Expression of guanylyl cyclase-B (GC-B/NPR2) receptors in normal human fetal pituitaries and human pituitary adenomas implicates a role for C-type natriuretic peptide

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Abstract

C-type natriuretic peptide (CNP/Nppc) is expressed at high levels in the anterior pituitary of rats and mice and activates guanylyl cyclase B receptors (GC-B/Npr2) to regulate hormone secretion. Mutations in NPR2/Npr2 can cause achondroplasia, GH deficiency, and female infertility, yet the normal expression profile within the anterior pituitary remains to be established in humans. The current study examined the expression profile and transcriptional regulation of NPR2 in normal human fetal pituitaries, normal adult pituitaries, and human pituitary adenomas using RT-PCR and immunohistochemistry. Transcriptional regulation of human NPR2 promoter constructs was characterized in anterior pituitary cell lines of gonadotroph, somatolactotroph, and corticotroph origin. NPR2 was detected in all human fetal and adult pituitary samples regardless of age or sex, as well as in all adenoma samples examined regardless of tumor origin. GC-B immunoreactivity was variable in normal pituitary, gonadotrophinomas, and somatotrophinomas. Maximal transcriptional regulation of the NPR2 promoter mapped to a region within −214 bp upstream of the start site in all anterior pituitary cell lines examined. Electrophoretic mobility shift assays revealed that this region contains Sp1/Sp3 response elements. These data are the first to show NPR2 expression in normal human fetal and adult pituitaries and adenomatous pituitary tissue and suggest a role for these receptors in both pituitary development and oncogenesis, introducing a new target to manipulate these processes in pituitary adenomas.

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Introduction

The particulate guanylyl cyclase (GC) receptors mediate the effects of natriuretic peptides, heat-stable enterotoxins, odor, and peptidase activity in a broad range of tissues by increasing the levels of cyclic guanosine 3’,5’-monophosphate (cGMP). GC-A and GC-B are probably the best characterized receptors in this family and act as specific receptors for atrial natriuretic peptide (ANP) and C-type natriuretic peptide (CNP) respectively. GC-B is expressed throughout the body but is present in many endocrine tissues and is widely expressed throughout the CNS (for review see Fowkes & McArdle (2000) and Potter et al. (2006)). Mice lacking the Npr2 gene, which encodes GC-B, are dwarf due to severe deficiency in the process of endochondral ossification and exhibit early lethality (Tamura et al. 2004). Intriguingly, these mice are also GH deficient, implicating a potential pituitary phenotype. Mutations in the gene (natriuretic peptide precursor C (Nppc)) encoding CNP essentially phenocopy those in Npr2 (Chusho et al. 2001), but to date, no mutations have been reported in the human NPPC gene. Instead, translocations have been shown to cause overexpression of NPPC, resulting in skeletal overgrowth and deformities (Bocciardi et al. 2007, Moncla et al. 2007). However, the role of GC-B receptors, or of CNP, in the anterior pituitary remains poorly understood.

Our previous molecular and pharmacological studies performed on well-established rodent anterior pituitary cell lines (Fowkes et al. 1999, 2000, Thompson et al. 2009) have shown that GC-B signaling is the major pathway used by CNP in most anterior pituitary cell types. Despite this, there is a paucity of data describing the expression of GC-B in human pituitaries and pituitary adenomas. In the current study, we have examined the mRNA expression of GC-B in a range of human pituitary adenomas and normal human fetal pituitaries. Human pituitary adenomas were obtained from the Thomas Willis Brain Bank (project ethics reference 07/H0606/85), Department of Neuropathology, John Radcliffe Hospital, Oxford, UK. Normal human fetal pituitary RNA samples were obtained from fetuses collected following medical termination of pregnancy (between 14 and 18 weeks of gestation), subject to local ethical approval (by the Lothian Paediatrics/Reproductive Medicine Research Ethics Subcommittee) as described previously (Pope et al. 2006). Normal pituitary samples from patients were obtained by autopsy within 6 h of death (University Clinical Centre, Belgrade, Serbia), as described previously (Butz et al. 2010). These individuals had no evidence of any endocrine disease. All biometric data relating to human samples are summarized in Tables 1, 2 and 3.

Materials and methods

Cell culture

αT3-1, LβT2, GH3, and AtT-20 cells were cultured as described previously (Fowkes et al. 2000, Thompson et al. 2009) using DMEM (Sigma–Aldrich) containing 10% FCS, penicillin, and streptomycin.

