biosynthesis and secretion of the gonadotropins, luteinizing hormone (LH) and follicle-stimulating hormone (FSH). The gonadotropins bind to their respective receptors on the gonadal cells, which stimulates germ cell development and hormone secretion in the ovaries (Rhoades and Pflanzer, 1996). GnRH, also named luteinizing hormone-releasing hormone (LHRH), is a linear hypothalamic decapeptide (Figure 1) and was first isolated and characterized by Schally et al. (1971). Several peptidic agonists and antagonists for the GnRH receptor have been approved for the treatment of a variety of sex-hormone dependent diseases, such as prostate and breast cancer and endometriosis (Conn and Crowley, 1994; Kiesel et al., 2002). Superagonists, a somewhat ambiguous term for chronically administered peptidic agonists, are used to desensitize and downregulate the GnRH receptor, resulting in gonadal suppression. Such use of agonists, however, produces an initial hormonal ‘flare’, resulting in a temporary activation of the pituitary, which can be prevented by giving peptidic antagonists instead. However, peptidic compounds often need to be administered by parenteral (subcutaneous or intramuscular) injection (Kiesel et al., 2002). Therefore intensive efforts have been initiated to develop non-peptidic antagonists, which have the potential to become orally available drugs (Armer and Smelt, 2004).

In the past decade several classes of non-peptidic GnRH receptor antagonists have been reported (e.g. Imada et al., 2006; DeVita et al., 1999; Chu et al., 2001; Pontillo et al., 2005). These ligands compete with a peptidic agonist for the same binding site on the receptor, providing evidence that they can be classified as orthosteric ligands. In addition,
Mutational analysis of the GnRH receptor has shown that these non-peptidic antagonists have overlapping, but non-identical binding sites (Betz et al., 2006). The orthosteric binding site of a GPCR has been defined as the site that is recognized by the endogenous ligand (May et al., 2007). For several GPCRs, however, another (allosteric) binding site has been identified, e.g. for muscarinic receptors (Class A), the corticotropin-releasing factor1 receptor (class B) and glutamate receptors (Class C) (for reviews, see Christopoulos and Kenakin, 2002; and Soudijn et al., 2004). In comparison to conventional orthosteric ligands, allosteric modulators can have the therapeutic advantage of greater selectivity and tissue-specificity. In addition, the risk of over-dosing is diminished by their saturability.

In the present study, the allosteric modulation of the human GnRH receptor was examined. Equilibrium and kinetic radioligand binding experiments were performed in the presence and absence of both non-specific [e.g. 5-(N,N-hexamethylene)amiloride (HMA)] and GnRH receptor-selective allosteric modulators [furan derivative-1 (FD-1)] (Figure 1). Amiloride derivatives have been well described as allosteric inhibitors for different GPCRs at concentrations in the high micromolar range (Gao and IJzerman, 2000), while FD-1 is a derivative of a recently described allosteric inhibitor for the GnRH receptor (Sullivan et al., 2006). The ability of a compound to modulate the dissociation rate of 125I-triptorelin was used as a measure for allosteric modulation. This revealed that there are two rather than one allosteric binding sites on this receptor. This emerging concept of multiple allosteric sites may offer further options to modulate GPCR activity.
MATERIALS AND METHODS

Materials. GnRH, triptorelin, guanosine-5’-triphosphate (GTP) and HMA were purchased from Sigma Aldrich Chemie B.V. (Zwijndrecht, The Netherlands). Amiloride, 5-(N-methyl-N-guanidinocarbonylmethyl)amiloride (MGCMA), 5-(N-methyl-N-isobutyl)amiloride (MIBA), Phenamil, Benzamil and dichlorobenzamil (DCB) were kindly provided by Dr EJ Cragoe (Lansdale, USA) and were synthesized as described previously (Cragoe et al., 1967). Suramin was a generous gift from Bayer AG (Wuppertal, Germany). (2-amino-4,5-dimethyl-3-thienyl)-[3-(trifluoromethyl)phenyl]methanone (PD81,723) and (N-(2,3-diphenyl-1,2,4-thiadiazol-5(2H)-ylidene)methanamine (SCH-202676) were synthesized in our own laboratory as described by Van der Klein et al. (1999) and Van den Nieuwendijk et al. (2004). Ganirelix was provided by Organon BioSciences (Oss, The Netherlands). 5-(N-benzyl-N-methylaminomethyl)1-(2,6-difluorobenzyl)-6-[4-(3-methoxyureido)phenyl]-3-phenylthieno[2,3-d]pyrimidine-2,4(1H,3H)-dione (TAK-013) and 5-(3,5,5,8,8-Pentamethyl-5,6,7,8-tetrahydro-naphthalen-2-yloxy)-furan-2-carboxylic acid (2,4,6-trimethoxy-pyrimidin-5-yl)-amide (FD-1) were prepared according to literature procedures (Furuya et al., 1997; Sun et al., 2002). Bovine serum albumin (BSA, fraction V) was purchased from Sigma (St. Louis, MO, U.S.A.), whereas BCA (bicinchoninic acid) protein assay reagent was from Pierce Chemical Company (Rockford, IL, U.S.A.). $^{125}$I-triptorelin (specific activity 2200 Ci/mmol) was purchased from Perkin Elmer Life Sciences (Groningen, The Netherlands). CHO (Chinese hamster ovary) cells stably expressing the human gonadotropin releasing-hormone receptor (GnRH) receptor was obtained from Euroscreen (Brussels, Belgium). The CHO-K1 cells expressing the wild-
type human GnRH receptor and Nuclear Factor Activated T-cell luciferase reporter gene (NFAT-luc) were provided by Organon BioSciences (Oss, The Netherlands). All other chemicals and cell culture materials were obtained from standard commercial sources.

