Rodent adrenocortical cells display high affinity binding sites and proteins for inhibin A, and express components required for autocrine signalling by activins and bone morphogenetic proteins

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Abstract

Inhibins are expressed in the adrenal cortex, but little is known of their binding or role in the adrenal. The aims of the present study were, first, to establish whether a mouse adrenocortical (AC) cell line expresses inhibins/activins and bone morphogenetic proteins (BMP), along with proteins required for inhibin to antagonise activin and BMP actions and, secondly, to characterise and compare inhibin binding sites and proteins in the rat adrenal gland and AC cells. AC cells were found to: (1) express mRNA for multiple BMPs (BMP-2, -3, -4, -6, -8a), growth/differentiation factors (GDF-1, -3, -5, -9), Lefty A and B, and the inhibin α, βA and βB subunits (2) secrete inhibin A and inhibin B and (3) express mRNA encoding the inhibin co-receptor, betaglycan, along with activin and BMP type I (ALK2–7) and type II (ActRII, ActRIIB, BMPRII) receptors, and binding proteins (follistatin, BAMBI, gremlin). When applied to sections of rat adrenal glands, [125I]inhibin A specifically bound to cells of the adrenal cortex, mainly in the zona reticularis. Scatchard analyses of in vitro [125I]inhibin A binding to dispersed rat adrenal cells and AC cells revealed sites of high affinity (Kd(1) of 0.18 and 0.15 nM, respectively) and low affinity (Kd(2) of 2.6 and 1.3 nM, respectively. Competition for [125I]inhibin A binding by activin A or B (30 nM) was negligible, whereas BMP-2, -6 and -7 competed for between 21 and 33% of specific inhibin A binding (IC50 between 0.2 and 0.3 nM). Inhibin B crossreaction with inhibin A binding sites was <8%. Multiple binding protein complexes (molecular weight ranging from 35 to >220 kDa) were affinity labelled by [125I]inhibin A on both the primary rat adrenal and AC cells. The species of >220 kDa were shown by immunoprecipitation to include betaglycan, the species of 105 kDa is consistent in size with type II receptors for activin/BMP, and that of 62 kDa co-migrates with the inhibin-follistatin complex.

In summary, the results show that inhibin A binds selectively and with both high and low affinity to AC cells via multiple binding proteins, including a single betaglycan–like species. The results support the role of glycosylated betaglycan in the high affinity binding of inhibin A, but provide consistent evidence from two independent sources of adrenal cells that inhibin A interacts with several membrane proteins in addition to those currently understood to mediate the anti-activin/BMP actions of inhibin.


Introduction

Inhibins and activins are members of the transforming growth factor-β (TGF-β) superfamily of pleiotropic growth and differentiation factors that includes bone morphogenetic proteins (BMP) (Piek et al. 1999, Chang et al. 2002). Inhibin A and inhibin B provide endocrine negative feedback from the gonads to the pituitary gonadotrophs, but local autocrine/paracrine actions of inhibins are also evident in tissues that synthesise and secrete them (Hsueh et al. 1987, Vale et al. 1988, Drummond et al. 2004, O’Connor & De Kretser 2004). Disulphide–linked dimers of inhibin β subunits form activins, the actions of which are opposed by inhibins in some cell types, most notably the pituitary gonadotroph, but not others (Vale et al. 1988).

TGF-β superfamily members such as activins initiate signalling by uniting a constitutively active serine/threonine kinase type II receptor (e.g. ActRII or ActRIIB in the case of activins) with a dormant serine/threonine kinase type I receptor (e.g. ActRIB or ALK7 in the case of activins) so that it transphosphorylates and is thereby
activated (Piek et al. 1999). Downstream signalling is mediated by type I receptor-activated Smads in combination with Smad4. Additional signalling may involve recruitment of ERK1/2, p38 MAP kinase, and phosphatidylinositol 3'-kinase/Akt (Cocolakis et al. 2001, Dupont et al. 2003). In contrast, inhibin signalling is less well understood. Although inhibin A binds with both high affinity (Kd(1)=0.1–0.3 nM) and low affinity (Kd(2)=2–5 nM) to cells from natural sources, including pituitary cells (Hertan et al. 1999, Farnworth et al. 2001, Harrison et al. 2001), no direct inhibin signalling has been demonstrated. Instead, it has been shown by over-expressing the TGF-β type III co-receptor, betaglycan, in model cell systems where inhibin promotes the formation of high affinity ternary complexes involving betaglycan, inhibin, and type II receptors for activin and BMP (ActRII/IIIB or BMPRII)(Lewis et al. 2000, Chapman et al. 2002, Wiater & Vale 2003). This results in the abolition of activin and BMP signalling by a dominant negative mechanism. In the absence of betaglycan, inhibin interacts directly with ActRII/IIIB (Martens et al. 1997, Gray et al. 2000, Lewis et al. 2000), but not with BMPRII (Wiater & Vale 2003). Inhibin also interacts with low affinity with follistatin (Shimonaka et al. 1991, Schneyer et al. 1994), a secreted glycoprotein better known for binding activin and BMP and neutralizing their actions (Lemura et al. 1998, Hashimoto et al. 2000). The short form of follistatin, follistatin-288, interacts with heparan sulphate proteoglycans on the cell surface where it binds activin (Sugino et al. 1993), but any physiological role for follistatin in inhibin binding is yet to be clarified.