Mouse primary pituitary cell culture

Pituitaries were removed from 8-week-old random cycling female C57/BL6 mice (20 per experiment) and subjected to enzymatic dispersion as described previously (McArdle & Poch 1992, Thompson et al. 2009). Dispersed cells were then cultured overnight in 24-well plates before transfection with the indicated NPr2 reporter gene constructs.

RNA extraction from human pituitary tumors and fetal pituitaries

Human pituitary adenomas were obtained from the Thomas Willis Brain Bank (project ethics reference 07/H0606/85), Department of Neuropathology, John Radcliffe Hospital, Oxford, UK. Tissue was collected immediately at the postoperative stage, snap frozen, and stored at −80 °C before extracting total RNA using the Trizol method followed by RNA cleanup and DNase treatment, as described previously (Thompson et al. 2009). Normal human fetal pituitary RNA samples were obtained from fetuses collected following medical termination of pregnancy (between 14 and 18 weeks of gestation), subject to local ethical approval (by the Lothian Paediatrics/Reproductive Medicine Research Ethics Subcommittee) as described previously (Pope et al. 2006). Normal pituitary samples from patients were obtained by autopsy within 6 h of death (University Clinical Centre, Belgrade, Serbia), as described previously (Butz et al. 2010). These individuals had no evidence of any endocrine disease. All biometric data relating to human samples are summarized in Tables 1, 2 and 3.

RT-PCR analyses of NPR2 and NPPC expression in human pituitary tissue

Following generation of the first-strand cDNA (Applied Biosystems, Paisley, UK), PCR was performed using components from the Qiagen Taq Core kit and Thermos-Start DNA polymerase and buffer kit. The following primer sets were used: NPR2: F, AACGGGCAGCAT-TTGTGATATCTGCGGC and R, TTATCACAGGATGGGTGTCGTCAAGTCA; NPPC: F, GCCAGGAGTTCTGTCTCTTC and R, TCAATGAGAA-GTTGT TGCG; POUIF1: F, TGGAGTGTAGGGCAGCAGTTAA and R, TTTCAACGGTTTTCTCTCGCT; and NPPC: F, CTGCTCACGCCGTGCTC and R, CCTTCTTGGTGCCCTTGTG. All PCR was performed between 30 and 35 cycles before analysis of products using 1.6% (w/v) agarose gel electrophoresis.
Immunohistochemistry for GC-B

Human gonadotroph and somatotroph adenoma paraffin-fixed samples were sectioned to 4 μm for analysis. Paraffin embedding was removed with Histoclear before subjecting the sections to antigen retrieval and immunohistochemistry for GC-B using a rabbit polyclonal antibody (Abcam, Cambridge, UK) according to the standard protocols described previously (Suliman et al. 2007). All slides were immersed in hematoxylin counterstain, washed, dehydrated, and then mounted on distrene-plasticizer-xylene before examination using a Leica microscope.

Bioinformatic analyses of transcription factor response elements in the human NPR2 promoter

The human NPR2 promoter sequence (accession number AY528561) was analyzed using two online databases, PATCH (http://www.gene-regulation.com/cgi-bin/pub/programs/patch/bin/patch.cgi) and WWW Promoter Scan (http://www-bimas.cit.nih.gov/molbio/proscan/index.html).

Plasmids and transient transfection studies

The reporter constructs encoding the human NPR2 promoter have been described previously (Rahmutula et al. 2004). All constructs were verified for orientation and correct sequence by restriction endonuclease digests. Large-scale preparation and purification of plasmids was performed by alkaline lysis and resin purification (Qiagen Ltd). For transfections, 3 × 10⁵ cells/well were plated in 24-well plates and transfected using Lipofectin (Invitrogen) with 1.25 μg/well of each reporter construct along with 0.5 μg/well BosGal, and protein extracts were assayed for reporter gene activity as described previously (Thompson et al. 2009). The data shown were normalized for protein content using a Nanodrop (ND1000, Thermo Scientific, Loughborough, UK).

