Differential secretion of gonadotrophins: investigation of the role of secretogranin II and chromogranin A in the release of LH and FSH in LβT2 cells

L Nicol, J R McNeilly, M Stridsberg¹ and A S McNeilly

MRC Human Reproductive Sciences Unit, Centre for Reproductive Biology, 49 Little France Crescent, Edinburgh EH16 4SB, UK

¹Department of Medical Sciences, Clinical Chemistry, University Hospital, S-751 85 Uppsala, Sweden

(Requests for offprints should be addressed to L Nicol; Email: l.nicol@hrsu.mrc.ac.uk)

Abstract

This study investigated the role of the secretory granule proteins, secretogranin II (SgII) and chromogranin A (CgA), in the differential secretion of FSH and LH from LβT2 mouse gonadotroph cells. Exogenous activin, which synergises with GnRH, is essential for the release of FSH from these cells, but also has stimulatory effects on LH and enhances GnRH-induced LH secretion. Two experiments are reported. In experiment 1, cultures were supplemented with activin (0–50 ng/ml), with and without a daily 1 h treatment of 10 nM GnRH, for 3 days. Protein secretion and mRNA levels were measured. In experiment 2, cells were treated with activin (50 ng/ml) alone, a daily 1 h treatment of 10 nM GnRH, or a combination of both for 6 days. In addition, cells exposed to activin+GnRH for 3 days were subsequently left untreated or given activin or GnRH alone for a further 3 days for comparison with cells maintained in activin+GnRH for 6 days. Protein secretion, intracellular protein and mRNA levels were measured. FSH secretion was stimulated, dose dependently, by activin and this effect increased synergistically in the presence of GnRH. The close correlation between secreted and intracellular FSH and FSHβ mRNA levels was maintained in cells that had undergone treatment withdrawal after previous exposure to activin+GnRH, but there was no correlation between FSH and the granins. These results are consistent with the view that FSH released in response to activin/GnRH is constitutively secreted via a granin-independent pathway. SgII secretion mirrored the GnRH-induced secretion of LH, but was unaffected by activin, which stimulated LH secretion and had a detrimental effect on CgA mRNA transcription. This confirms previous observations that the LH released in response to GnRH is co-released with SgII via a regulated, granin-dependent pathway, and, in addition, suggests that activin may stimulate LH secretion through a constitutive, granin-independent pathway.

Journal of Molecular Endocrinology (2004) 32, 467–480

Introduction

The control of reproduction requires that the secretion of the gonadotrophins luteinizing hormone (LH) and follicle-stimulating hormone (FSH) is tightly controlled, particularly in the female to allow selection and maturation of the prevulatory follicles in the ovary. LH and FSH are produced in bihormonal gonadotroph cells in the anterior pituitary (Liu et al. 1988, Currie & McNeilly 1995, Thomas & Clarke 1997, Crawford et al. 2002), but have distinctly different patterns of secretion (Childs et al. 1987, Lloyd & Childs 1988). While there is some basal, non-pulsatile secretion of LH (McNeilly et al. 1991, Crawford et al. 2002), this hormone is released predominantly from intracellular stores in discrete pulses under the influence of pulsatile hypothalamic gonadotrophin-releasing hormone (GnRH), a regulated pathway of secretion (Clarke & Cummins 1982, Burgess & Kelly 1987). In contrast, while there is limited pulsatile secretion of FSH, often independent of pulsatile GnRH (Farnworth 1995, Padmanabhan et al. 1997, Crawford et al. 2002), the bulk of this hormone appears to be constitutively secreted and thus the amount released is directly related to the rate of

Since both LH and FSH are produced in, and released from, the same gonadotrophs, there must be an intracellular mechanism controlling discrete release of the gonadotrophins, which both consist of a common α-subunit combined with a hormone-specific β-subunit and have a deduced similar tertiary structure (Lapthorn et al. 1994). A potential mechanism could involve differential intracellular packaging of LH and FSH within the gonadotroph, leading to different pathways of secretion. The principal cargo proteins in secretory granules are the granins, chromogranin A (CgA), chromogranin B (CgB) and secretogranin II (SgII). These proteins aggregate at low pH and high Ca$^{2+}$ concentrations (Yoo 1996), as found within the trans-Golgi network where granule formation is initiated, and thus have been proposed to function as helper proteins in packaging other proteins into secretory granules (Huttner & Natori 1995). Indeed it has been suggested that CgA specifically acts as the master ‘on/off’ switch regulating secretory granule formation in neuroendocrine cells (Kim et al. 2002). We (Crawford & McNeilly 2002, Crawford et al. 2002) and others (Watanabe et al. 1991, 1993) have shown that LH is co-packaged with SgII into electron-dense secretory granules in gonadotrophs and that pulsatile secretion of LH requires the presence of these granules (Crawford et al. 2002). Furthermore, basal secretion of LH in vitro is associated with granules containing only LH and no SgII (Crawford et al. 2002). Thus, packaging of LH into two different types of granule appears to determine the mode of secretion of LH.