Early studies identified the adrenal gland as a site of inhibin α and βA subunit expression (Crawford et al. 1987, Meunier et al. 1988), and of inhibin accumulation after the intravenous injection of [125I]inhibin A into mice (Woodruff et al. 1993). The adrenal is also a site of action for both activin and BMP (Spencer et al. 1999, Beuschlein et al. 2003, Suzuki et al. 2004). We wished to test the hypotheses that the expression of known inhibin binding proteins is the basis for adrenal gland binding of inhibin, and also that inhibin is potentially a paracrine/autocrine antagonist of activin and BMP actions in the adrenal. Determination of where and how inhibin binds in the adrenal gland are important steps in identifying its local actions. Therefore, the aims of the present study were to characterise and compare inhibin binding sites and proteins in the rat adrenal gland and a mouse adrenocortical (AC) cell line, and to demonstrate that the AC cells express the requisite ligands and associated binding/signalling proteins, that could allow antagonism of locally produced activin and BMP by inhibin to occur. The results suggest that a common set of proteins bind inhibin to rodent AC cells. The AC cells also express inhibin/activin subunits, several BMPs, and their respective binding and signalling molecules, including betaglycan, and secrete both inhibins. However, AC cells from both sources express several inhibin binding proteins that are not accounted for in the current model of inhibin action.

Materials and Methods

Materials

Adult male and female rats obtained from Central Animal House, Monash University (Clayton, Victoria, Australia) were maintained under standard conditions, with free access to food and water. The studies were performed in accordance with the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes, and procedures were approved by the Monash Medical Centre Animal Experimentation Ethics Committee. The AC cell line is derived from the Cα-1 cell line, generously provided by Drs Ilpo Huhtaniemi and Nafis Rahman (Institute of Reproductive and Developmental Biology, Imperial College London, UK and Department of Physiology, University of Turku, Finland; Kanen et al. 1996), but does not display its reported proliferative responses to activin and inhibin (P G Farnworth, P Leembruggen and Y Wang, unpublished observations).

Cell culture reagents and fetal bovine serum (FBS) were obtained from Trace Biosciences (Castle Hill, New South Wales, Australia), antibiotics (final concentrations of 100 U/ml penicillin, 100 µg/ml streptomycin, 250 ng/ml fungizone) were from Commonwealth Serum Laboratories (Parkville, Victoria, Australia), insulin was from Commonwealth Serum Laboratories-Novo (North Rocks, New South Wales, Australia), and other protein supplements, protease inhibitors, octyl-D glucopyranoside, and recombinant human inhibin B were obtained from Sigma Chemical Co. Recombinant human 31 kDa inhibin A and 25 kDa activin A (obtained in impure form from Biotech Australia, Roseville, NSW, Australia) were stored at –70 °C following purification in 0.1% trifluoroacetic acid/acetoniitrile (Harrison et al. 2001). Purified recombinant human follistatin-288 was provided by Biotech Australia. Activin B, BMP-2, -6 and -7, additional activin A, and antisera against human beta-glycan, ActRII, and BMPRII were obtained from R&D Systems (Minneapolis, MN, USA), and additional BMP-2 was from Research Diagnostics Inc. (Concord, MA, USA). Ultraspec for RNA extraction was from Fisher Biotech Australia (West Perth, WA, Australia). DNA-free was from Ambion Inc. (Austin, TX, USA). Protein G-agarose, Primer p(dT)15, Expand Reverse Transcription, FastStart DNA Master SYBR Green I and LightCycler capillaries were from Roche Diagnostics Australia. Na[125]I was a product of MP Biomedicals, Inc. (Irvine, CA, USA), bis-sulphosuccinimidyl suberate (BS3) was from Pierce Biotechnology, Inc. (Rockford, IL, USA), and [α-32P]-dCTP (3000 Ci/mmol), NAP-5 and PD-10 columns, and Sephadex G-100 were from Amersham Biosciences.
Culture of rat and mouse adrenal cells

Adult (60–90 day-old) rats were killed, and primary cultures of adrenal cells were prepared by trypsin/ deoxyribonuclease digestion of the diced tissue from 20–60 whole glands using procedures previously applied for preparing rat pituitary cell cultures (Farnworth et al. 1988). Primary adrenal cells were suspended in culture medium, consisting of a 1:1 (vol:vol) mixture of Dulbecco’s Modified Eagle’s Medium and Ham’s F12 Medium (DMEM:F12) buffered with bicarbonate, and containing antibiotics, nonessential amino acids for MEM, and supplementary glutamine (2 mM), and supplemented with 10% FBS for the pre-incubation of cultures. AC cells (passage #40–80) were maintained in culture medium containing 10% FBS, and passaged 1:20 on a weekly basis. AC and primary adrenal cells were initially plated in serum-containing medium that, after 1 day of culture cells were transferred to serum-free medium, which was prepared by diluting culture medium 9:1 with a chemically defined artificial serum (AS) composed of Dulbecco’s phosphate buffered saline (DPBS) with added CaCl₂ (1·3 mM), MgCl₂ (0·5 mM) and fatty acid-free BSA (60 g/l, final concentration of 0·6%), after which the medium was supplemented with transferrin (1·0 mg/l), and insulin (0·5 mg/l). All adrenal cell cultures prepared as described above were routinely maintained at 37 °C in a humidified atmosphere of 5% CO₂ in air.

Radioligand binding assays

Inhibin A (5 µg) was iodinated by a previously described lactoperoxidase method to a specific activity of approximately 120 µCi/µg (Hertan et al. 1999). Binding assays were conducted on day 2 of culture at room temperature (25 °C), as previously described (Farnworth et al. 2001, Harrison et al. 2001). For saturation binding studies, cells were incubated with various concentrations of radioiodinated inhibin, with or without a 50-fold excess of unlabelled inhibin.

For determination of [125I]inhibin A binding to rat adrenal in situ, 7 µm cryostat sections of whole adrenal glands frozen in OCT compound were transferred to glass microscope slides that had been coated with poly-L-lysine. Thawed sections were blocked overnight with binding buffer containing 1% dog serum albumin, washed twice with assay buffer, then incubated with [125I]inhibin A (approximately 250 pM) in the absence or presence of unlabelled inhibin A (20 nM) for 1·5 h at 37 °C in a humidified container. Tissue sections were then thoroughly washed with ice-cold DPBS, air dried, and analysed by exposure of Kodak MR x-ray film for 7 days.