**Cell Culture.** CHO cells stably expressing the human GnRH receptor were grown in Ham’s F12 medium containing 10 % (v/v) normal adult bovine serum, streptomycin (100 µg/ml), penicillin (100 IU/ml) and G418 (0.4 mg/ml) at 37 °C in 5 % CO₂ (Oosterom et al., 2005). The cells were subcultured twice weekly at a ratio of 1:20. For membrane preparation the cells were subcultured 1:10 and transferred to large 15-cm diameter plates.

**Membrane Preparation.** Cells were detached from the plates by scraping them into 5 ml PBS, collected and centrifuged at 700 g (3000 rpm) for 5 min. Pellets derived from 30 plates were pooled and resuspended in 20 ml of ice-cold 50 mM Tris-HCl buffer containing 2 mM MgCl₂, pH 7.4. An UltraThurrax (Heidolph Instruments, Germany) was used to homogenize the cell suspension. Membranes and the cytosolic fraction were separated by centrifugation at 100,000 g (31,000 rpm) in an Optima LE-80K ultracentrifuge (Beckman Coulter, Fullerton, CA) at 4 °C for 20 min. The pellet was resuspended in 10 ml of the Tris buffer and the homogenization and centrifugation step was repeated. Tris buffer (10 ml) was used to resuspend the pellet and the membranes were stored in 250 and 500 µl aliquots at –80 °C. Membrane protein concentrations were measured using the BCA method with BSA as a standard (Smith et al., 1985).

**Radioligand Displacement and Saturation Assays.** Membrane aliquots containing 5 - 7.5 µg protein were incubated in a total volume of 100 µl assay buffer (25 mM Tris HCl, pH 7.4, supplemented with 2 mM MgCl₂ and 0.1 % (w/v) BSA) at 22 °C for 45 min. For
saturation experiments unlabeled triptorelin was spiked with 20 % $^{125}\text{I}$-triptorelin resulting in final concentrations of 0.1 to 3 nM. Non-specific binding was determined at three concentrations of radioligand in the presence of 100 µM ganirelix. Displacement experiments were performed using eleven concentrations of competing ligand in the presence of 30,000 cpm ($\sim$ 0.1 nM) $^{125}\text{I}$-triptorelin. Here, non-specific binding was determined in the presence of 1 µM ganirelix and represented approximately 15 % of the total binding. Incubations were terminated by dilution with ice-cold Tris-HCl buffer. Separation of bound from free radioligand was performed by rapid filtration through Whatman GF/B filters pre-soaked with 0.25 % poly(ethylenimine) (PEI) for 1 h using a Brandel harvester. Filters were subsequently washed three times with 2 ml ice-cold wash buffer (25 mM Tris HCl, pH 7.4, supplemented with 2 mM MgCl$_2$ and 0.05 % BSA). Filter-bound radioactivity was determined in a $\gamma$-counter (Wizard 1470, PerkinElmer Life Sciences).

**Radioligand kinetic association and dissociation assays.** Association experiments were performed by incubating membrane aliquots containing 5 - 7.5 µg protein in a total volume of 100 µl assay buffer (25 mM Tris HCl, pH 7.4, supplemented with 2 mM MgCl$_2$ and 0.1 % BSA) at 22 ºC with 30,000 cpm of $^{125}\text{I}$-triptorelin. The amount of radioligand bound to the receptor was measured at different time intervals during incubation for 90 min. Dissociation experiments were performed by preincubating membrane aliquots containing 5 – 7.5 µg protein in a total volume of 100 µl assay buffer (25 mM Tris HCl, pH 7.4, supplemented with 2 mM MgCl$_2$ and 0.1 % BSA) at 22 ºC for 45 min with 30,000 cpm ($\sim$ 0.1 nM) $^{125}\text{I}$-triptorelin. After preincubation, dissociation was initiated by addition of 1 µM ganirelix in the presence or absence (control) of HMA (5-
(N,N-hexamethylene)amiloride), MIBA (5-N-methyl-N-isobutyl)amiloride, DCB (dichlorobenzamil), FD-1 (furan derivative-1) or TAK-013 in a total volume of 5 µl. The amount of radioligand still bound to the receptor was measured at various time intervals for a total of 2 h. Incubations were terminated and samples were obtained and analyzed as described under Radioligand Displacement and Saturation Assays.

‘Competitive' kinetic radioligand dissociation assays. Dissociation experiments were mainly performed as described above. After preincubation, dissociation was initiated by addition of 1 µM ganirelix in the presence or absence (control) of different concentrations FD-1 (1, 3 or 10 µM) and in the presence or absence (control) of six different concentrations of HMA (5 – 100 µM) in a total volume of 5 µl. The amount of radioligand still bound to the receptor was measured after 30 min. Incubations were terminated and samples were obtained and analyzed as described under Radioligand Displacement and Saturation Assays.

Luciferase Assays. CHOhGnRH_luc cells were cultured as described under Cell Culture. However, Dulbecco’s Modified Eagle’s Medium (DMEM) was added to the culture medium (1:1 with F12). On the day of the assay, cells were washed with PBS and then harvested using trypsol (0.25% (w/v) in PBS containing 4.4 mM EDTA). Cells were resuspended in assay medium consisting of DMEM and F12 (1:1) supplemented with 1 µg/ml insulin and 5 µg/ml apo-transferrin. Typically, a well contained 30 µl of a certain concentration triptorelin, 30 µl of modulator (HMA or FD-1) or assay medium (control) and 30 µl cell suspension containing 7.5 × 10^5 cells/ml. After 4 h stimulation, 50 µl of luclite (PerkinElmer Life Sciences) was added to each well for detection of luciferase protein and plates were left at room temperature for 30 minutes in the dark.
Finally, the luminescence signal was quantified on the Microbeta Trilux 1450 Luminescence Counter (PerkinElmer Life Sciences).