Nuclear protein extraction and electrophoretic mobility shift assay

Nuclear protein extracts were prepared from 1 × 10⁶ GH3 or LβT2 cells using a modification of a method described previously (Schreiber et al. 1989, Thompson et al. 2009). Probes were created by filling in the 5’-AGCT overhangs of the annealed NPR2 oligonucleotides with Klenow polymerase, and EMSAs were performed as described previously (Thompson et al. 2009). The following primer sets were used: NPR2-PROX: F, AGCTCAGGGGGAGGGGCGG-GGCGGGCGGGCCT and R, AGCTAAGGGCGCCCCGC-CCCGCCCCCTCCCGGCTG; NPR2-MID: F, AGCTCAGGGGGAGGGGCGG-GGCGGGCGGGCCT and R, AGCTAAGGGCGCCCCCTCCCGGCTG; NPR2-DIST: F, AGCTGAGGCCCCGTGGGTTGGG and R, AGCTAAGGGCGCCCCCTCCCGGCTG.

For gel shifts, 2 μl Spt1 or Spt3 antibodies (Santa Cruz Biotechnology, Santa Cruz, CA, USA) were added to the reaction to identify the components of the specific protein complexes, and these samples were incubated on ice for 60 min. The reactions were then incubated for 15 min at 30 °C in the presence of 1 ng probe. Complexes were electrophoresed on a 5% native acrylamide gel, dried, and visualized by autoradiography.

Statistical analysis and data presentation

For reporter gene activities in pituitary cell lines, the data shown were normalized and pooled to represent the mean ± S.E.M. of at least four independent

<table>
<thead>
<tr>
<th>Sample</th>
<th>Age at termination</th>
<th>Sex</th>
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<tbody>
<tr>
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<td>M</td>
</tr>
<tr>
<td>2</td>
<td>14w/4d</td>
<td>F</td>
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<td>3</td>
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Table 2 Biometric data of human fetal pituitary samples
experiments, each performed in triplicate. The reporter gene assays in primary mouse pituitary cells represent the mean ± s.e.m. of four individual transfections. Numerical data were subjected to ANOVA and were followed, where appropriate, by Bonferonni’s multiple comparisons test, accepting \( P < 0.05 \) as significant, using inbuilt equations in GraphPad Prism 5.0 (GraphPad, San Diego, CA, USA).

Results

Expression of NPR2 and NPPC in normal human fetal and adult pituitaries

Having recently established that mouse pituitaries and gonadotroph cell lines of different developmental origin expressed most components of an intact natriuretic peptide system (Thompson et al. 2009), we initially examined a series of normal human fetal pituitary samples for the expression of NPR2 and NPPC transcripts. RNA was extracted from eight normal human fetal pituitaries and four normal adult pituitaries. As shown in Fig. 1A, NPR2 and NPPC transcripts were detected in all fetal pituitary samples, regardless of age or sex. Expression of POU1F1 (encoding Pit-1) and NR5A1 (encoding SF-1) was also detected in all fetal samples. Similarly, NPR2 and POU1F1 transcripts were also detected in all the normal adult pituitary samples (Fig. 1B). Interestingly, NPPC transcripts were detected in 3/4 normal pituitary samples, and NR5A1 being detected in 2/4 normal pituitary samples. Collectively, these data suggest that NPR2 and NPPC are expressed in both developing and adult human anterior pituitary tissues.

Expression of NPR2 in human pituitary adenomas

We broadened our investigations to determine the expression of NPPC and NPR2 in human pituitary adenomas. RT-PCR was performed on RNA samples extracted from a range of tumors. As shown in Fig. 2A, all pituitary tumors of gonadotroph origin expressed NPR2, and for those in which sufficient cDNA remained, NPPC transcripts were also detected (tumors 3–8). As expected, all these tumors expressed the gonadotroph-specific marker, NR5A1. Interestingly, POU1F1 transcripts were detected in the majority of these gonadotroph origin tumors, albeit at variable intensity. Identical RT-PCR screens were performed on RNA extracted from somatotrophinomas (Fig. 2B) as well as null cell adenomas, silent ACTH tumors, and a normal pituitary sample (Fig. 2C). Again, all samples examined expressed NPR2 transcripts, and where sufficient cDNA remained, NPPC transcripts were also detected (tumors 12–15). Expression of NR5A1 and POU1F1 was absent in the two corticotroph tumors, whereas both null cell adenomas expressed POU1F1, but only one expressed NR5A1. In keeping with previous studies, some somatotrophinomas expressed NR5A1 transcripts (Aylwin et al. 2001). These studies represent the first description of NPR2 and NPPC transcripts in a range of human pituitary adenomas.