While there is an association between levels of FSHβ mRNA, synthesis and release of FSH, and plasma FSH levels, little is known about the role that packaging of FSH may play in this type of secretion (McNeilly 1988, Farnworth 1995, McNeilly et al. 2003). FSH appears to be localised in different regions of the gonadotrophs compared with LH (Thomas & Clarke 1997) and preliminary results suggest that FSH is associated with electron-lucent bodies and is not present within the LH+ve/SgII+ve electron-dense granules (Crawford et al. 2002). Indeed, the differential pattern of LH and FSH secretion would predict that the two hormones should be in different storage granules prior to release, or such different patterns of secretion could not occur.

Previously, studies using the LβT2 gonadotroph cell line showed that in vitro LH release in response to GnRH was closely associated with a parallel release of SgII (Nicol et al. 2002). While no clear correlation was observed between the release or storage of LH and CgA, this granin has been localised to the periphery of LH+ve/SgII+ve granules in the sheep pituitary (Crawford & McNeilly 2002) as well as in light-dense vesicles containing FSH in the rat pituitary (Watanabe et al. 1991). Furthermore, we have previously shown that mRNA levels for CgA increased in response to GnRH, suggesting a possible role in the regulated release of LH (Nicol et al. 2002).

Early reports utilising LβT2 cells had suggested that they were unable to synthesise and secrete FSH (Turgeon et al. 1996), so the relationship between the granins and FSH secretion was not evaluated. However, combined activin and GnRH treatment has recently been shown to stimulate FSHβ mRNA levels and subsequent secretion of FSH in these cells (Graham et al. 1999). Thus, in the present study we have utilised this finding to manipulate the patterns of synthesis and secretion of FSH, as well as LH, in order to evaluate interactions between the gonadotrophins and the granins. The results support the concept that FSH secretion is via a distinct intracellular pathway, independent of LH and granin release.

Materials and methods

Cell culture

LβT2 cells were kindly provided by Dr P. Mellon (University of California, San Diego, CA, USA) and cultures were maintained as described previously (Nicol et al. 2002). For experimental purposes cells were cultured on six-well plates coated with phenol-red-free Matrigel (1:3; BD Biosciences Clontech, Cowley, Oxford, UK), in phenol-red-free Dulbecco’s modified Eagle’s medium (DMEM) (1 g/l glucose) supplemented...
with 10% charcoal-treated fetal calf serum, 3·5 g/l glucose, 4 mM L-glutamine, 1 × non-essential amino acids, 20 nM dexamethasone, 50 U/ml penicillin and 50 µg/ml streptomycin. Cell culture reagents were obtained from Sigma unless otherwise indicated.

Experiment 1
To confirm the appropriate concentration of activin for use in subsequent experiments, an activin dose response was carried out in the presence and absence of GnRH. LβT2 cells were seeded at a density of 2 × 10^6 cells per well (three wells per treatment group), allowed to attach overnight, then exposed to recombinant human activin A (R&D Systems, Abingdon, Oxon, UK) at 0, 10, 20 or 50 ng/ml, with and without a daily 1 h treatment of 10 nM GnRH (Peninsula Laboratories Europe Ltd, St Helens, Merseyside, UK), for 3 days, as described by Graham et al. (1999). Daily protein secretion and day 4 mRNA levels were measured.

Experiment 2
There were two parts to this experiment. (A) In an attempt to further stimulate levels of FSH/LH production and secretion, observed as a result of the treatment regime described above, the duration of treatment was extended. Cells were plated at a density of 1·25 × 10^6 cells/well (six wells per treatment group) and treated with activin/GnRH as described above, except that activin was used at 50 ng/ml only and the treatment period was extended to 6 days. (B) The effects of withdrawal of activin, GnRH or activin+GnRH from cells previously exposed to activin+GnRH were assessed. Cells were plated at 1·25 × 10^6 cells per well (six wells per group), treated with activin (50 ng/ml)/GnRH as described above for 3 days, then transferred to untreated or activin-only conditions or given daily 1 h GnRH treatments only for a further 3 days and compared with cells maintained in activin+GnRH for 6 days. For both parts of this experiment daily protein secretion was measured (six wells per group). On day 7 each group was split into two: three wells for measurement of mRNA levels and three wells for measurement of intracellular protein.