**Data Analysis.** All binding data was analyzed using the non-linear regression curve-fitting program GraphPad Prism v. 5.00 (GraphPad Software Inc, San Diego, CA). EC\textsubscript{50} values were directly obtained from the dose-response curves and inhibitory binding constants (K\textsubscript{i} values) were derived from the IC\textsubscript{50} values according to K\textsubscript{i} = IC\textsubscript{50}/(1 + [C]/K\textsubscript{d}) where [C] is the concentration of the radioligand and K\textsubscript{d} its dissociation constant (Cheng and Prusoff, 1973). The K\textsubscript{d} value of \textsuperscript{125}I-triptorelin at CHOhGnRH membranes was obtained by computer analysis of saturation curves. Dissociation constants, k\textsubscript{off}, were obtained by computer analysis of the exponential decay of the percentage of \textsuperscript{125}I-triptorelin bound to the receptor. Association rates were calculated according to the equation k\textsubscript{on} = (k\textsubscript{obs} - k\textsubscript{off})/[L], where k\textsubscript{obs} was obtained by computer analysis of the exponential association of the percentage of \textsuperscript{125}I-triptorelin bound to the receptor and [L] is the amount of radioligand used for the association experiments. The EC\textsubscript{50} from competitive dissociation experiments was obtained from dose response-curves of enhanced dissociation by different concentrations of HMA, where the non-specific binding was set at 0 % and either the true control (buffer) or own control binding (1, 3 or 10 \textmu M FD-1) after 30 min was set at 100 %. All values obtained are means of at least three independent experiments performed in duplicate.

**Simulation of cooperativity between FD-1 and HMA.** A mathematical model (Eq. 1) for two distinct allosteric sites (Lazareno et al., 2000) was implemented in MatLab (version 7.1) to simulate the effects of different cooperativities between HMA and FD-1 on the EC\textsubscript{50} of HMA in enhancing \textsuperscript{125}I-triptorelin dissociation.
\[ EC_{50}^{HMA} = \frac{1 + [\text{FD-1}] \cdot K_{FD-1}^{\text{TRIPTORELIN}}}{K_{HMA}^{\text{TRIPTORELIN}} \cdot (1 + [\text{FD-1}] \cdot K_{FD-1}^{\text{TRIPTORELIN}} \cdot \delta)} \] (Eq. 1)

in which \( EC_{50}^{HMA} \) is the observed EC\(_{50}\) of HMA in enhancing \(^{125}\)I-triptorelin binding. \( K_{FD-1}^{\text{TRIPTORELIN}} \) and \( K_{HMA}^{\text{TRIPTORELIN}} \) are the affinities on the triptorelin-occupied receptor for FD-1 and HMA, respectively. \( \delta \) is the parameter defining the cooperativity between HMA and FD-1.
RESULTS

Radioligand saturation experiments. Saturation experiments were performed with unlabeled triptorelin spiked with 20% $^{125}$I-triptorelin on CHO cells expressing the human GnRH receptor. The results of a representative saturation experiment are shown in Figure 2. Although the non-specific binding was high, the receptor binding of $^{125}$I-triptorelin was saturable and best characterized by a one-site receptor model. A $K_D$ and $B_{\text{max}}$ value of 0.35 nM (0.33 - 0.37) and 217 fmol/mg protein (207 - 227), respectively, were obtained from two independent saturation experiments. The $K_D$ value for $^{125}$I-triptorelin obtained with these experiments was used to derive $K_i$ rather than IC$_{50}$ values in the following paragraph.

Radioligand displacement assays. Experiments were performed to assess the ability of various ligands to compete with the binding of $^{125}$I-triptorelin to CHOhGnRH cell membranes were performed with different ligands. The endogenous agonist, GnRH, a derivative, triptorelin, a peptidic antagonist, ganirelix and two non-peptidic antagonists, TAK-013 and FD-1 (Figure 1), were used to displace radioligand binding. The displacement curves and affinity values are shown in Figure 3 and Table 1, respectively. All ligands were able to fully displace $^{125}$I-triptorelin with affinities ranging from 0.42 nM for triptorelin to 4.9 nM for FD-1. From Figure 3 it follows that the curve of GnRH had a smaller Hill coefficient than that of the other ligands. Computational analysis indeed showed that it was best described by a two-site competition model with a higher ($K_H$) and a lower affinity ($K_L$) of $0.54 \pm 0.004$ nM and $21 \pm 10$ nM (mean $\pm$ SEM, $n = 3$), respectively, with $69 \pm 3\%$ of high-affinity receptors ($R_H$).
Allosteric modulation $^{125}$I-triptorelin binding. The effect of some allosteric modulators was tested on equilibrium binding of $^{125}$I-triptorelin. As shown in Figure 4a, PD81,723, a selective adenosine A$_1$ receptor modulator, had no effect on radioligand binding to the GnRH receptor. The addition of GTP, suramin and sodium ions had a modest effect on the binding of $^{125}$I-triptorelin. Both SCH-202676 and HMA (Figure 1), however, had a detrimental effect on radioligand binding, as almost no radioactivity was detected after incubation with these agents. To investigate the effects of HMA and other amiloride derivatives, a similar experiment was performed with amiloride, MGCMA, MIBA, phenamil, benzamil and DCB. From Figure 4b follows that most amilorides had little effect and that only MIBA and DCB were able to inhibit $^{125}$I-triptorelin binding. Therefore, displacement of $^{125}$I-triptorelin equilibrium binding by HMA, MIBA and DCB at different concentrations was determined (Figure 5). The obtained inhibition curves were best described by a one-site receptor model and resulted in similar potencies for HMA ($IC_{50} = 29 \pm 3 \text{ µM}$), MIBA ($IC_{50} = 39 \pm 7 \text{ µM}$) and DCB ($IC_{50} = 30 \pm 3 \text{ µM}$) with a pseudo-Hill coefficient of $1.4 \pm 0.06$, $1.3 \pm 0.02$ and $1.6 \pm 0.2$, respectively (Table 2).