Activin A (1 µg) was iodinated by a previously described chloramine T method (Buzzard et al. 2003). For [125I]activin binding and affinity labelling studies, monolayers of 1 × 10⁶ AC cells per well in 6-well cluster plates were incubated with ~90 000 c.p.m. [125I]activin/0·60 ml/well (corresponding to a final concentration of 120–200 pM) for 2 h at 25 °C with gentle agitation in the presence or absence of unlabelled inhibin A or activin A (20 nM final concentration).

Chemical crosslinking and immunoprecipitation

Affinity labelling of inhibin binding proteins on the AC cells employed the synthetic, bifunctional crosslinking agent, BS3 (0·25 mM final concentration), as previously described (Harrison et al. 2001). For analysis of AC cell membrane proteins, affinity labelled monolayers from 4–6 dishes (each containing 5 × 10⁶ cells) were collected by scraping and pooled, washed 4 times in 10 ml ice-cold crosslinking buffer (50 mM HEPES, pH 7·5, containing 130 mM NaCl, 5 mM KCl, 5 mM MgSO₄, 1·2 mM CaCl₂ and protease inhibitors), then homogenised in 2 ml quench buffer (80 mM Tris, 30 mM NaCl, pH 7·4) containing PMSF (3 mM), EDTA (4 mM) and 0·25% sucrose on ice using a Waring blender. After removal of nuclei and debris by a low speed spin (160 g, 5 min, 4 °C), the membrane fraction was collected by a high speed spin (30 000 g for 60 min), and dissolved in 0·1–0·25 ml lysis buffer. After removal of undisolved material by centrifugation, membrane lysates were analysed as for whole cell lysates.

For the analysis of betaglycan-like species, aliquots of clarified lysates from whole cells (50 µl) or membranes (20 µl) were diluted with 0·20 ml quench buffer, then immunoprecipitated with 10 µg/ml affinity purified polyclonal antisera against human betaglycan, as previously described (Harrison et al. 2001).

Affinity labelled complexes in lysates and immunoprecipitates were separated using non-reducing 7·5% SDS–PAGE. Dried gels were analysed by autoradiography after exposure of Kodak MS films for 1–28 days using BioMax TranScreen-HE intensifying screens (Eastman Kodak). The molecular masses of the separated complexes and polypeptides, respectively, were calculated according to their Rf values run against molecular weight standards (Bio-Rad Laboratories).

RNA extraction and analysis

Adrenal cell monolayers were dissolved in 1 ml UltraSpec, extracted total RNA was subsequently treated with DNA-free, then aliquots (0·5 µg) were run on 1·2% agarose gels and stained with ethidium bromide to check RNA integrity, and to allow 18S RNA contents to be estimated by densitometry. Profiling of TGF-β superfamily-related gene expression by AC cells was achieved with mouse GE SuperArray filters (GEArray Series Q; SuperArray Bioscience Corp, MD, USA) consisting of 96 mouse target genes. Total RNA (4 µg) was reverse-transcribed, and cDNA probes were synthesised according to the method suggested by the manufacturer. After the 30-cycle
Inhibin secretion by AC cells

Monolayers of $2 \times 10^6$ AC cells were incubated overnight in culture medium containing either 10% FBS or 10% AS, conditioned media were collected, cell debris was removed by centrifugation, then inhibin A and inhibin B were determined by specific ELISAs (Groome et al. 1994, 1996) according to the manufacturer’s instructions (Oxford Bio-Innovations, Oxfordshire, UK) against standards diluted in the respective matching unconditioned medium. For inhibin A, the standard was the World Health Organization human inhibin A standard #91/624, the detection limit was 4 pg/ml, and cross-reaction with inhibin B is below 0.1% (Groome et al. 2001). For inhibin B, the standard was an ‘in-house’ rat ovarian extract, as previously described (Drummond et al. 2000), the detection limit equates to 7 pg/ml of the World Health Organization human inhibin B standard #96/784, and cross-reaction with inhibin A is approximately 0.5% (Groome et al. 1996).

Expression of inhibin subunits and binding proteins by AC cells

The first aim of this study was to determine whether inhibins and their known binding proteins are produced by the mouse AC cell line. Expression of inhibin $\alpha$, $\beta_A$ and $\beta_B$ subunits was demonstrated by RT-PCR (Fig. 1a).

Table 1 Oligonucleotide primer sequences used to amplify mouse activin and BMP receptors, betaglycan, and follistatin mRNAs. The position of the 5′-sense and antisense nucleotide of each primer within the sequence is shown in parentheses

<table>
<thead>
<tr>
<th>Product</th>
<th>Primer sequence</th>
<th>GenBank accession no.</th>
<th>Product size (bp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMPRII</td>
<td>5′-GTG ACA GGG CAG TCC ATT CT-3′ (3030)</td>
<td>XM007561</td>
<td>199</td>
</tr>
<tr>
<td></td>
<td>5′-GCT GAC AGG AGG TAA AAG CA-3′ (3228)</td>
<td>Z23154</td>
<td>127</td>
</tr>
<tr>
<td>ALK3</td>
<td>5′-ATG CGT GAG GTT GTG TGT G-3′ (1408)</td>
<td>Z23143</td>
<td>122</td>
</tr>
<tr>
<td>ALK6</td>
<td>5′-AAC CCT TGC CAA AAT GTC AG-3′ (1653)</td>
<td>XM194020</td>
<td>191</td>
</tr>
<tr>
<td>ALK7</td>
<td>5′-ATG ACT GGG CAG TCC ATT CT-3′ (1874)</td>
<td>NM011578</td>
<td>564</td>
</tr>
<tr>
<td>Betaglycan</td>
<td>5′-TGA A AA GAT GGT GGT AGC TGT AG-3′ (1727)</td>
<td>NM007561</td>
<td>199</td>
</tr>
<tr>
<td></td>
<td>5′-TTG GAG ATG TGA GAG GAT AAG CAG G-3′ (2290)</td>
<td>Z29532</td>
<td>286</td>
</tr>
<tr>
<td>Follistatin</td>
<td>5′-AAC GCC TAC TGT GTG ACC TGC G-3′ (556)</td>
<td>Z29532</td>
<td>199</td>
</tr>
<tr>
<td></td>
<td>5′-GGC GTC TCC TCC GAC TTA CTG T-3′ (842)</td>
<td>Z29532</td>
<td>286</td>
</tr>
</tbody>
</table>
ELISAs performed on medium collected from AC cell cultures showed that the cells secreted inhibin A, reaching a final concentration of 90 pg/ml in the culture medium, whereas inhibin B secretion was low but detectable (i.e. approximately 20 pg/ml). These data show that each inhibin subunit mRNA was translated into protein, albeit at low levels.