Media samples were collected at each medium change for RIA to measure protein secretion. In experiment 1 all cells (day 4), and in experiment 2 half of each group (day 7) were suspended in RNazol B (Tel-Test, Inc., TX, USA) and total RNA prepared, according to the manufacturer’s protocol, for quantitative reverse transcription (RT)-PCR analysis of mRNA levels. In experiment 2 the remaining cells on day 7 were used to prepare intracellular protein extracts as described previously (Nicol et al. 2002) for analysis by RIA.

Radioimmunoassays

Gonadotrophins
Secreted and intracellular FSH and LH were measured by RIA as previously described (McNeilly et al. 1996), using agents supplied by Dr A Parlow (National Institute of Diabetes and Digestive and Kidney Diseases, Torrance, CA, USA). The reference preparations were AFP-5308D and rLH-RP-1, and the minimum detectable concentrations were 1 ng/ml and 200 pg/ml, for FSH and LH respectively. The intra- and inter-assay coefficients of variation were < 10% for both assays.

Granins
SgII was measured as described previously (Stridsberg et al. 1995, Nicol et al. 2002), using an antibody against the human SgII amino acid sequence 154–165 (hSgII154–165). CgA was measured using an antibody to human CgA amino acid sequence 324–337 (hCgA324–337), which detects the WE-14 region of CgA, as described previously (Portela Gomes & Stridsberg 2001, Nicol et al. 2002). The detection limits were < 10 fmol and the total assay variation was < 10% for both assays.

Quantitative RT-PCR
Levels of mRNA for LHβ, FSHβ, SgII, CgA, GnRH receptor (GnRH-R), inhibin/activin βB-subunit and the activin receptors IIA (ARIIA), IIB (ARIIB) and IB (ARIB) were measured using quantitative Taqman RT-PCR. This was performed as described previously for LHβ (Nicol et al. 2002). Primer and probe sequences were designed using Primer Express software (PE Biosystems, Warrington, UK) and were synthesized either by PE Biosystems or by Biosource Europe S.A.,
Nivelles, Belgium). The probe and primer sets used for all sequences are shown in Table 1.

**Statistical analysis**

Data are reported as means ± s.e.m. Comparisons between experimental groups were determined using one-way ANOVA, and where a significant interaction was found, post-hoc analysis was performed using Tukey’s test. Analysis of interaction between activin and GnRH in the dose–response experiment was carried out using two-way ANOVA and the Bonferroni method. All statistical analyses were performed using GraphPad Prism version 4 (GraphPad software Inc., San Diego, CA, USA). P<0.05 was considered significant.

**Results**

**Experiment 1: Activin dose response**

This experiment examined the effects of constant exposure to 0, 10, 20 and 50 ng/ml activin A for 3 days, in the presence and absence of daily GnRH treatment, on the secretion of FSH, LH, SgII and CgA and on mRNA levels for FSHβ, LHβ, SgII and CgA. Secretion profiles for each protein, representing the total protein secreted during the 1 h GnRH treatment and the subsequent overnight incubation, and the corresponding day 4 mRNA levels, are depicted in Fig. 1.

**FSH**

Activin alone (20 and 50 ng/ml) increased FSH secretion (P<0.01) on day 3, whereas GnRH alone had no effect (Fig. 1A(i)). While activin+GnRH had a small stimulatory effect (P<0.01) on FSH secretion even on day 1, by days 2 and 3 the combined treatment markedly stimulated (P<0.001) FSH release, in a dose-dependent manner, compared with untreated controls and individual treatments (Fig. 1A(i)). FSHβ mRNA was unaffected by individual treatments, but was up-regulated (P<0.001) by activin (50 ng/ml)+GnRH (Fig. 1B(i)).

**LH**

All concentrations of activin stimulated (P<0.001) LH secretion on days 1 and 2, but on day 3 only 50 ng/ml had a stimulatory (P<0.01) effect (Fig. 1A(ii)). GnRH alone also stimulated (P<0.001) daily LH secretion (Fig. 1A(ii)). Combined activin+GnRH further increased LH secretion (P<0.001) beyond levels observed with individual treatments, but this effect was similar at all concentrations of activin (Fig. 1A(ii)). Activin (50 ng/ml)+GnRH increased (P<0.01) LHβ mRNA transcription (Fig. 1B(ii)).

**SgII**

Activin alone had little effect on SgII secretion overall, with only a slight increase obtained in response to 50 ng/ml (P<0.05) on day 2, whereas GnRH alone markedly increased (P<0.001) SgII secretion each day (Fig. 1A(iii)). On day 3 activin (20 and 50 ng/ml)+GnRH increased SgII secretion (P<0.01 and P<0.001 respectively) compared with GnRH alone (Fig. 1A(iii)). SgII mRNA levels were not significantly affected by any treatment (Fig. 1B(iii)).