Detection of GC-B immunoreactivity in human pituitary adenomas

Having established that NPR2 is expressed in all pituitary adenoma samples examined and in human fetal pituitaries, we next examined whether GC-B protein could be detected in tissue from some of the adenoma samples analyzed previously.

Table 3 Biometric data of normal adult pituitary samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Age</th>
<th>Sex</th>
<th>Cause of death</th>
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<td>1</td>
<td>37</td>
<td>M</td>
<td>Road traffic accident</td>
</tr>
<tr>
<td>2</td>
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<td>Road traffic accident</td>
</tr>
<tr>
<td>3</td>
<td>72</td>
<td>M</td>
<td>Myocardial infarction</td>
</tr>
<tr>
<td>4</td>
<td>68</td>
<td>M</td>
<td>Cerebral hemorrhage</td>
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Immunohistochemistry was performed for GC-B immunoreactivity (GC-B-ir) in a range of sections taken from some of the gonadotrophinoma and somatotrophinoma samples characterized for the molecular expression analyses. Initial optimization studies were performed on tissues known to express GC-B protein, and specific GC-B-ir was detected in mouse Purkinje cells of the cerebellum and posterior pituitary tissue (Fig. 3A), as described previously (Herman et al. 1996, Müller et al. 2009). Normal adult human pituitary tissue also revealed specific GC-B-ir (Fig. 3B). These optimized conditions were used on the human pituitary adenoma samples, and, GC-B-ir was detected in the gonadotrophinomas (Fig. 3C) and somatotrophinomas (Fig. 3D) examined, although the intensity of the apparent GC-B expression was variable. These data suggest that GC-B protein is also expressed in human pituitary adenomas and normal human pituitary tissue.

**Transcriptional regulation of the human NPR2 promoter in anterior pituitary cell lines**

The expression profile of NPR2 in both normal and adenomatous human pituitary tissue, regardless of cellular origin, suggested that the control of NPR2 expression in all anterior pituitary cell types might share a common mechanism. To examine whether cell-type-specific regulation of the NPR2 promoter could occur, we transiently transfected well-established pituitary tumor cell lines representative of gonadotrophs (αT3-1 and LßT2), somatolactotrophs (GH3), and corticotrophs (AtT-20) with a series of human NPR2 promoter deletion constructs, as described previously (Rahmutula et al. 2004). Promoter activity was determined after 24 h by reporter gene assays.

**Gonadotroph cell lines**

The promoter was active in both early- (αT3-1, Cga expressing) and later-stage (LßT2, Cga, Lhb, and Fshb expressing) gonadotrophs (see Fig. 4), and in both cell lines, the most proximal −214 bp of the human NPR2 promoter was sufficient to drive maximal reporter gene activity (to $7.9 \pm 1.8$-fold ($P < 0.001$) and $3.2 \pm 0.2$-fold ($P < 0.05$) in αT3-1 and LßT2 cells respectively). Furthermore, in LßT2 cells, but not in αT3-1 cells, the $K_{214}$ construct also showed maximal activity (3.6$\pm$0.8-fold, $P < 0.01$), suggesting that additional transcriptional activity is switched on during the process of gonadotroph development.

**Somatolactotroph and corticotroph cell lines**

As shown in Fig. 4, the NPR2 reporter gene constructs were active in both GH3 (Gh and Prl expressing) and AtT-20 (Pomc expressing) cells, with the −214 construct driving maximal transcriptional activity (to $7.8 \pm 1.3$-fold ($P < 0.001$) and $2.9 \pm 0.5$-fold ($P < 0.01$), in GH3 and AtT-20 cells respectively). Finally, to determine whether the most active NPR2 promoter constructs could also function in non-immortalized cells, similar transfections were performed in cultures of mouse pituitary cells. As shown in Fig. 4E, the −214 and −441 constructs showed significant transcriptional activity compared with pGL3LUC (to $13.5 \pm 3.1$-fold ($^{*}P < 0.05$) and $15.3 \pm 2.8$-fold ($^{**}P < 0.01$) respectively). Collectively, these data suggest that sequences residing within this region regulate basal expression of NPR2 and that this is common to all anterior pituitary cell types.