Kinetic association and dissociation experiments. The dissociation constant ($K_D$) of $^{125}$I-triptorelin in the absence of modulators was also derived from kinetic experiments and the resulting dissociation and association rate constants. Equilibrium binding was reached after approximately 45 min with an association rate constant of $0.28 \pm 0.08 \text{ nM}^{-1} \text{ min}^{-1}$. Under control conditions the radioligand dissociated from the receptor with a dissociation rate constant of $0.021 \pm 0.002 \text{ min}^{-1}$. Together this resulted in a ‘kinetic’ $K_D$ value of $0.74 \text{ nM}$, which was in good agreement with the $K_D$ value ($0.35 \text{ nM}$) obtained in the ‘spiked’ saturation analysis. Next, the dissociation kinetics of $^{125}$I-triptorelin from
CHOhGnRH receptor membranes was determined in the presence of modulator (Figure 6 and Table 2). All compounds, except TAK-013, increased the dissociation rate in comparison to the control off-rate, indicative of their allosteric nature and negative modulation of the receptor. The dissociation rate constant of $^{125}$I-triptorelin was increased 2.5-fold to $0.053 \pm 0.006 \text{ min}^{-1}$ with the addition of 0.1 mM HMA, which was a more potent allosteric inhibitor than MIBA and DCB, although their effect on the equilibrium binding was similar (Table 2). Similarly, the addition of 3 µM of the non-peptidic antagonist FD-1 resulted in a 3.2-fold increase of the dissociation rate constant, $0.068 \pm 0.009 \text{ min}^{-1}$. The simultaneous addition of HMA and FD-1 in the above concentrations resulted in an additive effect on the dissociation rate constant, which increased 5.2-fold under this condition ($k_{off} = 0.11 \pm 0.01 \text{ min}^{-1}$).

**Allosteric modulation of receptor activation.** The effect of HMA and FD-1 on receptor activation by triptorelin was measured using a NFAT-induced luciferase assay (Figure 7 and Table 3). HMA at three concentrations did not cause a shift in potency of triptorelin ($EC_{50} = 0.24 \pm 0.02 \text{ nM}$). However, increasing concentrations of HMA resulted in a dose-dependent lowering of the maximal effect ($E_{\text{max}}$). For example, the presence of 10 µM HMA resulted in an $E_{\text{max}}$ value of 58 ± 1 % compared to control (100 %). This indicated non-competitive antagonism, which agrees with the allosteric inhibition seen in the kinetic dissociation experiments. FD-1 at three concentrations caused parallel rightward shifts in the dose-response curves of triptorelin, proof rather of competitive antagonism. However, addition of FD-1 also resulted in a suppression of the $E_{\text{max}}$ value, indicative for its allosteric nature. For example, addition of 3 µM FD-1 decreased the $E_{\text{max}}$ value to 72 ± 5 % of the control value.
Effect of HMA on FD-1 binding. In order to determine whether the allosteric effects described above occurred through an interaction at different allosteric sites, displacement of $^{125}$I-triptorelin by different concentrations of FD-1 was determined in the presence and absence of three concentrations of HMA (Figure 8 and Table 4). It follows from Figure 8 that the addition of HMA alone (data points on Y-axis) inhibited the binding of $^{125}$I-triptorelin dose-dependently, as shown by the decrease in $B_{\text{max}}$ in Table 4 and corresponding to the results shown in Figure 5. FD-1 potently displaced the binding of the radioligand in a concentration-dependent manner. The addition of HMA, however, did not impede the displacement by FD-1. Interestingly, at 30 µM HMA, the affinity of FD-1 was significantly increased (Table 4), indicating a possible allosteric interaction between these compounds.

Competitive dissociation experiments. Another series of experiments were performed to determine if FD-1 and HMA bound at a different allosteric site. As FD-1 also acts as an orthosteric antagonist (Figure 8), ‘competitive dissociation’ experiments were performed to solely study allosteric interactions. The concentration-dependent effect of HMA on $^{125}$I-triptorelin dissociation was studied in the absence and presence of three concentrations of FD-1 (Figure 9). The data obtained are represented in two formats. In Figure 9a is shown that the addition of FD-1 enhanced the dissociation and under every condition HMA dose-dependently further enhanced that dissociation. Figure 9b shows that the addition of FD-1 did not affect the modulating potency of HMA ($EC_{50} = 49 \pm 7$ µM), which indicates a non-competitive interaction of these two compounds. It is noteworthy that FD-1 has a 10-fold higher modulating potency than HMA, namely $5.0 \pm 1$ µM (Table 2).
Simulation of cooperativity between FD-1 and HMA. Equation 1 in the Materials & Methods section, taken from Lazareno et al. (2000), was used to simulate the effects of different cooperativities between HMA and FD-1 on the potency of HMA in enhancing the 125I-triptorelin dissociation. When $\delta = 1$, the binding of two allosteric modulators is noninteracting (neutral cooperativity). When $\delta < 1$ or $\delta > 1$, they exhibit either negative (competitive) or positive (enhancement) cooperativity. These simulations, shown in Figure 10, demonstrate that the data points we had gathered comply with a $\delta$ value of 1, thus indicating a neutral cooperativity between the binding of HMA and FD-1.
**DISCUSSION**