**CgA**

Activin alone had no effect on CgA secretion, whereas GnRH stimulated (day 1, P<0.05; days 2

### Table 1 Sequences of primers and probes used for Taqman RT-PCR analysis

<table>
<thead>
<tr>
<th>Gene</th>
<th>Forward Primer</th>
<th>Reverse primer</th>
<th>Probe (FAM labelled)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSHβ</td>
<td>ggagagcaatctgctgcata</td>
<td>gcagaaacggcactcttcct</td>
<td>ctgtaaatcaccatcaacctctcagtaag</td>
</tr>
<tr>
<td>LHβ</td>
<td>tgtgtgacccactgcagctt</td>
<td>cggctgcctcttcctggtc</td>
<td>cggctgcttcaccatctgcag</td>
</tr>
<tr>
<td>GnRH-R</td>
<td>tgtgtgacccactgcacgtt</td>
<td>cggctgcctcttcctggtc</td>
<td>cggctgcttcaccatctgcag</td>
</tr>
<tr>
<td>β-subunit</td>
<td>atgctcctgcagttca</td>
<td>gcagaaacggcactcttcct</td>
<td>cggctgcctcttcctggtc</td>
</tr>
<tr>
<td>ARIIA</td>
<td>aagtctcctgcagttca</td>
<td>gcagaaacggcactcttcct</td>
<td>cggctgcctcttcctggtc</td>
</tr>
<tr>
<td>ARIIB</td>
<td>ggcagagcaatctgctgcata</td>
<td>gcagaaacggcactcttcct</td>
<td>cggctgcctcttcctggtc</td>
</tr>
<tr>
<td>ARIIB</td>
<td>ccatgaagacatcacaactgcgtat</td>
<td>gcagaaacggcactcttcct</td>
<td>cggctgcctcttcctggtc</td>
</tr>
</tbody>
</table>

---

**Journal of Molecular Endocrinology (2004) 32, 467–480**
Figure 1 Activin dose response. (A) Total daily secretion of (i) FSH, (ii) LH, (iii) SgII and (iv) CgA from LβT2 cell cultures supplemented with human recombinant activin A (0, 10, 20 and 50 ng/ml), with and without a daily 1 h treatment of 10 nM GnRH, for 3 days. Each value represents the total protein secreted during the 1 h GnRH (or corresponding control) treatment and the subsequent overnight incubation. (B) mRNA levels for (i) FSHβ, (ii) LHβ, (iii) SgII and (iv) CgA from LβT2 cells cultured as described above and harvested on day 4. Different letters indicate significant differences between treatment groups. Values represent means±S.E.M.; n=3.

Granins and gonadotrophin secretion in LβT2 cells · L NICOL and others

Journal of Molecular Endocrinology (2004) 32, 467–480

Downloaded from Bioscientifica.com at 03/28/2019 11:17:09AM via free access
and 3, \( P<0.001 \) release of this protein (Fig. 1A(iv)). However, when GnRH was combined with activin, a decrease in CgA release (\( P<0.001 \)), compared with the GnRH-stimulated levels was observed, although the amounts of CgA released remained higher (\( P<0.05 \)) than those obtained with activin alone (Fig. 1A(iv)). Activin (50 ng/ml)+GnRH increased (\( P<0.05 \)) CgA mRNA compared with activin alone (Fig. 1B(iv)).

The results from this experiment indicated that 50 ng/ml activin, in the presence of GnRH, was required to have an effect on FSH mRNA levels in LβT2 cells. This concentration of activin also produced the greatest stimulation of FSH release and was effective in enhancing the stimulatory effects of GnRH on LH secretion. Consequently, 50 ng/ml activin was used in the subsequent experiments.

Experiment 2(A): effects of 6 days treatment with activin, GnRH and activin+GnRH

The effects of constant exposure to 50 ng/ml activin A, in the presence and absence of a daily 1 h treatment of 10 nM GnRH, for 6 days, on the secretion (day 3 and day 6 results are reported) and intracellular storage (on day 7) of FSH, LH, SgII and CgA were determined. In addition, day 7 FSHβ, LHβ, SgII, CgA, GnRH-R, \( \beta \)-subunit and activin receptor (IB, IIA and IIB) mRNA levels were measured.