Inhibins are known to interact with the transmembrane proteoglycan, betaglycan, type II receptors for activin and BMP, and the secreted activin-binding protein, follistatin. AC cells expressed mRNA encoding betaglycan (Fig. 1b; 0.6 fg per µg total RNA), activin receptors type II and IIB (Fig. 1c; ActRII and ActRIIB expressed at 3 and 50 fg per µg total RNA, respectively), and the BMP type II receptor (Fig. 1c; BMPRII expressed at 8 fg per µg total RNA), as determined by quantitative real-time PCR analyses. Thus, the AC cells have the capacity to make the complement of binding proteins that subserve the anti-activin and anti-BMP actions of inhibin. The cells also expressed follistatin mRNA (Fig. 1d; 20 fg per µg total RNA).

**Figure 1** Expression of mRNA encoding (a) inhibin α, βA, and βB subunits, (b) betaglycan, (c) type II activin and BMP receptors, and (d) follistatin by mouse AC cells. In each case, RT-PCR was performed on total RNA extracted from AC cells cultured under serum-free conditions. Mouse ovarian cDNA was included as a positive control. Molecular weight markers were run in the first lane of each panel. +RT and -RT signify amplification yields after the inclusion and omission of reverse transcriptase, respectively.

*AC cell expression of activins, BMPs, and their signalling components*

cDNA membrane array analyses indicated that AC cells, in addition to expressing inhibin α and βA subunits (Fig. 2a:
7F and 7G, respectively), also expressed mRNA for the inhibin βE subunit (Fig. 2a: 8B), BMP-2, -3, -4, -6 and -8a (Fig. 2a: 2D, 2E, 2F, 2H and 3B, respectively), along with growth/differentiation factor (GDF)-1, -3, -5 and -9 (Fig. 2a: 5G, 6B, 6C and 6F, respectively), and Lefty A and B (Fig. 2a: 5A and 9A, respectively). In addition to betaglycan (Fig. 2a: 12E), expression of mRNA for activin receptor type I (ActRIB/ALK4) and the alternate activin B signalling receptor, ALK7, also was evident, as was the expression of some other signalling components of the activin/TGF-β and BMP pathways (Smads 2 and 6; Fig. 2a: 9C, 9E, 9F and 9H, respectively), TGF-β type II receptor (Fig. 2a: 12D), and other type I receptors for activin and BMP (ALK2, ALK4, ALK6) (Fig. 2a: 1A, 1B, and 3E, respectively) were below the threshold for detection in this assay.

RT-PCR analyses showed that AC cells expressed mRNA for the activin receptor type I (ActRIB/ALK4) and the alternate activin B signalling receptor, ALK7 and noggin (Fig. 2a: 4D, 10B and 10D, respectively), were also evident, as was the expression of some other signalling components of the activin/TGF-β and BMP pathways (Smads 2 and 6; Fig. 2a: 9D and 9G, respectively). Smads 1, 3, 5 and 7 (Fig. 2a: 9C, 9E, 9F and 9H, respectively), TGF-β type II receptor (Fig. 2a: 12D), and other type I receptors for activin and BMP (ALK2, ALK4, ALK6) (Fig. 2a: 1A, 1B, and 3E, respectively) were below the threshold for detection in this assay.

RT-PCR analyses showed that AC cells expressed mRNA for the activin receptor type I (ActRIB/ALK4) and the alternate activin B signalling receptor, ALK7.
(Fig. 2b; expressed at 0·5 and 0·03 fg per µg total RNA, respectively), along with BMP signalling receptors ActRI (ALK2) and BMPRIB (ALK6) (Fig. 2c; expressed at 20 and 1 fg per µg total RNA, respectively). RT-PCR analysis also confirmed the presence of mRNA for BMPRIA (Fig. 2c; expressed at 8 fg per µg total RNA).

**Binding of \(^{125}\)I-inhibin to the mouse AC cell line**

Binding of \(^{125}\)I-inhibin A to AC cells was routinely conducted at 25 °C for 4 h. Unlabelled inhibin A dose-dependently competed for a maximum of 80% of total \(^{125}\)I-inhibin A binding to AC cells (i.e. non-specific binding averaged 20% of total) with an IC\(_{50}\) of 0·13 nM (Fig. 3a; Table 2). Saturation binding studies (Fig. 3b) and Scatchard analyses (e.g. Fig. 3b inset) of inhibin A binding to AC cells revealed binding sites of high affinity (K\(_{d}(1)=0·15\) nM; 4300 sites/cell) and low affinity (K\(_{d}(2)=1·3\) nM; 17 000 sites/cell; also see Table 3). An additional large population of very low affinity sites (K\(_{d}(3)>5\) nM; more than 50 000 sites/cell) could also be discriminated (e.g. Fig. 3b inset).

Inhibin B competed over a wide concentration range (0·01–50 nM) for all of the specific \(^{125}\)I-inhibin A binding to AC cells with an estimated IC\(_{50}\) of 1·7 nM (Table 2; Farnworth et al. 2001). In contrast, BMP-2, -6 and -7 competed for 21–33% of specific inhibin A binding to AC cells, with similar potencies (IC\(_{50}\) values of 0·2–0·3 nM; Fig. 3c, Table 2).