In the present study it was demonstrated that human GnRH receptors are allosterically modulated by amiloride derivatives and a non-peptidic antagonist (FD-1). Radioligand displacement assays were performed, where four reference compounds were tested (Figure 3 and Table 1). For GnRH, a shallow displacement curve was obtained, which was best fitted with a two-site competition model. In the presence of 1 mM GTP the favored mode of binding for GnRH shifted towards a one-site competition model with a $K_i$ value of $18 \pm 0.6$ nM (data not shown). Note that the latter affinity equals the affinity found for the low-affinity receptors in the absence of GTP ($K_L = 21 \pm 10$ nM). This can be explained by the ternary complex model, in which the presence of GTP causes a shift to a higher $K_i$ value through uncoupling of the receptor from the G protein (Lefkowitz et al., 1981). Notably, triptorelin binding was best described by a one-site competition model, although the presence of GTP did decrease radioligand binding (Figure 4a).

Beckers et al. reported the affinity of GnRH obtained in a $^{125}$I-triptorelin displacement assay, where they used whole LTK cells transfected with the human GnRH receptor (2001). A 5-fold lower affinity ($5.4 \pm 1.8$ nM) was found, which may be caused by a higher amount of endogenous GTP present in whole cells. The affinities reported for triptorelin and ganirelix, however, were in good agreement with the affinities reported here (Table 1). For TAK-013, an $IC_{50}$ value of 2.5 nM was reported (Sasaki et al., 2003), while we found a $K_i$ value of $1.9 \pm 0.7$ nM. Lastly, FD-1 was tested, which belongs to a different class of non-peptidic antagonists (Table 1). FD-1 had a $K_i$-value of $4.9 \pm 1$ nM, which was comparable to the affinity reported for an analogue of this compound, CMPD-1 ($K_i = 6.0 \pm 0.8$ nM) (Anderes et al., 2003).
The modulation of $^{125}$I-triptorelin binding was explored in the absence and presence of different generally known modulators (Figure 4a). GTP and suramin are compounds that have an effect on G protein coupling. It was shown that they had only a modest effect on $^{125}$I-triptorelin binding. The effect of PD81,723 on the adenosine A$_1$ receptor has been extensively studied (Bruns and Fergus, 1990). It has been shown to be a selective allosteric enhancer at the adenosine A$_1$ receptor, and as might be expected, it did not affect $^{125}$I-triptorelin equilibrium binding to the GnRH receptor. The influence of a high concentration of sodium ions was also examined at the human GnRH receptor. On other GPCRs, for example adenosine A$_2$A, $\alpha_2$-adrenergic and dopamine D$_2$ receptors, it has been shown that sodium ions regulate ligand binding (Horstman et al., 1990; Neve et al., 1991; Gao and IJzerman, 2000). However, on the GnRH receptor, sodium ions do not have such a profound effect. In contrast HMA, which has been shown at higher micromolar concentrations to modulate the same receptor subtypes as sodium ions (Leppik and Birdsall, 2000; Hoare and Strange, 1996; Gao and IJzerman, 2000), was able to fully inhibit radioligand binding. In addition, SCH-202676 was shown to have a similar effect on equilibrium binding as HMA. However, this compound was recently shown to be a protein modifier rather than an allosteric modulator (Göblyös et al., 2005). To further explore the modulation of $^{125}$I-triptorelin binding by HMA, other amiloride derivatives were tested (Figure 4b). Two other amiloride derivatives, MIBA and DCB, showed inhibition of equilibrium binding. It had been shown previously that MIBA was the most potent of this class of inhibitors next to HMA (Hoare and Strange, 1996; Gao and IJzerman, 2000).
Allosteric inhibition of $^{125}$I-triptorelin binding was shown by the increase in its dissociation rate from human GnRH receptors in the presence of HMA or MIBA (Figure 6). Recently, an allosteric inhibitor for the GnRH receptor was described (Sullivan et al., 2006). Previously, the same compound (Furan-1 or CMPD-1) had been demonstrated to be a potent non-peptidic antagonist (Anderes et al., 2003), whereas its allosteric effects occur at higher concentrations. FD-1 belongs to the same class of non-peptidic antagonists with only some small structural differences (Figure 1). It was demonstrated that, as for HMA, MIBA and DCB, FD-1 was also able to increase the dissociation rate (Figure 6). As mentioned above HMA was shown to be an allosteric inhibitor on different GPCRs, e.g. at the adenosine $A_{2A}$ receptor (Gao and IJzerman, 2000). The selectivity of FD-1 was therefore tested on this receptor; FD-1 did not modulate the dissociation rate of the $A_{2A}$ receptor radioligand (data not shown). FD-1 is therefore a selective allosteric inhibitor, unlike HMA. The simultaneous addition of HMA and FD-1 resulted in an additive effect on the dissociation rate. However, addition of a high concentration (10 $\mu$M) of FD-1 further enhanced the dissociation (Figure 9a). Therefore, this did not indicate $per$ $se$ that the observed additive effect was due to the presence of two allosteric binding sites, although the two compounds are structurally different. The effect on $in$ $vitro$ functional efficacy was also determined (Figure 7 and Table 3). The functional data showed that HMA is a pure non-competitive antagonist (allosteric inhibitor) of the effects of triptorelin. On the other hand, FD-1 showed a mixed type of antagonism, indicating both orthosteric and allosteric characteristics. In this assay HMA and FD-1 showed the same effects when the endogenous ligand GnRH was used (data not shown), even though the binding sites of triptorelin and GnRH are not identical (Fromme et al., 2001).
Furthermore, FD-1 seemed to be a more potent allosteric inhibitor than Furan-1 (Sullivan et al., 2006). To prove that the allosteric characteristics of FD-1 were specific for this non-peptidic antagonist only, TAK-013 was also examined. It was shown that TAK-013 had no effect on the dissociation rate of $^{125}\text{I}$-triptorelin (Figure 6). This suggests that the allosteric nature of FD-1 is not a general feature of all non-peptidic antagonists, but due to structural aspects of FD-1 itself. Importantly, trypan blue exclusion tests showed that cell viability always exceeded 95%, which ruled out that the decrease in maximal response was caused by any cytotoxic effects of the relatively high concentrations of HMA or FD-1. In addition, reversible binding was shown in a luciferase assay where the cells were pre-incubated with the highest concentrations used of HMA and FD-1. After washing of the cells according to a method described by Lu and coworkers (2007), full agonist responses were obtained, while unwashed pre-incubated cells still showed a decreased maximal response.