**FSH**

Activin+GnRH increased (\( P<0.001 \)) FSH secretion on days 3 (Fig. 2A(i)) and 6 (Fig. 2B(i)), whereas individual treatments had no effect. Similarly, intracellular FSH (Fig. 2C(i)) and FSHβ mRNA (Fig. 2D(i)) levels increased (\( P<0.001 \)) in response to activin+GnRH only.

**LH**

On day 3, activin alone (\( P<0.01 \)) and GnRH alone (\( P<0.001 \)) both increased LH secretion, with GnRH producing the higher (\( P<0.01 \)) response (Fig. 2A(ii)). Combined activin+GnRH enhanced (\( P<0.001 \)) LH secretion approximately 2-fold compared with individual treatments. Activin alone (\( P<0.01 \)) and GnRH alone (\( P<0.05 \)) increased LH secretion on day 6 also, but there was no difference between these two responses (Fig. 2B(ii)). Combined activin+GnRH again enhanced (\( P<0.001 \)) LH secretion compared with individual treatments (Fig. 2B(ii)). Intracellular LH and LHβ mRNA were increased (\( P<0.01 \), Fig. 2C(ii) and \( P<0.05 \), Fig. 2D(ii) respectively) by activin+GnRH.

**SgII**

GnRH alone increased (\( P<0.001 \)) SgII secretion on days 3 and 6 (Fig. 2A (iii) and 2B (iii) respectively). Activin had no effect on SgII release. However, activin increased (\( P<0.05 \)) intracellular SgII (Fig. 2C(iii)), whereas GnRH and activin+GnRH reduced (\( P<0.01 \) and \( P<0.05 \) respectively) intracellular levels of this protein (Fig. 2C(iii)).

**CgA**

GnRH increased (\( P<0.001 \)) CgA secretion on day 3. However, when GnRH was combined with activin, CgA secretion was similar to control levels (Fig. 1A(iv)). After 6 days of treatment there were no differences in secretion or intracellular protein levels (Fig. 2B(iv)). While CgA mRNA from all treatment groups was unchanged compared with controls, GnRH-stimulated cells had significantly higher (\( P<0.05 \)) levels of this mRNA compared with cells treated with activin alone (Fig. 2D(iv)).

GnRH receptor, \( \beta \)-subunit and activin receptor mRNAs

GnRH-R mRNA levels were increased (\( P<0.05 \)) by activin+GnRH (Fig. 3A(i)). \( \beta \)-subunit mRNA from all treatment groups was unchanged compared with controls, but was lower (\( P<0.05 \)) in GnRH-treated cells compared with activin-treated cells (Fig. 3A(iii)). Activin receptor mRNA levels were unchanged by the treatments given (data not shown).

Experiment 2(B): effects of activin, GnRH or activin+GnRH withdrawal after prior exposure to activin+GnRH

After exposure to activin plus daily GnRH treatment, for 3 days, cells were transferred to either untreated medium (AG/C) or given activin.
Figure 2  Effects of continual exposure to activin, GnRH and activin+GnRH for 6 days. (A) Day 3 secretion of (i) FSH, (ii) LH, (iii) SgII and (iv) CgA from LjT2 cell cultures supplemented with human recombinant activin A (50 ng/ml), in the presence (AG) and absence (A) of a daily 1 h treatment of 10 nM GnRH, or with GnRH alone (G) for 6 days. Each value represents the total protein secreted during the 1 h GnRH (or corresponding control) treatment and the subsequent overnight incubation. (B) Day 6 secretion of (i) FSH, (ii) LH, (iii) SgII and (iv) CgA from LjT2 cells cultured as described. (C) Intracellular levels of (i) FSH, (ii) LH, (iii) SgII and (iv) CgA in LjT2 cells cultured as described and harvested on day 7. (D) mRNA levels for (i) FSH, (ii) LH, (iii) SgII and (iv) CgA in LjT2 cells cultured as described and harvested on day 7. Different letters indicate significant differences between treatment groups. Values represent means±S.E.M.; n=6 (A and B), n=3 (C and D).
(AG/A) or GnRH (AG/G) alone and cultured for a further 3 days (see Fig. 4A). Results were compared with those from cells maintained in activin+GnRH (AG) for the duration of the experiment.