Neither activin A nor activin B provided significant competition for \(^{125}\)I-inhibin A binding to AC cells (Table 2; Farnworth et al. 2001). In contrast, BMP-2, -6 and -7 competed for 21–33% of specific inhibin A binding to AC cells, with similar potencies (IC\(_{50}\) values of 0·2–0·3 nM; Fig. 3c, Table 2).

**Binding of \(^{125}\)I-inhibin to rat adrenal cells**

Binding of inhibin was examined in sections of rat adrenal tissue. \(^{125}\)I-inhibin A bound to cells of the adrenal cortex, but not the medulla, in adult male rat adrenal tissue (Fig. 4a), and this binding was competed by unlabelled inhibin A (20 nM)(Fig. 4b), consistent with the binding of \(^{125}\)I-inhibin A by the AC cell line. The most intense labelling occurred in the inner cortical zone, corresponding to the zona reticularis (Fig. 4a).

Binding of inhibin was then examined in primary cultures of adrenal cells. Monolayer cultures of cells prepared from whole adult rat adrenals bound substantial amounts of radiolabelled inhibin A, like the AC cell line, and unlabelled inhibin A dose-dependently blocked 61% of total binding (Fig. 5a) with an IC\(_{50}\) of 0·11 nM (Table 2), but inhibin A binding was insensitive to competition by activin A (Fig. 5a; Table 2). Similar results were obtained with adrenal cells obtained from adult female rats (data not shown).

Saturation binding studies (Fig. 5b) and Scatchard analyses (e.g. Fig. 5c) of inhibin A binding to primary adrenal cell cultures at 25 °C revealed sites of both high affinity (K\(_{d}(1)=0·18\) nM; 710 sites/cell) and low affinity (K\(_{d}(2)=2·6\) nM; 2500 sites/cell; also see Table 3). The pattern of high and low affinity sites was comparable to that seen in the mouse AC cells, but with fewer of each type of site per cell.

\[^{125}\]I-inhibin A affinity labelling of AC cell binding proteins, including betaglycan

\[^{125}\]I-inhibin A was crosslinked to cell surface proteins of AC cells using the bifunctional crosslinking agent, BS\(^3\). The affinity labelled protein complexes in whole cell lysate samples were separated by 7·5% non-reducing SDS–PAGE. At least nine affinity labelled complexes of 50, 62, 74–80, 95, 105, 118, 145–148 and >220 kDa, respectively, (and two additional, poorly resolved smaller species) were detected by autoradiography (Fig. 6a). Each complex is assumed to include a contribution of approximately 30 kDa from the iodinated inhibin. Complexes migrating at 50 and 90 kDa were observed in the tracer alone (e.g. Fig. 6b, left lane), and presumably represent covalently-linked aggregates of inhibin molecules. Thus, the 50 kDa complex extracted from affinity labelled AC cells may include, or consist entirely of, covalently-linked pairs of inhibin molecules. The 145–148 and >220 kDa complexes were the most intensely labelled, while the complex migrating at 118 kDa varied greatly in its labelling intensity between experiments. \[^{125}\]I-inhibin A affinity labelling of all nine protein species on AC cells was abolished by the addition of excess unlabelled inhibin A (20 nM), but not activin A (20 nM)(Fig. 6a). Exogenous follistatin-288 (20 nM) selectively intensified the band migrating at 62 kDa, with little change in the labelling intensity for other species (Fig. 6a).

Protein complexes extracted in whole cell lysates of AC cells after their affinity labelling with \[^{125}\]I-inhibin A were subjected to immunoprecipitation with antibodies directed against human betaglycan. Only the complexes of >220 kDa were identified by the antiserum (Fig. 6b, right lane). This species is consistent in size with glycosylated betaglycan (Lewis et al. 2000).

Detergent extracts prepared from AC cell membrane preparations after their affinity labelling with \[^{125}\]I-inhibin A displayed the same complement of complexes as were seen in whole cell lysates (Fig. 6c, left lane), confirming the association of all these binding proteins with the AC cell membrane. As with the whole cell lysates, only complexes of >220 kDa were immunoprecipitated from the membrane protein pool by anti-betaglycan serum (Fig. 6c, right lane).

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Separate monolayers of AC cells were incubated with \([^{125}\text{I}]\)inhibin A and progressively increasing concentrations of unlabelled inhibin A (0.08–5 nM), the affinity labelled protein complexes were separated by 7.5% non-reducing SDS–PAGE (Fig. 7a), then the labelling intensity for individual protein complexes was titrated using densitometric analysis of the resulting autoradiographs. Each complex displayed a sensitivity to competition from

Figure 3 Binding of \([^{125}\text{I}]\)inhibin A to mouse AC cells. In all cases, binding was conducted at 25 °C with 0.2 × 10⁶ cells/well in 0.125 ml assay buffer. (a) A comparison of the competition provided by increasing concentrations of unlabelled inhibin A or inhibin B (0.03–20 nM) for the binding of \([^{125}\text{I}]\)inhibin A. Specific binding represented 10.6%, and non-displaceable binding was 2.6%, of input radioactivity. (b) A saturation curve analysis for the high affinity binding of \([^{125}\text{I}]\)inhibin A to AC cell monolayers. AC cells were incubated with increasing concentrations of \([^{125}\text{I}]\)inhibin A in the absence (total binding; ) and presence (non-specific binding; △) of excess unlabelled inhibin A, from which the difference (specific binding; ○) was determined. In this experiment, non-linear regression analysis of the specific binding data identified sites of both high affinity \([K_d(\text{high})]=0.07 \text{nM}; 1600 \text{ sites/cell}] and low affinity \([K_d(\text{low})]=3 \text{nM}; 48 \text{ 000 sites/cell}\). The inset shows a Scatchard analysis of inhibin binding data, from which three sites were deduced, as follows: \([K_d(1)]=0.10 \text{nM}; \text{with 2000 sites/cell}; K_d(2)=0.70 \text{nM}; \text{with 13 000 sites/cell};\] \([K_d(3)=5.6 \text{nM}; \text{with 50 000 sites/cell}\]. (c) A comparison of the competition provided by increasing concentrations of unlabelled inhibin A, BMP-6 or BMP-7 for the binding of \([^{125}\text{I}]\)inhibin A to AC cells. The data presented in each panel are from single representative experiments, and aggregate data are summarised in Table 2 (a and c) and Table 3 (b).
unlabelled inhibin A that was similar to the sensitivity determined for total binding of $[^{125}I]$inhibin A to the AC cell monolayers (Fig. 7b).