Lastly we examined whether HMA and FD-1 exert their effect through two distinct allosteric sites on the GnRH receptor. Lazareno et al. (2000) and Lanzafame et al. (2006) have reported two allosteric sites for the M$_1$ and M$_4$ muscarinic receptor, respectively. In addition, three distinct allosteric sites were reported by Schetz and Sibley (2001) for the dopamine D$_4$ receptor. To explore if HMA and FD-1 compete for the same allosteric binding site further experiments were conducted. Firstly, the effect of HMA on the displacement of $^{125}\text{I}$-triptorelin by FD-1 was determined (Figure 8 and Table 4). It was shown that HMA has no competitive interaction with FD-1. However, the allosteric nature of FD-1 only occurs at high concentrations (micromolar range), which makes it difficult to observe an effect of HMA. Secondly, a competitive dissociation assay was
performed, in which the effect of FD-1 on HMA-induced dissociation was examined. Especially from Figure 9b it follows that the presence of FD-1 had no effect on the modulatory potency of HMA. This suggests that FD-1 acts at a site distinct from the binding site of HMA and that there is no interaction between the binding of FD-1 and HMA. To strengthen this, a simulation was performed using a model according to Lazareno et al. (2000). As demonstrated in Figure 10, HMA and FD-1 indeed have neutral cooperativity ($\delta = 1$). It is quite feasible that other GPCRs modulated by amilorides, can also be modulated by a receptor-specific modulator from a second allosteric site. For example, the dopamine D$_2$ receptor, which was earlier shown to be modulated by amiloride analogues (Leppik and Birdsell, 2000) is also influenced allosterically by the tripeptide L-prolyl-L-leucyl-glycinamide (PLG) (Verma et al., 2005).

In conclusion, we have demonstrated that the GnRH receptor can be allosterically modulated by amiloride analogues. In addition, FD-1 was shown to have both orthosteric and allosteric binding properties. Furthermore, we demonstrate that these two chemically unrelated compounds have two distinct allosteric binding sites on the human GnRH receptor, and that these sites show neutral cooperativity. The allosteric sites revealed in this study may provide novel targets at the GnRH receptor for orally available, low molecular weight compounds.
Acknowledgements

The authors would like to thank Dr. Guido J. R. Zaman (Organon BioSciences, Oss, The Netherlands) for helpful comments and critical reading of the manuscript. We are grateful to Top Institute Pharma (TI Pharma, The Netherlands) for continuation of this project.
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Dopamine Receptor Subtypes by L-Prolyl-L-leucyl-glycinamide and a Peptidomimetic Analog. J Pharmacol Exp Ther 315:1228-1236.
Legends for figures

Figure 1. Sequences of GnRH, triptorelin (agonists), ganirelix (antagonist) and chemical structures of FD-1 (antagonist and allosteric inhibitor), HMA, MIBA, DCB (allosteric inhibitors) and TAK-013 (antagonist).

Figure 2. Saturation of $^{125}$I-triptorelin binding to human gonadotropin-releasing hormone receptors. The specific binding (SB) was determined by subtracting the non-specific binding (NSB) from the total binding (TB). The $K_D$ value was 0.35 nM (0.33 -0.37) and the $B_{max}$ value was 217 fmol/mg protein (207 - 227). Representative graphs from one experiment performed in duplicate.

Figure 3. Displacement of $^{125}$I-triptorelin from human gonadotropin-releasing hormone receptors stably expressed on CHO cell membranes by GnRH, triptorelin, ganirelix, TAK-013 and FD-1. Representative graphs from one experiment performed in duplicate (see Table 1 for affinity values).

Figure 4. $^{125}$I-triptorelin equilibrium binding to human gonadotropin-releasing hormone receptors stably expressed on CHO cell membranes in the absence (control, 100 %) or presence of a) GTP, suramin, sodium, SCH-202676, PD 81,723 and HMA and b) 0.1 mM amiloride derivatives. Values are means (± S.E.M.) from at least three independent experiments, performed in duplicate. (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ versus control)
Figure 5. Inhibition of $^{125}$I-triptorelin equilibrium binding to human gonadotropin-releasing hormone receptors stably expressed on CHO cell membranes by HMA and MIBA. Representative graphs from one experiment performed in duplicate (see Table 3 for affinity values).