**Molecular characterization of the proximal human NPR2 promoter**

The reporter gene assay data suggested that −214 bp of the proximal human NPR2 promoter was sufficient for maximal basal promoter activity (see Fig. 4A, B, C, D and E). We further characterized the region between −135 and −214, initially through a bioinformatic screen to establish the presence of relevant
transcription factor binding sites. As no cell-type-specific promoter activity had been detected (Fig. 4), we were particularly interested in ubiquitously expressed transcription factors that have previously been implicated in the transcriptional control of the NPR2 promoter, namely members of the specificity protein family (Rahmutula et al. 2004). As shown in Fig. 5A, numerous consensus Sp1/Sp3 binding sites were found in this proximal promoter region. We subdivided these GC-rich ‘hotspots’ into proximal (prox), middle (mid), and distal (dist) regions and generated 32P-labeled probes to perform EMSA analyses. As shown in Fig. 5B, all the three NPR2 probes (prox, mid, and dist) formed complexes with nuclear extracts from GH3 and LβT2 cells. Each of these regions was capable of competing for protein complexes, as excess unlabeled prox, mid, and dist annealed oligonucleotides successfully competed for 32P-labeled prox probe (Fig. 5C). However, it was clear from these initial EMSAs that the prox and mid regions of the NPR2 promoter yielded the more intense complex formation. Therefore, subsequent supershift experiments were performed using these two probes only. As shown in Fig. 5D and E, the presence of Sp1

Figure 3 (A, B, C and D) Detection of GC-B immunoreactivity (GC-B-ir) in human pituitary gonadotrophinomas and somatotrophinomas. (A) Optimization images of GC-B-ir in mouse primary Purkinje cells (left) and posterior pituitary cells (right). (B) GC-B-ir in two independent normal human pituitary samples. The negative control slide was generated without incubation with primary antibody. (C and D) GC-B-ir in sections of gonadotrophinomas (tumors 1, 9) and somatotrophinomas (tumors 12, 16). The brown staining indicates GC-B-ir, and the blue/purple is hematoxylin counterstain. All images were taken at either 20× or 40× magnification.
and Sp3 antibodies in the incubation reaction resulted in either a reduction and/or supershift of complexes formed by the interaction of nuclear extracts with prox and mid probes. Collectively, these data reveal that Sp1 and Sp3 proteins, acting either as homo- or heterodimers, form complexes with the human NPR2 promoter that may regulate basal gene transcription in pituitary cells.

**Discussion**

Many previous studies have established the presence of the CNP and its receptor, GC-B, in rat, mouse, and sheep pituitaries (Komatsu et al. 1991, Konrad et al. 1992, Minamino et al. 1993, Yandle et al. 1993, McArdle et al. 1994, Herman et al. 1996, Thompson et al. 2009), yet the expression of GC-B in human pituitary tissue has not been reported. We show for the first time that NPR2 expression is found in normal human fetal pituitary samples, ranging from 12 to 20 weeks of gestation, suggesting that natriuretic peptide signaling is required during pituitary development in humans. In addition, the presence of NPR2 transcripts in normal adult pituitary tissue would support a role for GC-B signaling in later life as well. Furthermore, using a selection of human pituitary adenomas, NPR2 expression was detected at both the mRNA and protein level, regardless of the cellular origin of the tumor.

Our present studies, combining RT-PCR, reporter gene assays, and immunohistochemistry, convincingly show that NPR2 is expressed in a broad range of both normal, developing fetal and adult pituitaries and human pituitary adenomas of different cellular origin. The presence of NPR2 transcripts in tumors of multiple anterior pituitary cell lineages again supports our previous studies that showed potent CNP-stimulated cGMP accumulation occurs in immortalized anterior pituitary cell lines of all origins (Fowkes et al. 2000, Thompson et al. 2009). It is clear that natriuretic peptide signaling is likely to be responsible for significant production of cGMP in the human anterior pituitary. Whether gonadotroph cells are the major source of CNP-stimulated cGMP in the pituitary, as we have shown in rat and mouse pituitaries and cell lines (Fowkes et al. 2000, Thompson et al. 2009), remains to be established.