$[^{125}I]$inhibin A affinity labelling of rat adrenal binding proteins

Primary cultures of cells from adult male and female rat adrenal glands displayed a common pattern of affinity labelling with $[^{125}I]$inhibin A (Fig. 8a), and this pattern qualitatively resembled that obtained in the mouse AC cells (Fig. 8b). However, compared with the levels of labelling in the cell line, the 95 kDa complex was barely evident in the primary cultures, and the band at 145–148 kDa was less prominent (Fig. 8, a & b). Unlabelled inhibin A prevented affinity labelling of rat adrenal cell proteins in a dose-dependent manner, unlike activin A (Fig. 8a). As with AC cells, affinity labelling of the 118 kDa complex was inconsistently observed in primary adrenal cell cultures but, when evident, was prevented by excess unlabelled inhibin A. When the binding of $[^{125}I]$inhibin A to male rat adrenal cell cultures was terminated at various times between 0·5 and 4 h after addition of the tracer at 25°C, and affinity labelled complexes were investigated by autoradiography, the labelling of the 35, 40, 50, 74–80, 105 and >220 kDa complexes was already evident at the earliest time-point, and intensified with time (Fig. 8b). In contrast, the 118 and 145–148 kDa complexes were barely evident at 0·5 h, but intensified from 1 h onward (Fig. 8b).

Table 2 Inhibition of $[^{125}I]$inhibin A binding to AC and male rat adrenal cells provided by TGF-$eta$ superfamily members through direct competition during 4 h at 25°C.

<table>
<thead>
<tr>
<th>Competitor</th>
<th>Proportion inhibited (%)a</th>
<th>IC$_{50}^b$ (nM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC cells</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inhibin A</td>
<td>100$^{cd}$</td>
<td>0·13 ± 0·01 [44]</td>
</tr>
<tr>
<td>Inhibin B</td>
<td>74 ± 6$^d$</td>
<td>1·7 ± 0·8 [3]</td>
</tr>
<tr>
<td>BMP-2</td>
<td>21 ± 2$^d$</td>
<td>0·23 ± 0·08 [8]</td>
</tr>
<tr>
<td>BMP-6</td>
<td>33 ± 2$^d$</td>
<td>0·28 ± 0·08 [7]</td>
</tr>
<tr>
<td>BMP-7</td>
<td>28 ± 3$^d$</td>
<td>0·28 ± 0·10 [5]</td>
</tr>
<tr>
<td>Primary adrenal cells</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inhibin A</td>
<td>100$^{df}$</td>
<td>0·11 ± 0·03 [8]</td>
</tr>
</tbody>
</table>

Results are mean ± S.E.M. of [n] replicate experiments.

*a: proportion of specific binding was determined after correction of data for non-specific inhibin binding; b: IC$_{50}$ = median inhibitory concentration; c: total binding ranged between 4 and 15% of total input counts, and non-specific binding ranged between 1 and 4%; d: P < 0·05; e: n.a., not assessable; f: total binding averaged 3·9% of total input counts, and non-specific binding averaged 1·4%.

Table 3 Dissociation constants (K$_d$) and binding site concentrations estimated by Scatchard analysis for the binding of $[^{125}I]$inhibin A to mouse AC cells and primary cultures of adult male rat adrenal cells during 4 h incubation at 25°C. Results are mean ± S.E.M. of data from n separate experiments.

<table>
<thead>
<tr>
<th>Inhibin A</th>
<th>binding site 1</th>
<th>binding site 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC cells</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K$_d$ (nM)</td>
<td>0·15 ± 0·01 [n=24]</td>
<td>1·3 ± 0·1</td>
</tr>
<tr>
<td>Binding site concentration (molecules/cell)</td>
<td>4 300 ± 200</td>
<td>17 000 ± 1 300</td>
</tr>
<tr>
<td>Primary adrenal cells (male)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K$_d$ (nM)</td>
<td>0·18 ± 0·03 [n=8]</td>
<td>2·6 ± 0·6</td>
</tr>
<tr>
<td>Binding site concentration (molecules/cell)</td>
<td>710 ± 150</td>
<td>2 500 ± 600</td>
</tr>
</tbody>
</table>

Figure 4 Specific binding of $[^{125}I]$inhibin A to frozen sections of male rat adrenal gland. Binding of $[^{125}I]$inhibin A to thawed sections was conducted at 37°C in the absence (a) and presence of an excess of unlabelled inhibin (final concentration 20 nM). m indicates medulla, zr represents zona reticularis. The experiment was replicated, with similar results.
Inhibin antagonism of activin A binding in AC cells

AC cell monolayers in crosslinking experiments bound low levels of [125I]activin A (1·7% of total counts added). Excess unlabelled activin A (20 nM) competed for an average 51±4% of total [125I]activin A binding (mean±S.E.M., n=5) (i.e. non-specific binding of [125I]activin A averaged 49%). Inhibin A (20 nM) competed for 38±6% (mean±S.E.M., n=5) of total activin A binding. Inhibition of activin A binding by both competitors was statistically significant (P<0·001).

Discussion

This study has established that mouse adrenocortical (AC) cells express inhibin subunits, secrete inhibins A and B, bind radiolabelled inhibin A via high and low affinity sites, and express mRNA encoding known inhibin binding proteins, including activin type II and IIB and BMP type II receptors, the inhibin/TGF-β co-receptor, betaglycan, and follistatin. Inhibins therefore fulfil some of the requirements to be classed as autocrine factors for this cell line, since these transmembrane proteins can mediate inhibitory actions of inhibin against activins (and BMPs) in accordance with the current model of inhibin action (Lewis et al. 2000, Wiater & Vale 2003).