To demonstrate the immediate effects of the treatment changes Fig. 4B depicts protein secretion in the transition period from day 3, with all cells still under the effects of activin+GnRH, over to day 4, the first day of treatment withdrawal. Day 3 secretion for all four groups treated with activin+GnRH was similar so results for one group only are shown. Compared with cells maintained in activin+GnRH, FSH secretion on day 4 (Fig. 4B(i)) was reduced (AG/C and AG/G, $P<0.001$; AG/A, $P<0.05$) in all groups where individual or combined treatments were withdrawn. However, cells transferred to activin only continued to secrete more FSH than cells transferred to control medium ($P<0.05$) or given GnRH only ($P<0.01$). LH secretion in cells transferred to untreated or activin-only conditions was slightly reduced on day 4, compared with activin+GnRH-treated cells, but this did not reach significance (Fig. 4B(ii)). Cells transferred to GnRH only had unchanged LH secretion compared with activin+GnRH-treated cells, but secreted significantly more ($P<0.01$) LH compared with cells cultured in the absence of GnRH (Fig. 4B(ii)). SgII secretion was reduced ($P<0.001$) in cells transferred to untreated or activin-only conditions, compared with cells maintained in activin+GnRH or those given GnRH only (Fig. 4B(iii)). Day 4 CgA secretion was unchanged by withdrawal of GnRH and activin+GnRH (Fig. 4B(iv)). However, withdrawal of activin, but continued GnRH, resulted in increased CgA compared with all other groups (AG, $P<0.05$; AG/C and AG/A, $P<0.001$).

Day 6 protein secretion and day 7 intracellular protein and mRNA levels are shown in Fig. 5.

**FSH**

Withdrawal of GnRH; but continued activin-reduced ($P<0.001$) FSH secretion to approximately half that from cells maintained in activin+GnRH, whereas withdrawal of activin ± GnRH resulted in basal levels (see Fig. 2B(i)) of FSH secretion (Fig. 5A(i)). Similar results were obtained for intracellular protein (Fig. 5B(i)) and FSHβ mRNA levels (Fig. 5C(i)), but in the latter case levels were maintained closer to those in activin+GnRH-treated cells by continued activin treatment.

**LH**

LH secretion was reduced ($P<0.01$), compared with activin+GnRH-treated cultures, in cells transferred to untreated or activin-only conditions (Fig. 5A(ii)), whereas there were no significant changes in intracellular LH levels in response to any of the treatment regimes (Fig. 5B(ii)). LHβ...
Figure 4 Effects of individual or combined treatment withdrawal in cells previously exposed to activin+GnRH: protein secretion on days 3 and 4. (A) Treatment protocol. LβT2 cells were cultured in human recombinant activin A (50 ng/ml), in the presence of a daily 1 h treatment of 10 nM GnRH (AG), for 3 days, then transferred to untreated (AG/C), activin only (AG/A) or GnRH only (AG/G) conditions and cultured for a further 3 days, and compared with cells maintained in activin+GnRH (AG) for 6 days. (B) Day 3 (prior to treatment withdrawal) and day 4 (after treatment withdrawal) secretion of (i) FSH, (ii) LH, (iii) SgII and (iv) CgA from LβT2 cells cultured as described above. Each value represents the total protein secreted during the 1 h GnRH (or corresponding control) treatment and the subsequent overnight incubation. Different letters indicate significant differences between treatment groups. Values represent means±S.E.M.; n=6.
mRNA levels were reduced \( (P<0.05) \) after transfer to untreated or GnRH-only conditions, and, while there was a small reduction after transfer to activin only, this did not reach significance (Fig. 5C(ii)).

Withdrawal of all treatments reduced \( (P<0.001) \) SgII secretion compared with activin+GnRH-treated cells. However, activin-stimulated cells secreted more \( (P<0.001) \) SgII than cells trans-
ferred to untreated conditions, and GnRH-treated cells released more \( (P<0.001) \) SgII compared with cells transferred to activin only (Fig. 5A(iii)).

**CgA**

Withdrawal of GnRH and activin+GnRH reduced \( (P<0.001) \) CgA secretion compared with activin+GnRH-treated cells, whereas cells that continued to receive daily GnRH secreted similar amounts of CgA as activin+GnRH-treated cells (Fig. 5A(iv)).

**GnRH receptor, activin βB-subunit and activin receptor mRNAs**

Activin and activin+GnRH withdrawal reduced \( (P<0.05) \) GnRH-R mRNA levels, compared with activin+GnRH-treated cells (Fig. 3B(ii)), but had no significant effects on βB-subunit mRNA levels (Fig. 3B(ii)) or on activin receptor mRNA (data not shown).

**Discussion**

Previously we have demonstrated a close correlation between the GnRH-stimulated release of both LH and SgII in vitro (Nicol et al. 2002), and the co-localisation and co-release of LH and SgII in vivo (Crawford et al. 2002), suggesting that SgII plays an important role in the regulated secretion of LH. In the current report we have extended these studies to examine in detail the relationship between the synthesis, storage and secretion of FSH, as well as LH and the granins in LβT2 cells, to investigate further the role of granin proteins in the differential secretion of the gonadotrophins.