The detection of NPPC transcripts are the first to document the developmental expression in human pituitaries and suggest that, along with NPR2, CNP is involved in the local regulation of the developing anterior pituitary gland. Furthermore, we were also able to detect NPPC transcripts in gonadotrophinoma and somatotrophinoma samples and in three of the four normal human pituitary samples (Figs 1 and 2A, B). The relatively variable expression of the NPPC transcripts might indicate an mRNA stability issue of the NPRC gene in archival tissue, and in this regard, highly conserved 3'-untranslated regions have been identified in the nppc gene of several elasmobranch species that are associated with mRNA stability and translational efficiency (Hyodo et al. 2006). However, it is also possible that NPPC is expressed in a cell-type-specific manner in the pituitary as we, and others, have reported previously in rodents (McArdle et al. 1993, Thompson et al. 2009), and the variable expression in the current study is merely a reflection of the relative contribution of those cell types in each of the tumors or normal pituitary samples examined.
The factors regulating the expression of NPR2 are still not fully defined. Initial cloning and molecular characterization studies on the human NPR2 promoter in rat aortic smooth muscle cells uncovered a requirement of Sp1 factors in controlling NPR2 transcription (Rahmutula et al. 2004). Our current studies reveal that an NPR2 promoter construct containing only 214 bp of the proximal promoter is sufficient to drive maximal promoter activity, in keeping with the previous pattern of promoter activity reported in rat aortic smooth muscle cells (Rahmutula et al. 2004). There are numerous Sp1/Sp3 response elements within this region of the human promoter (see Fig. 5A), so it is likely that Sp1 family proteins are

Figure 5 (A, B, C, D and E) Molecular characterization of the proximal human NPR2 promoter. (A) Bioinformatic screening of the human NPR2 promoter revealed the presence of numerous, consensus Sp1 and Sp3 binding throughout the proximal 214 bp of the promoter. Three areas of this region were identified for further characterization by EMSA analysis (prox, mid, and dist). (B) EMSA analyses using nuclear extracts from GH3 and LβT2 cells, and three probes encoding the prox, mid, and dist regions of the NPR2 promoter. (C) Competitor assay using excess unlabeled prox, mid, and dist oligonucleotides to compete specific binding to the prox probe, in the presence of GH3 nuclear extracts. (D and E) Supershift assays, using Sp1 and Sp3 antibodies to identify the putative specific protein complexes detected by EMSA in the presence of either the prox (D) or mid (E) probes. The data shown are representative of at least two such experiments.
also major regulators of NPR2 expression in pituitary tissue. Sp1 is ubiquitously expressed and has been implicated in the regulation of gonadotroph-specific genes (Kaiser et al. 2000, Weck et al. 2000, Bachir et al. 2003, Thompson et al. 2009). As the profile of NPR2 transcriptional activity remained comparable in all cell lines investigated in our study, this suggests that any potential role of Sp1 in the control of NPR2 expression is common to all pituitary cell lineages and is unlikely to contribute to any cell-type-specific expression of NPR2. Our detailed EMSA analyses, using nuclear protein extracts from GH3 and LBT2 cells, revealed complexes indicative of Sp1/Sp3 homo- and heterodimers, strongly implicating these transcription factors in the basal regulation of NPR2 transcription. However, while the use of pituitary tumor-derived cell lines is informative in demonstrating that endogenous Sp1/Sp3 proteins can bind to the proximal NPR2 promoter, further investigations are required to establish whether these GC-rich elements of the NPR2 promoter are important in vivo. Nevertheless, previous transcriptional studies on the NPR2 promoter in rat aortic smooth muscle cells showed that mutation of these putative Sp1/Sp3 binding sites results in up to 90% inhibition of basal promoter activity, whereas overexpression of exogenous Sp1 or Sp3 protein can activate NPR2 promoter activity (Rahmutula et al. 2004), clearly supporting a role for Sp1/Sp3 proteins in the expression of human GC-B receptor.

While we acknowledge that Sp1 family proteins are ubiquitous, it is interesting to note that Sp1 is involved in the transcriptional regulation of other members of the natriuretic peptide/GC/cGMP signaling pathway. Both the promoters for ANP (NPPA) and the GC-A receptor (NPR1) have been shown to be regulated by Sp1 (Liang et al. 1999, Kumar et al. 2010, Hu et al. 2011), and we, and others, have indicated a role for Sp1/Sp3 in controlling Nppc transcription in pituitary cell lines (Ohta et al. 1993, Thompson et al. 2009). The other major regulator of cGMP signaling is the gaseous neurotransmitter, nitric oxide (NO), and both neuronal and endothelial forms of the NO-synthesizing enzyme, NO synthase (NOS1 and NOS3, respectively), are transcriptionally controlled by Sp1 (Kleinert et al. 1998, Bachir et al. 2003). Finally, the promoters for the cGMP-selective phosphodiesterase 5 enzyme genes (PDE5A1 and PDE5A2) have also been shown to contain Sp1 response elements (Yanaka et al. 1998, Kotera et al. 1999). Collectively, it appears that transcriptional control of proteins involved in cGMP signaling is heavily influenced by Sp1 family proteins.