Figure 6. Dissociation kinetics of $^{125}$I-triptorelin binding to human gonadotropin-releasing hormone receptors stably expressed on CHO cell membranes. Dissociation was either initiated by the addition 1 µM ganirelix mixed with buffer (control) or modulator. Representative graphs from one experiment performed in duplicate (see Table 2 for kinetic parameters).

Figure 7. Concentration-effect curves of triporelin on NFAT-induced luciferase production through human gonadotropin-releasing hormone receptors in the presence and absence (control) of different concentrations HMA or FD-1. Representative graphs from one experiment performed in duplicate (see Table 3 for EC$_{50}$ and E$_{max}$ values).

Figure 8. Displacement of $^{125}$I-triptorelin by FD-1 binding at human gonadotropin-releasing hormone receptors stably expressed on CHO cell membranes in the presence or absence (control) of three concentrations of HMA. Representative graphs from one experiment performed in duplicate (see Table 4 for affinity and B$_{max}$ values).
Figure 9. Effect of HMA on single point dissociation of $^{125}$I-triptorelin from human gonadotropin-releasing hormone receptors stably expressed on CHO cell membranes in the presence or absence (control) of three concentrations of FD-1. The top graph (a) shows data normalized to the control measured in the absence of FD-1 and the lower graph (b) shows data normalized to the four conditions in the absence of HMA. Graphs are mean ± SEM from at least four independent experiments, performed in duplicate.

Figure 10. Neutral cooperativity between HMA and FD-1 in enhancing $^{125}$I-triptorelin dissociation. The experimental data of different concentrations of FD-1 affecting the modulating potency of HMA is displayed with standard deviation. The lines show the fit of the data to eq. 1 (see material and methods), where the situations are simulated that two compounds exhibit positive ($\delta > 1$), neutral ($\delta = 1$) and negative cooperativity ($\delta < 1$).
Table 1

Receptor affinity of peptidic agonists, GnRH and triptorelin, peptidic antagonist, ganirelix, and non-peptidic antagonists, TAK-013 and FD-1, expressed as $K_i$ values.

<table>
<thead>
<tr>
<th>Compound</th>
<th>$K_i$ (nM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GnRH*</td>
<td>1.2 ± 0.1</td>
</tr>
<tr>
<td>Triptorelin</td>
<td>0.42 ± 0.07</td>
</tr>
<tr>
<td>Ganirelix</td>
<td>3.8 ± 0.4</td>
</tr>
<tr>
<td>TAK-013</td>
<td>1.9 ± 0.7</td>
</tr>
<tr>
<td>FD-1</td>
<td>4.9 ± 1</td>
</tr>
</tbody>
</table>

* Displacement of specific $^{125}$I-triptorelin binding from human gonadotropin-releasing hormone receptors stably expressed in CHO cell membranes.

* According to computer analysis of the binding curve of GnRH, a two-site competition model of higher (H) and lower (L) affinity was statistically preferred with $K_H = 0.54 ± 0.004$ nM, $K_L = 21 ± 10$ nM and $RH = 69 ± 3$ %.

Values are means ( ± S.E.M.) of at least three separate assays performed in duplicate.
Table 2

Displacement, dissociation and allostERIC modulation of $^{125}$I-triptorelin binding by HMA, MIBA, DCB and FD-1, expressed as IC$_{50}$, k$_{off}$ and EC$_{50}$ values.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Inhibitory potency$^a$</th>
<th>Modulatory potency$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IC$_{50}$ (µM)</td>
<td>k$_{off}$ (min$^{-1}$)$^b$</td>
</tr>
<tr>
<td>Control</td>
<td>-</td>
<td>0.021 ± 0.002</td>
</tr>
<tr>
<td>+ HMA</td>
<td>29 ± 3</td>
<td>0.053 ± 0.006</td>
</tr>
<tr>
<td>+ MIBA</td>
<td>39 ± 7</td>
<td>0.045 ± 0.006</td>
</tr>
<tr>
<td>+ DCB</td>
<td>30 ± 3</td>
<td>0.035 ± 0.006</td>
</tr>
<tr>
<td>+ FD-1</td>
<td>-</td>
<td>0.068 ± 0.009</td>
</tr>
<tr>
<td>+ HMA, + FD-1</td>
<td>-</td>
<td>0.11 ± 0.01</td>
</tr>
</tbody>
</table>

$^a$ Displacement of specific $^{125}$I-triptorelin binding from human gonadotropin-releasing hormone receptors stably expressed in CHO cell membranes.

$^b$ The value of the kinetic dissociation rate constant was obtained by analysis of the exponential dissociation curve of $^{125}$I-triptorelin bound to human gonadotropin-releasing hormone receptors in the presence of buffer (control), 0.1 mM HMA, MIBA, DCB, 3 µM FD-1 or 0.1 mM HMA and 3 µM FD-1.

$^c$ The shift is defined as the ratio of k$_{off}$ values in the presence and absence (control) of modulator, respectively.

$^d$ The value for the concentration at half-maximal enhancement of dissociation kinetics.

Values are means (± S.E.M.) of at least three separate assays performed in duplicate.