Early studies on LβT2 cells indicated that they did not express FSHβ mRNA or secrete FSH (Turgeon et al. 1996). The ability of activin (±GnRH) to stimulate FSH production in these cells has since been reported (Graham et al. 1999, Pernasetti et al. 2001), which has further elevated the importance of the LβT2 cell line as a model for investigating gonadotroph function. It must be recognised, however, that the use of these immortalised cell lines can only give an indication of potential mechanisms involved in differential LH and FSH secretion and may not completely, or accurately, reflect gonadotroph function in vivo. Nevertheless, they do provide a reproducible model gonadotroph system with which to explore potential in vivo mechanisms.

While FSH secretion in LβT2 cells was stimulated, in a dose-dependent manner, by activin alone, and was unaffected by GnRH alone, there was a synergistic effect between the two treatments. In contrast to the previous report (Graham et al. 1999), we observed a significantly higher maximal FSH response (approx 11-fold after 72 h) to activin in the presence of GnRH compared with activin alone. Very similar response patterns were obtained for secreted and intracellular FSH and FSHβ mRNA levels. This correlation was maintained in cells subjected to treatment withdrawal after previous exposure to activin+GnRH. The close correlation between stored and secreted FSH, and FSHβ mRNA levels, and the lack of any correlation between the secretion of FSH and that of the granins, lead to the conclusion that the FSH produced in LβT2 cells under activin/GnRH stimulation is constitutively secreted via a granin-independent pathway. Since GnRH is ineffective in stimulating or maintaining FSH production in the absence of exogenous activin, endogenous activin would appear to be absent or at very low levels in LβT2 cells, despite the fact that they do express βB-subunit mRNA (see Fig. 3), and this presumably is one of the reasons why FSH was reportedly absent from these cells in earlier experiments (Turgeon et al. 1996).

While the effect of the interaction between activin and GnRH on FSH production and secretion has been previously noted (Weiss et al. 1992, 1993), the exact nature of the interaction is still unclear. While activin alone stimulated FSH secretion as described previously (Graham et al. 1999) it appears that GnRH requires the presence of activin in order to exert its actions. Furthermore activin alone was able to maintain FSHβ mRNA at the levels induced by activin+GnRH when GnRH stimulation has been removed, possibly due to post-transcriptional effects on FSHβ mRNA stability (Carroll et al. 1991). In perfused rat pituitary cultures GnRH at least doubled the increase in FSHβ mRNA induced by exogenous activin (Weiss et al. 1993), and it is estimated that GnRH controls about 50–67% of FSHβ mRNA levels at a particular concentration of activin (Miller et al. 2002). Studies in GH3 cells engineered
to express the rat GnRH-R (rGnRH-R) and in LβT2 cells have indicated the presence of GnRH-responsive elements (enhancers) on the rat and ovine FSHβ (oFSβ) promoters (Kaiser et al. 1995, Pernasetti et al. 2001) and it has been reported that two activating protein-1-like enhancers on the oFSHβ proximal promoter are required for GnRH induction of oFSHβ-Luc transcription (Strahl et al. 1998), suggesting a mechanism whereby GnRH can directly influence FSHβ transcription (Miller et al. 2002). Regardless of the mechanisms by which activin and GnRH increase or maintain FSHβ mRNA levels, the present results, showing a close relationship between FSHβ mRNA levels and the secretion of FSH, are compatible with the concept of release of FSH mainly through a constitutive, granin-independent pathway.

Activin also had a stimulatory effect on LH secretion, although this response was not dose dependent. After 6 days of treatment the amount of LH secreted in response to activin was similar to that released in response to GnRH. Combined activin+GnRH induced a further increase over individual treatment levels, which appeared to be additive rather than synergistic. Activin A has previously been shown to stimulate the synthesis of GnRH receptors, through a different mechanism from GnRH (Braden & Conn 1992) and, although neither activin nor GnRH alone appeared to have any effect on GnRH-R mRNA levels in this study, there was a significant increase after the combined treatment, and this may be one mechanism whereby the activin/GnRH-stimulated secretion of LH and FSH is regulated.