While the predominant regulatory region involved in controlling NPR2 transcription appears to reside within the most proximal 214 bp, our current findings demonstrate some differential regulation of the human NPR2 promoter in gonadotroph cell lines. The −645 bp promoter was also maximally active in LBT2 cells, whereas activity of this construct in the developmentally immature αT3-1 cells was not significant. *In silico* analysis of this region of the human NPR2 promoter reveals numerous putative response elements for nuclear hormone receptors (e.g., for glucocorticoids, estrogen, and retinoic acid). It remains to be established whether responsiveness to these hormones is enhanced in the more mature gonadotroph to subsequently alter NPR2 transcription.

Expression of natriuretic peptide receptors has previously been shown in tumors of other cellular origin. The GC-A receptor, encoded by NPR1/Npr1, is highly expressed in prostate cancer cells (Wang et al. 2011), and natriuretic peptides have been demonstrated to act as anticancer therapies to treat pancreatic, breast, and lung carcinomas implanted within athymic mice (Vesely 2009). Our demonstration that pituitary tumor tissue also expresses NPR2/GC-B raises the intriguing possibility that these receptors might be useful in generating novel therapies, although pituitary adenomas are usually slow growing and rarely malignant (Melmed 2003). It remains to be established whether GC-B receptors in human pituitary tissue can act as secretagogue modulators, although previous studies suggest that both CNP and NO are capable of stimulating GH secretion from rodent pituitaries (Shimekake et al. 1994), human fetal pituitaries, and human pituitary adenomas (Rubinek et al. 2005).

While there are some reports on pituitary roles for natriuretic peptide signaling, such as increasing GH secretion (Hartt et al. 1995, Shimekake et al. 1994, Eckert et al. 2003) or inhibiting ACTH secretion (Guild & Cramb 1999), these effects may well be cell-type specific and are not known to be recapitulated in humans. Genetically manipulated mouse models of disrupted Nppc or Npr2 also point to a pituitary role for CNP and GC-B (Chuslo et al. 2001, Tamura et al. 2004), given the profound growth and reproductive disruption to these animals, yet these intriguing possibilities remain to be determined within a pituitary-specific context. Our current observations of NPR2 expression in all endocrine cell types of the human anterior pituitary support previous suggestions that CNP acts as an autocrine or paracrine regulator in the pituitary, but the nature of this paracrinicity is unknown (Denef 2008). Although the presence of a pituitary natriuretic peptide system in other vertebrate species suggests that cGMP signaling is important for normal pituitary function, understanding of whether a
similar system is present in human pituitaries is very limited. Before our current observations of pituitary NPPC and NPR2 expression, previous studies on humans suggest that normal pituitary tissue expresses NPPB (encoding BNP), PKG2 (encoding protein kinase G II), and PDE11A (encoding phosphodiesterase 11A) (Gerbes et al. 1994, Fawcett et al. 2000, Zhan & Desiderio 2004). The presence of both PKG2 and PDE11A in human pituitaries indicates potential cGMP-target proteins, which might regulate the effects of CNP/GC-B signaling. PDE11A acts as a dual-specificity cyclic nucleotide phosphodiesterase that causes cAMP and cGMP hydrolysis (Francis et al. 2011) and, intriguingly, mutations within PRD11A are associated with several endocrine neoplasias (Horvath et al. 2006, 2009). It is, therefore, feasible that a pituitary natriuretic peptide system in humans might serve to regulate cyclic nucleotide-regulated hormone secretion. Alternatively, as CNP and GC-B are major local regulators of the cardiovasculature, it is tempting to speculate that NPR2 expression is contributing to the local dynamic control of pituitary blood flow, in both normal and adenomatous tissue, given the highly vascularized properties of the anterior pituitary (Turner et al. 2000). It is clear that understanding the physiological relevance of our expression studies within human pituitary tissue remains to be established.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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