ND, not determined
Table 3

Receptor activation by triptorelin in the presence or absence of different concentrations of HMA or FD-1, expressed as EC\textsubscript{50} and E\textsubscript{max} values.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Activity in luciferase assay\textsuperscript{a}</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Triptorelin</td>
<td>EC\textsubscript{50} (nM)</td>
<td>E\textsubscript{max} (%)</td>
</tr>
<tr>
<td>+ 3 µM HMA</td>
<td>0.21 ± 0.03</td>
<td>95 ± 5</td>
</tr>
<tr>
<td>+ 5 µM HMA</td>
<td>0.24 ± 0.03</td>
<td>89 ± 3***</td>
</tr>
<tr>
<td>+ 10 µM HMA</td>
<td>0.29 ± 0.02*</td>
<td>58 ± 1***</td>
</tr>
<tr>
<td>+ 0.3 µM FD-1</td>
<td>2.7 ± 0.04***</td>
<td>93 ± 1***</td>
</tr>
<tr>
<td>+ 1 µM FD-1</td>
<td>10 ± 2***</td>
<td>84 ± 5***</td>
</tr>
<tr>
<td>+ 3 µM FD-1</td>
<td>44 ± 12***</td>
<td>72 ± 5***</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Ca\textsuperscript{2+}-mediated luciferase activity in CHO cells that stably express the human gonadotropin-releasing hormone receptor and NFAT-luciferase reporter gene.

Values are means (± S.E.M.) of at least three separate assays performed in duplicate. (\* p < 0.05, *** p < 0.001 versus control)
Table 4

Receptor affinity of FD-1 and radioligand binding capacity (in the absence of FD-1) in the presence or absence of different concentrations of HMA, expressed as $K_i$ and $B_{max}$ values, respectively.

<table>
<thead>
<tr>
<th>Compound</th>
<th>$K_i$ (nM)</th>
<th>$B_{max}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD-1</td>
<td>4.9 ± 1</td>
<td>100 ± 5</td>
</tr>
<tr>
<td>+ 3 µM HMA</td>
<td>5.9 ± 2</td>
<td>87 ± 5*</td>
</tr>
<tr>
<td>+ 10 µM HMA</td>
<td>5.3 ± 1</td>
<td>75 ± 6**</td>
</tr>
<tr>
<td>+ 30 µM HMA</td>
<td>2.3 ± 0.7*</td>
<td>47 ± 5***</td>
</tr>
</tbody>
</table>

*Displacement of specific $^{125}$I-triptorelin binding from human gonadotropin-releasing hormone receptors stably expressed in CHO cell membranes.

Values are means (± S.E.M.) of at least three separate assays performed in duplicate. (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$ versus control)
Figure 1

GnRH: pGlu-His-Trp-Ser-Tyr-Gly-Leu-Arg-Pro-Gly.NH₂
Triptorelin: pGlu-His-Trp-Ser-Tyr-D-Trp-Leu-Arg-Pro-Gly.NH₂
Ganirelix: D-Nal-D-Phe-D-Pal-Ser-Tyr-D-hArg-Leu-hArg-Pro-D-Ala

HMA: R¹=azepane, R²=H
MIBA: R¹=isobutyl-methyl-amine, R²=H
DCB: R¹=NH₂, R²=2,4-dichlorobenzyl
Figure 2

![Graph showing specific 125I-triptorelin binding (dpm) vs. 125I-triptorelin (nM). The graph includes three lines with different symbols: squares, diamonds, and circles. The x-axis represents concentrations of 125I-triptorelin (nM) ranging from 0 to 3, and the y-axis represents specific 125I-triptorelin binding (dpm) ranging from -1000 to 4000.](molpharm.aspetjournals.org)
Figure 3

![Graph showing the comparison of ligand binding affinity for different molecules: GnRH, Triptorelin, Ganirelix, TAK-013, and FD-1. The graph plots the percentage of specific 125I-triptorelin binding against the logarithm of the ligand concentration (M) on a semi-log scale.]
Figure 4

(a) % specific $[^{125}]$triptorelin binding

Control + 1 mM GTP + 0.1 mM suramin + 1 M NaCl + 10 μM SCH-202676 + 10 μM PD 81,723 + 0.1 mM HMA

(b) % specific $[^{125}]$triptorelin binding

Control + amiloride + MGCMA + MIBA + phenamil + benzamil + DCB
Figure 5

![Graph showing % specific 125-I-triptorelin binding versus log[ligand (M)]. The graph compares the binding of HMA, MIBA, and DCB.](molpharm.aspetjournals.org)
Figure 6

The graph shows the percentage of specific 125I-triptorelin binding over time for different conditions:

- **Control**
- + 0.1 mM HMA
- + 0.1 mM MIBA
- + 0.1 mM DCB
- + 3 µM FD-1
- + 0.1 mM HMA, + 3 µM FD-1
- + 3 µM TAK-013

The x-axis represents time in minutes, ranging from 0 to 120, while the y-axis represents the percentage of specific binding, ranging from 0 to 125. The graph illustrates the decrease in specific binding over time for each condition.
Figure 9

a

% enhancement of $^{125}$I-triptorelin dissociation

$\log [\text{HMA (M)}]$

- Control
- $+ 1 \mu\text{M FD-1}$
- $+ 3 \mu\text{M FD-1}$
- $+ 10 \mu\text{M FD-1}$

b

% enhancement of $^{125}$I-triptorelin dissociation

$\log [\text{HMA (M)}]$

- Control
- $+ 1 \mu\text{M FD-1}$
- $+ 3 \mu\text{M FD-1}$
- $+ 10 \mu\text{M FD-1}$
Figure 10

The graph shows the relationship between [FD-1 (μM)] and EC$_{50}$ HMA (μM) for different values of δ (dashed lines: δ = 0.1, dotted line: δ = 1, dashed-dotted line: δ = 10). The black boxes with error bars represent the experimental data points.