SgII secretion, in contrast to that of LH, was stimulated only by GnRH, and combined activin/GnRH produced no additive or synergistic effects. The present results suggest that the LH released in response to GnRH is co-released with SgII via a regulated secretory pathway and that the activin-stimulated LH release is probably via a constitutive, SgII-granule-independent pathway. It is likely that this pathway of release is also CgA independent, as activin had a detrimental effect on CgA mRNA levels and CgA secretion. Studies in mice have indicated that LH+ve/SgII−ve storage granules are released constitutively to maintain basal LH concentrations (Crawford et al. 2002) and it is possible that activin may be influencing the amount of LH which is directed into this type of granule. While intracellular SgII was reduced in GnRH- and activin+GnRH-stimulated cells, presumably reflecting the ongoing secretion of LH+ve/SgII+ve granules in response to GnRH, levels were increased in activin-stimulated cells. Intracellular LH was also raised in activin-treated cells. This raises the possibility that, due to the lack of GnRH input and the associated regulatory pathway stimulation and release, there was an increase in the number of LH+ve/SgII+ve granules in activin-treated cells as seen in vivo after GnRH immunoneutralisation in mice (Crawford et al. 2002).

The aggregative properties of SgII within the trans-Golgi network are considered to be important in facilitating the packaging of LH into LH+ve/SgII+ve secretory granules, thus controlling the LH available for release through the regulated pathway, in response to GnRH stimulation (Gerdes et al. 1989, Watanabe et al. 1991, Crawford & McNeilly 2002, Crawford et al. 2002). However the lack of evidence for the presence of SgII-only granules in mouse or sheep gonadotrophs (Crawford & McNeilly 2002, Crawford et al. 2002) suggests that LH may have more influence on the formation of LH+ve/SgII+ve gonadotroph secretory granules than was previously predicted and may actually have an active role in the co-aggregation with SgII during granule formation. A role for SgII in the GnRH responsiveness of secretory granules at the time of granule exocytosis has also been envisaged (Crawford et al. 2002), but it may be that CgA contributes more to this effect than SgII (see below).

CgA secretion was maintained by GnRH and reduced below control levels by transfer to activin only, confirming the effects of GnRH and activin on secretion of CgA that were observed in the other experiments described here and in our previous study (Nicol et al. 2002). With the concomitant up-regulation of FSHβ and down-regulation of CgA gene expression in response to activin, it would appear counter-intuitive to conclude that CgA played a major role in the constitutive secretion of FSH. However, there is evidence to suggest that CgA and FSH are found within the same type of granule within gonadotrophs (Watanabe et al. 1991) and that CgA+ve granules increase in number shortly after the LH surge, at a time of higher plasma FSH concentrations (Watanabe et al. 1998). Thus a role for CgA in exocytosis associated with the constitutive pathway...
cannot be ruled out and will require further investigation.

While CgA has been proposed as the master ‘on/off’ switch regulating the formation of dense-core secretory granules (Kim et al. 2002), the precise role of CgA in the regulated pathway of secretion remains to be fully explained. CgA within gonadotrophs appears punctate, thought to be due to compartmentalisation of this granin at the granule periphery (Crawford & McNeilly 2002, Crawford et al. 2002). In addition, inositol trisphosphate receptors (IP3Rs) on secretory granule membranes have been shown to interact with IP3 binding sites on CgA (Yoo & Jeon 2000), thus contributing to intracellular Ca2+ control mechanisms and influencing regulated secretion. Together, these findings suggest that CgA may have an important role in granule exocytosis, but results in the current study, and in our previous report (Nicol et al. 2002), indicate that the release of CgA in response to GnRH does not correlate with that of LH, which suggests that CgA may be retained within the cell along with the associated granule membrane (Crawford et al. 2002).

In summary, the results reported in this study demonstrate that activin-/GnRH-induced FSH secretion in LβT2 cells is directly related to the rate of FSH synthesis and shows no correlation with either SgII or CgA, and thus appears to be released via a constitutive, granin-independent pathway. The activin-stimulated release of LH also appears to be granin-independent, suggesting constitutive release. In contrast, GnRH-induced secretion of LH correlates with that of SgII, and appears to involve CgA, suggesting release via a granin-related, regulated pathway. Further studies, involving the direct manipulation of granin levels, will be required to determine the precise role of these proteins in gonadotrophin secretion. However, the results presented here contribute further evidence for the importance of the specialised secretory granule proteins, SgII and CgA, in the differential secretion of the gonadotrophins.

Acknowledgements

We thank Janet Crawford for many helpful discussions and Dr A Parlow, NIDDK, for supplying some of the reagents.

Funding

This study was supported by the Medical Research Council.

References


Childs GV, Unabia G, Tibolt R & Lloyd JM 1987 Cytological factors that support nonparallel secretion of lutecizing hormone and follicle-stimulating hormone during the estrous cycle. Endocrinology 121 1801–1813.

Clarke IJ & Cummins JT 1982 The temporal relationship between gonadotropin releasing hormone (GnRH) and luteinizing hormone (LH) secretion in ovariectomized eces. Endocrinology 111 1737–1739.


Received in final form 12 December 2003
Accepted 22 December 2003