By secreting inhibins, the AC cell line resembles the adrenal cortex and tumours arising from it, which strongly express the inhibin α-subunit and weakly express both β-subunits (Crawford et al. 1987, Meunier et al. 1988, Voutilainen et al. 1991, Munro et al. 1999, Arola et al. 2000), and the human AC H295R cell line, which also makes and secretes activin A and both inhibin A and inhibin B (Vanttinen et al. 2002). The present results also show that AC cells express mRNA encoding several BMP/GDF ligands (BMP-2, -3, -4, -6 and -8a; GDF-1, -3, -5 and -9) and Lefty A and B, for which autocrine roles in the adrenal cortex are yet to be identified. Nevertheless, such roles seem likely, because AC cells express mRNA encoding multiple activin and BMP receptors and their respective downstream signalling components, and respond to exogenous activin and BMP (Ooi et al. 2002).

Binding of radiolabelled inhibin A to mouse AC and rat primary adrenal cells shows common characteristics. Scatchard analyses reveal two classes of binding sites, K_d(1) of 0·15–0·18 nM and K_d(2) of 1·3–2·6 nM, with 710–4300 high affinity, and 2500–17 000 low affinity binding sites/cell. The concentrations and affinities estimated for these binding sites resemble those determined for the binding of inhibin A to Leydig (TM3) and Sertoli (TM4) cell lines (Harrison et al. 2001). An additional very low affinity (K_d(3)>5 nM) inhibin A binding site was
also observed. The rat adrenal and AC cell binding sites show high specificity for inhibin A over activin A, and little crossreaction with activin B. They also crossreact only weakly with inhibin B, as previously seen with TM3 and TM4 cells (Harrison et al. 2001). Nevertheless, sufficient inhibin B blocks all of the specific binding of inhibin A to AC cells, with most of the competition occurring in two phases (apparent IC50 values of approximately 3 and 30 nM, respectively). The high affinity, capacity and specificity of the identified inhibin A binding sites suggest the AC cells may be targets for inhibin A from both adrenal (i.e. local) and endocrine sources.

Several lines of evidence suggest that inhibins and activins play significant roles in the adrenal gland. First, activin A inhibits mitogenesis while enhancing ACTH-stimulated cortisol secretion in human adrenal fetal zone cells (Spencer et al. 1990, 1992). Secondly, both inhibin A and activin A increase the level of P450c17 protein in H295R cells, although the mechanism by which inhibin mimics this activin action is not known (Wang et al. 2003). Thirdly, mice that cannot make inhibin α-subunit, and hence are inhibin-deficient, rapidly develop gonadal tumours from which they die, whereas early removal of the gonads results in subsequent development of adrenal tumours, qualifying inhibin as an adrenal tumour suppressor (Matzuk et al. 1992, 1994), again by an unknown mechanism. A similar pattern of events occurs in transgenic mice that express SV-40 T-antigen under the control of a 6 kb portion of the inhibin α-subunit promoter (Kananen et al. 1996). In the latter scenario, adrenal cell lines have been established from tumours that arose in the adrenal glands of gonadectomised mice (Kananen et al. 1996, Rahman et al. 2001), and the AC cell line is derived from one of these. While the AC cell line is believed to have arisen from the fetal X zone of the adrenal cortex (Kananen et al. 1996), the binding of inhibin A to adult rat adrenal cells suggests that inhibins have ongoing physiological roles in the adrenal cortex throughout development.

The substantial inhibin binding capacity of AC cells found here is consistent, in part, with an earlier study, in which mice that had been injected with [125]inhibin A concentrated radiolabel in the adrenal glands. The tissue: blood ratio reached a peak of 3 one hour after tracer injection, and binding/accumulation of [125]inhibin A was blocked by co-administration of excess unlabelled inhibin A (Woodruff et al. 1993). Although that study reported binding of [125]inhibin A in both the adrenal medulla and

![Image](https://example.com/figure6.png)

**Figure 6** Affinity labelling of AC cell inhibin binding proteins. In each case, binding was conducted for 4 h at 23 °C, [125]inhibin A was crosslinked to its binding proteins using BS3, and extracted protein complexes were separated by 7.5% non-reducing SDS–PAGE. (a) and (b) show labelled species in lysates of whole AC cells, and (c) shows labelled species in the lysate of an AC cell membrane preparation obtained by differential centrifugation of homogenised AC cells. The representative autoradiograph in panel a compares the [125]inhibin A affinity labelled protein complexes obtained from AC cells that had been incubated in the absence of competitor (control), or presence of excess unlabelled inhibin A, activin A or follistatin-288 (each 20 nM). (b) and (c) provide comparisons of the distribution of [125]inhibin in the tracer alone (Tc), and in affinity labelled protein complexes before (total) and after immunoprecipitation (anti-BG) using antiserum directed against betaglycan. The sizes of each labelled complex indicated by arrows in (a)–(c) were deduced by comparison with marker proteins run in parallel.
cortex, we find that $^{[125]I}$inhibin A binds specifically 
and almost exclusively to cells of the adrenal cortex, 
principally to those of the inner cortical zone.

Protein complexes of 35, 40, 50, 62, 74–80, 105, 118, 
145–148 and >220 kDa are obtained from mouse AC and 
rat primary adrenal cells following their affinity 
labelling with $^{[125]I}$inhibin A, which suggests that the AC cells 
provide a suitable model for inhibin A interactions with 
normal AC cells. A significant anomaly is the appearance 
of an additional 95 kDa complex in AC cells. The affinity 
labelling of multiple membrane proteins with $^{[125]I}$inhibin 
A in AC cells provides a more complex pattern than 
that obtained from cells which overexpress betaglycan 
alongside type II receptors for activin or BMP. In those 
cases, only three complexes [175–250 kDa (glycosylated 
betaglycan), 110 kDa (betaglycan core protein) and 
75–85 kDa (type II receptor)] have been reported.

Figure 7 Comparison of competition from unlabelled inhibin A for 
$^{[125]I}$inhibin A binding to whole AC cells in monolayer (total) and 
to individual affinity labelled protein complexes. (a) The distribution 
of radioactivity in complexes separated by 7.5% non-reducing 
SDS–PAGE. For (b), the level of labelling of each complex (>220, 
145–148, 105, 74–80 and 50 kDa) was determined by 
densitometry from the autoradiograph shown in (a), and in each 
case was normalised against the labelling intensity in the control 
sample. The experiment was repeated once, with similar results.

Figure 8 Affinity labelling of primary rat adrenal cell inhibin 
binding proteins with $^{[125]I}$inhibin A. Each panel shows labelled 
species in cell lysates after their separation by 7.5% non-reducing 
SDS–PAGE. Other details are as described in the legend to Fig. 6. 
The representative autoradiograph in panel a compares the 
$^{[125]I}$inhibin affinity labelled protein complexes obtained from adult 
female and male rat adrenal cell monolayers that had been 
incubated in the absence of competitor (control), or presence of 
unlabelled inhibin A or activin A (each at 0.1 and 20 nM). 
(b) shows the time-course for the $^{[125]I}$inhibin affinity labelling of 
proteins from adult male rat primary adrenal cell cultures for 
periods between 0.5 and 4 h. The sizes of each labelled complex 
indicated by arrows in each panel were deduced by comparison 
with marker proteins run in parallel.

Lewis et al. 2000, Wiater & Vale 2003). The AC cells 
express betaglycan mRNA, and $^{[125]I}$inhibin A affinity 
labelled protein complexes of >220 kDa are immuno-
precipitated with antibodies against betaglycan, in partial 
agreement with the earlier studies. However, the beta-
glycan antiserum does not recognise the 145–148 kDa 
complex in AC cells, but recognises slightly smaller 
species, consistent in size with betaglycan core protein, in
Inhibin binding to adrenal cells

P G Farnworth and others

the TM3 and TM4 cell lines (P G Farnworth and Y Wang, unpublished observations). The 145–148 kDa complex in AC cells is therefore unlikely to be betaglycan core protein, and its identity is yet to be determined.

Inhibin A interacts with type II receptors for activin and BMP (Martens et al. 1997, Gray et al. 2000, Lewis et al. 2000, Chapman et al. 2002, Wiater & Vale 2003), AC cells express mRNA for all three receptors, and appropriately sized protein complexes are affinity labelled with 

\[ ^{[125]}I \text{Inhibin A} \]

on primary adrenal and AC cells. However, attempts to identify these complexes as native receptors for activin and/or BMP by immunoprecipitation were unsuccessful (P G Farnworth and Y Wang, unpublished observations), perhaps reflecting low levels of receptor expression under physiological conditions. Although the binding of \( ^{[125]}I \text{Inhibin A} \) to rat adrenal and AC cells is unresponsive to competition from activin A (up to 50 nM), this finding agrees with results in other cell types, and probably reflects the increase in inhibin A affinity for activin type II receptors conferred by betaglycan (Lewis et al. 2000, Chapman et al. 2002) rather than a lack of involvement of such receptors in adrenal inhibin A binding. In contrast to the lack of competition provided by activins, picomolar concentrations of BMP-2, -6 and -7 compete for up to a third of specific inhibin A binding to AC cells, consistent with a role for BMP binding proteins in inhibin binding to AC cells.

A 62 kDa protein complex that is faintly labelled with 

\[ ^{[125]}I \text{Inhibin A} \]

in AC cells from both sources is greatly intensified in AC cells after exposure to follistatin-288, suggesting that inhibin interacts with endogenous follistatin to some extent under physiological circumstances. The intensity of affinity labelling of other inhibin binding species is little changed by exogenous follistatin-288. Thus, follistatin does not seem to promote inhibin binding, or to ‘present’ inhibin, to other proteins on the cell surface. On the other hand, inhibin A competes almost as effectively as activin A for 

\[ ^{[125]}I \text{Activin A} \]

binding to AC cells, and affinity labelling studies provided evidence that inhibin A mainly displaces 

\[ ^{[125]}I \text{Activin A} \]

from species consistent in size with follistatin, rather than activin receptors (P G Farnworth and Y Wang, unpublished observations).

In conclusion, the identification of inhibin A binding sites of high affinity and specificity, and characterization of multiple binding proteins on cells of the adrenal cortex raise questions about what physiological roles inhibins, locally produced and endocrine, might play in regulating adrenal functions. AC cell systems express betaglycan, and the type II receptors for activins and BMPs, which should provide for betaglycan-mediated blockade of activin/BMP action by inhibin. Moreover, AC cells express multiple TGF-β superfamily members, and requisite components of their signalling pathways, suggesting potential roles of activins and BMPs as autocrine factors. However, AC cells bind inhibin A via a number of proteins additional to those that mediate inhibin antagonism of activin and BMP action. As an extension of these studies, we are currently investigating whether inhibins affect adrenal cell functions, including steroidogenesis, either through antagonism of activin/BMP actions or by independent means.

Acknowledgements

The authors acknowledge the gifts of follistatin-288 provided by the NIDDK (NIHDDK, NICHDH, USDA), and inhibin A, activin A and follistatin-288 provided by Biotech Australia (Sydney, Australia). We thank Peter Stanton for purifying activin A, Nafis Rahman and Ilpo Huhtaniemi for providing Cat-1 cells, and Ann Drummond for establishing conditions for the inhibin subunit and activin receptor RT-PCR assays.

Funding

This study was funded by Program Grants (Reg Key Nos. 983212 & 241000) and Fellowships for J K F (Reg Key No. 198705) and D M R (Reg Key No. 198708) from the National Health and Medical Research Council of Australia. The authors declare that there is no conflict of interest that would prejudice the impartiality of this scientific work.

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Received 16 November 2005
Accepted 28 November 2005